An experimental method to study high speed sliding characteristics during forward and reverse slip

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Abstract

This paper introduces an experimental technique to investigate dynamic friction characteristics of sliding interfaces at normal pressures up to 125 MPa, slip speeds up to 15 m/s and slip distances of approximately 10 mm. This new apparatus involves a novel modification of the conventional torsional Kolsky bar apparatus employed extensively in the past to investigate high-strain-rate behavior of engineering materials. The experimental configuration allows critical frictional parameters such as the friction-stress, slip speed and slip displacement to be resolved on a micro-second time scale without the use of transducers at the frictional interface. Moreover, the experiment provides information on the evolution of dynamic friction stress during forward as well as reverse slip.

Using this experimental configuration dynamic friction experiments were conducted on 6061-Al (T6)/1018 steel and 7075-Al (T6)/tool-steel (D3) tribo-pairs. The results of experiments on 6061-Al (T6)/1018 steel indicate that steady-state kinetic friction is obtained within the rise time of the torsional loading pulse. The coefficient of kinetic friction is observed to increase with the roughness of the tribo-pair surfaces. For a soft/hard tribo-pair interface (7075 Al/tool-steel (D3)) the surface roughness of the harder material (tool-steel (D3)) constituting the tribo-pair is observed to control the frictional force. The measured coefficient of kinetic friction is approximately independent of the interfacial slip velocity for sliding velocities in the range of 2–10 m/s and normal pressures of approximately 100 MPa. Moreover, it is observed that the dynamic friction stress during reverse slip is almost twice as large when compared to friction stress in the forward direction. This increase in friction stress is understood to be due to frictional contact between fresh metallic surfaces formed by the breakdown of oxide and other surface films and anisotropy in frictional surfaces developed during the forward slip. © 2001 Published by Elsevier Science B.V.

Keywords: High-speed-friction; Torsional Kolsky bar; Wave-propagation; 7075-T6 Al; Tool-steel

1. Introduction

High-speed sliding at dissimilar material interfaces plays an important role in the design of several tribo-elements including bearings, gears, friction clutches, high performance brake liners for the aerospace industry, tribological coatings performing under strict tolerances in extreme environments, friction and explosion driven welding processes, interfaces of bodies during high velocity impact, rocket driven vehicles on rails, to name a few. Dynamic friction during contact-impact conditions are also important in characterization of dynamic material failure, for example, fragmentation, pulverization and flow of brittle materials, fiber-matrix debonding in composite materials, and crack propagation in multi-layered material systems.

Several experimental studies have been conducted in the past to study dynamic friction under high-speed slip conditions. These include studies by Williams and Griffen [1], Montgomery [2], Kadhim and Earles [3], Lim et al. [4], Ogawa [5], Tanimura et al. [6], Bowden and Persson [7], and Bowden and Freitag [8], to name a few. Despite these excellent contributions, models that can accurately predict friction and wear of surfaces in dynamic contact are still elusive. Some of the difficulties in developing such predictive models are because frictional tractions between two bodies in contact is a complex process that is not only affected by factors such as interface constitution, surface roughness, time scales of contact, inertia and thermal effects, history of loading, chemical composition, environment, etc., but also on the dynamic parameters of experimental apparatus such as the mass, stiffness and damping. In an attempt to develop experimental methods to investigate dynamic friction that is independent of stiffness and damping characteristics of the load train, the pressure-shear plate-impact friction experiment was introduced by Prakash and Clifton [9]. More recently,
the plate impact pressure shear friction experiment has been extended to study dynamic friction characteristics at elevated temperatures by Irfan and Prakash [10], and near melt and fully melt temperatures by Prakash and coworkers [11]. These studies have helped to clarify the role of normal pressure, slip speeds and temperature in controlling the evolution of friction stress under contact impact sliding conditions.

In the present paper, a modified torsional Kolsky bar friction experiment is presented to investigate sliding resistance of frictional interfaces at normal pressures of up to 100 MPa, slip speeds up to 10 m/s and slip distances of approximately 10 mm. This new apparatus involves a novel modification of the conventional torsional Kolsky bar apparatus employed extensively in the past to investigate high-strain-rate behavior of engineering materials. The experimental configuration allows critical frictional parameters such as the friction-stress slip speed and slip displacement to be resolved on a microsecond time scale without the use of transducers at the frictional interface. Moreover, a novel feature of the experiment is that it provides information on the evolution of friction stress during forward as well as reverse dynamic slip.

The conventional torsional Kolsky bar apparatus is a reliable apparatus for testing the dynamic response of engineering materials in the $10^{2}$–$10^{4}$ s$^{-1}$ plastic strain-rate range. The apparatus consists of an incident bar and a transmitted bar supported along its length by Teflon bearings. The torsional loading pulse is generated by a sudden release of stored torque. This requires a torque pulley system at the end of the incident bar and a frictional clamp positioned a short distance from the pulley end. The torque is generated by employing a hydraulic actuator to twist the pulley attached to the end of the incident bar. The frictional clamp designed by Hartley et al. [12] for the torsional Kolsky bar, allows the desired torque to be held without slipping and releases the torque rapidly enough — when the pre-notched bolt breaks — to release a sharp fronted stress pulse which travels towards the specimen sandwiched between both the bars. The design of the frictional clamp is critical; if the mechanism is asymmetrical, longitudinal or flexural waves will also be generated in the bar. Two sets of strain gages are mounted on the Kolsky bar, one upstream and the other downstream of the specimen. The upstream gage monitors the incident torsional pulse and the pulse reflected from the specimen, whereas the downstream gage monitors the pulse transmitted through the specimen. The former provides a measure of the average strain rate, and by integration the strain as a function of time. The transmitter gage provides an output proportional to the shear stress in the specimen.

The schematic of the modified torsional Kolsky bar apparatus employed in the present study is shown in Fig. 1. In this modified configuration, a thin-walled tubular specimen is mounted at the end of the solid incident bar. The tubular specimen represents one of the materials constituting the tribo-pair. The motivation for the use of the tubular thin-walled specimen is because the thin tubular section minimizes errors due to the averaging of the frictional stress and the interfacial slip speeds across the face of the specimen. Moreover, the transmitter bar of the conventional torsional Kolsky bar is replaced by a rigid support. Besides providing a rigid boundary condition the support also represents the other half of the tribo-pair. To conduct the dynamic friction experiments the specimen on the incident bar, which has been lapped flat prior to mounting, is placed in contact with the face of the rigid support (which represents the other half of the tribo-pair) by applying a static compressive force of pre-determined magnitude. This axial compressive force is applied by a hydraulic actuator provided at the pulley end of the modified torsional Kolsky bar apparatus. The clamping mechanism is similar to the one used in the conventional torsional Kolsky bar. The amplitude of the desired input torque and angular velocity is a determining factor in selecting the notched-pin material and the depth of the notch. Pulse rise time is also affected by the choice of the material for the notched pin. The pin must show limited ductility and be able to prevent premature fracture before the clamp is tightened to ultimate load. In the present study a 6061-T6 Al pin with a notch depth of approximately 12 mm is
employed. Some researchers have experimented with steel pins, but even brittle steels produce longer rise times than do aluminum alloys. For each experiment a fresh tubular specimen is employed. The mating surfaces of the tribo-pair are lapped and then cleaned with acetone before being statically compressed.

The incident bar is 25.4 mm in diameter and is fabricated from 6061-T6 Al. For the experiments presented in this paper the thin-walled tubular specimen is made from either 6061-T6 Al or 7075-T6 Al. The rigid support which represents the other half of the tribo-pair is fabricated from either 1018 steel or Carpenter Hampden (CH) tool-steel. The steel disk is 75 mm in diameter and approximately 25.4 mm in thickness. The validity of the steel disk to represent a rigid support is ensured by comparing the ratio of the mechanical impedance of the tribo-pair interface, i.e. the ratio of the impedance of the thin-walled tubular specimen to the impedance of the steel disk, which is approximately 1:500 for the present experiments. This condition ensures that the angular velocity of the steel disk is essentially zero and the angular velocity of the thin-walled Al specimen at the tribo-pair interface is the angular slip velocity.

In order to conduct the dynamic friction experiment the aluminum alloy specimen is epoxied to the end of the incident bar. Upon application of the normal force the incident tube with the epoxied specimen slides axially in the alignment fixture and comes into contact with the face of the lapped steel disk. An important consideration in the implementation of the experiment is that while the interfacial sliding is in progress the sliding faces of the tribo-pair must be in contact at all times. This is achieved by using an alignment fixture [13] which ensures that the tubular specimen is aligned perpendicular to the other surface of the tribo-pair, i.e. the surfaces in contact — which are lapped flat prior to the experiment — are parallel to each other, at all times.

The shear strain in the incident bar is measured by strain gages attached to the surface of the incident thin-walled tube. As the pulse travels down the incident bar, it is detected by a four-arm electric resistance strain gage (Measurement Group SK-13-120NC-10C) bridges mounted 45° at the strain-gage station A and powered by a 30 V direct current supply. This strain gage is positioned such that there is no overlap of the incident wave and the reflected wave from the specimen end. The axial strains in the incident bar are measured by means of axial strain gages attached to the incident bar at gage station B. The gage station B consists of two linear resistance strain gages which form the two opposite arms of a Wheatstone bridge, thereby helping to eliminate bending contributions. Outputs from the respective Wheatstone bridges are fed to a differential amplifier (Textronix 511A) and then onto a digital oscilloscope (Textronix TDS 420).

2.1. Wave propagation in the modified torsional Kolsky bar apparatus

The wave propagation diagram is illustrated in Fig. 2. Position of the wave front versus time is detailed. Time $t = 0$ corresponds to the time at which the frictional clutch is released. At this instant, the mechanical state in the bar to the left of the frictional clamp corresponds to the applied torque $T = T_0$, and zero angular velocity. This mechanical state is represented by State 0 in Fig. 2. The mechanical state in the solid incident bar to the right of the clamp is denoted by State 2 and corresponds to zero torque and zero angular velocity. When the frictional clamp is released, half of the input torque propagates as a torsional pulse to the

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**Fig. 1. Schematic of the modified torsional Kolsky bar apparatus employed to investigate dynamic friction.**
left of the frictional clamp and the other half propagates to the right towards the tribo-pair interface. The corresponding stress and particle velocity states on either side of the frictional clamp are denoted by State 1. The torsional wave propagating to the left of the frictional clamp reflects from the pulley end (rigid end) and travels towards the clamp, unloading the bar to the mechanical state represented by State 3. The strain gage at station A sees State 1 until the wave reflected from the pulley end of the solid bar returns to the gage station A. The resulting mechanical state is denoted by State 3. The wave reflected from the tribo-pair interface returns to the gage station A and results in State 5. This returning wave carries information regarding the frictional state at the tribo-pair interface. By measuring the torsional strains at the gage location A during States 1 and 5, the critical interfacial friction parameters, i.e. the frictional stress, the interfacial slip speed and the accumulated slip displacement can be obtained by using the framework of one-dimensional plane-wave analysis. Details of this analysis are presented in Section 4.

In the present experiments, the mismatch in torsional impedance at the incident bar/specimen interface results in reverberations of the incident stress-wave within the length of the specimen. To better understand the effect of these reflections the loci of all attainable torque and angular velocity states is shown in Fig. 3. The thick solid lines represent the loci of all attainable torque and angular velocity states in the incident bar. The slope of the solid line represents the mechanical impedance of the incident bar. The dashed line represents the critical frictional strength for no-slip at the tribo-pair interface. The slope of the thin solid line represents the mechanical impedance of the tubular speci-
men. The thin solid line represent the reverberations of the stress wave within the tubular specimen before a uniform state is attained. Approximately, 5–6 reverberations are necessary before the attainment of steady-state interfacial conditions. It must be noted that the torque versus angular velocity diagram, shown in Fig. 3, represents the case for which a steady frictional state is present at the interface.

For situations in which the interfacial friction stress can strengthen or weaken, the time duration before equilibrium conditions are attained is expected to increase. For the present investigation the length of the tubular specimen is 12.5 mm, and for a torsional wave speed in aluminum of 3100 m/s, the time taken for each reverberation in the specimen is approximately $\frac{4}{9262}$ s. This implies that it can take up to approximately 30 $\frac{4}{9262}$ s before a steady state is attained at the tribo-pair interface. Since in the present experiments this time is well within the rise time of the torsional pulse, and the mismatch in the shear impedance at the specimen/bar interface is expected to lead to no significant errors.

In order to obtain the frictional characteristics of the tribo-pair interface during reverse frictional loading, consider the reflected wave as it propagates left towards the pulley after the initial loading of the tribo-pair interface. This wave reflects off the pulley (fixed end) and propagates towards the tribo-pair interface to load it again. Upon arrival of the loading wave at the frictional interface, the mechanical state at the frictional interface changes from States 7 to 10, where State 7 corresponds to a zero torque and zero angular velocity state. The state at the gage station A, which was at State 7, changes to State 8 and then returns to a zero state (State 9) after the passage of the loading pulse. Upon arrival of the reflected wave from the tribo-pair interface the state at the gage station A changes from States 9 to 11. This reflected wave carries information required to obtain the frictional characteristics when it is loaded for the second time in reverse slip. The details of the analysis are presented in Section 4.

3. Specimen preparation

The rubbing surfaces of the tribo-pair interface are ground and lapped flat prior to the experiments. Lapping is carried out by using a water-based aluminum oxide lapping compound. The roughness of the tubular aluminum specimen is varied from R$q = 0.1$ to $0.45\mu m$ by hand polishing for different time durations using 15 and $3\mu m$ diamond polishing compound. The surface of the ground steel disk is also lapped and polished to vary the surface roughness over the range of R$q$ from 0.1 to $0.2\mu m$. The surface roughness profiles are obtained by using a Hommel® T500 diamond stylus surface profile measurement device.

Once the tribo-pair materials are ready for testing, the incident bar and the tubular specimen are epoxied by employing a two-part epoxy Hysol 143, with a theoretical shear strength of approximately 50 MPa. The magnitude of the applied torque for a given level of the applied axial force is determined by the condition that precludes yielding of the epoxy under the combined state of stress. Also, the magnitude of the applied torque is limited by the torque that can be resisted by the frictional clamp without slip. Next, the normal force is applied resulting in the tubular specimen to come into contact with the surface of the tribo-pair (steel disk in this case). Under the superimposed normal force the epoxy is allowed to cure for 24 h.

4. Analysis

The objective of the analysis is to obtain the critical frictional characteristics, i.e. the interfacial tractions, the slip speed and the slip distance from the measurements of the shear strains at the strain gage location A. The propagation of elastic torsional waves in the incident bars is governed by a system of first order hyperbolic partial differential equations, i.e.

$$\frac{1}{J\mu} \frac{\partial T}{\partial t} - \frac{\partial \omega}{\partial x} = 0,$$

$$J\rho \frac{\partial \omega}{\partial t} - \frac{\partial T}{\partial x} = 0,$$

where $J$ is the polar moment of inertia, $\mu$ the shear modulus, $T$ the torque and $\omega$ is the angular velocity.

The solution to the system of partial differential equations represented by Eq. (1) can be obtained by employing the method of characteristics to yield

$$\frac{dT}{dt} + \rho JC \frac{d\omega}{dt} = 0 \quad \text{along} \quad \frac{dx}{dt} = \mp C.$$  

Using appropriate initial conditions the loci of all states that can be attained in the incident tube at the tribo-pair interface.
can be represented by the torque versus angular velocity diagram shown in Fig. 3. For the case in which there is full sticking at the tribo-pair interface the state at the frictional interface is represented by point B. For any other case in between, i.e. when the torque supported by the tribo-pair interface is \( T_{\text{interface}} \), the corresponding angular slip speed at the frictional interface is given by

\[
\omega_{\text{interface}} = \frac{T_{\text{interface}} - 2T_1}{\rho C J_{\text{bar}}},
\]

where \( T_1 \) is the known input torque at the tribo-pair interface.

In order to obtain the frictional torque at the tribo-pair interface \( T_{\text{interface}} \), a backward drawn characteristic joining states \( (T_{\text{interface}}, \omega_{\text{interface}}) \) and \( (T_8, \omega_8) \), and a forward drawn characteristic joining \( (T_3, \omega_3) \) and \( (T_5, \omega_5) \) are used. Moreover, using the result that State 3 is a zero state the torque at the tribo-pair interface can be expressed in terms of the measured torques \( T_5 \) and \( T_1 \), i.e.

\[
T_{\text{interface}} = T_1 + T_5.
\]

Once the interfacial torque and the interfacial angular slip-speeds are obtained, the average interfacial friction stress and the average interfacial slip speeds at the tribo-pair interface can be obtained using

\[
\tau_{\text{interface}}(t) = \frac{\int_{r_1}^{r_0} r \tau(r, t) \, dr}{\int_{r_1}^{r_0} r \, dr}, \quad \text{where } \tau(r, t) = r T_{\text{interface}}(t) J_{\text{specimen}}
\]

and

\[
V_{\text{slip}}(t) = \frac{\int_{r_1}^{r_0} r^2 \omega_{\text{interface}}(t) \, dr}{\int_{r_1}^{r_0} r \, dr}.
\]

In Eqs. (5) and (6), \( r_1 \) and \( r_0 \) are the inner and outer radii of the thin-walled tubular specimen, respectively.

The normal stress at the interface can be obtained from the measured axial strain in the incident bar, i.e.

\[
\sigma_{\text{interface}} = E \varepsilon_{\text{bar}} \frac{A_{\text{bar}}}{A_{\text{specimen}}},
\]

where \( E \) is the elastic modulus in the incident bar, and \( \varepsilon_{\text{bar}} \) is the measured axial strain in the bar.

The accumulated slip distance can be evaluated by integrating the slip velocity history as given in Eq. (6) and the coefficient of kinetic friction \( \mu_k \) is evaluated from the interfacial shear stress (Eq. (5)) and the normal stress (Eq. (7))

\[
\mu_k(t) = \frac{\tau_{\text{interface}}(t)}{\sigma_{\text{interface}}}. \tag{8}
\]

In order to obtain the frictional state at the tribo-pair interface \( T_{\text{interface}} \), under repeated (reverse) frictional loading, a backward drawn characteristic joining the \( (T_{\text{interface}}, \omega_{\text{interface}}) \) (State 10) and \( (T_11, \omega_11) \), and a forward drawn characteristic joining \( (T_8, \omega_8) \) and \( (T_11, \omega_11) \) are used. Using the result that State 9 is a zero state the torque at the tribo-pair interface can be expressed in terms of the measured torques \( T_8 \) and \( T_{11} \), i.e.

\[
T_{\text{interface}} = T_8 + T_{11}, \tag{9}
\]

and

\[
\omega_{\text{interface}} = \frac{T_{\text{interface}} - 2T_8}{\rho C J_{\text{bar}}}. \tag{10}
\]

Once the \( T_{\text{interface}} \) and \( \omega_{\text{interface}} \) are obtained the frictional shear stress and the interfacial slip velocity are obtained using Eqs. (5)–(10).

### Table 1

<table>
<thead>
<tr>
<th>Experiment no.</th>
<th>Input torque (kN m)</th>
<th>Normal pressure (MPa)</th>
<th>6061-T6 Al Rq (µm)</th>
<th>1018 Steel Rq (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fric 4</td>
<td>0.064</td>
<td>34.5</td>
<td>0.10 (smooth)</td>
<td>0.21 (rough)</td>
</tr>
<tr>
<td>Fric 5</td>
<td>0.059</td>
<td>34.5</td>
<td>0.10 (smooth)</td>
<td>0.21 (rough)</td>
</tr>
<tr>
<td>Fric 6</td>
<td>0.070</td>
<td>34.5</td>
<td>0.10 (smooth)</td>
<td>0.10 (smooth)</td>
</tr>
<tr>
<td>Fric 7</td>
<td>0.057</td>
<td>39.2</td>
<td>0.41 (rough)</td>
<td>0.18 (rough)</td>
</tr>
</tbody>
</table>

The first series of experiments was designed to study the effect of surface roughness of the tribo-pair materials on the friction stress. The tribo-pair under investigation was 1018 steel/6061-T6 Al. In this series of four experiments (Fric 4–7) the surface roughness of the tribo-pair surfaces was progressively varied from \( \text{Rq} = 0.1 \) to \( 0.45 \, \mu\text{m} \) for 6061-T6 Al, and \( \text{Rq} = 0.1 \) to \( 0.2 \, \mu\text{m} \) for 1018 steel. The normal
Table 2
Summary of experiments representing the second and the third series of experiments

<table>
<thead>
<tr>
<th>Experiment no.</th>
<th>Input torque (kN m)</th>
<th>Normal pressure (MPa)</th>
<th>7075-T6 Al (soft) Rq (μm)</th>
<th>Carpenter Hampden steel (hard), Rq (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fric 8</td>
<td>0.06</td>
<td>97.6</td>
<td>0.40</td>
<td>0.10</td>
</tr>
<tr>
<td>Fric 9</td>
<td>0.056</td>
<td>99.5</td>
<td>0.45</td>
<td>0.03</td>
</tr>
<tr>
<td>Fric 10</td>
<td>0.078</td>
<td>97.6</td>
<td>0.45</td>
<td>0.06</td>
</tr>
<tr>
<td>Fric 11</td>
<td>0.054</td>
<td>90.4</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>Fric 13</td>
<td>0.098</td>
<td>113.9</td>
<td>0.40</td>
<td>0.07</td>
</tr>
<tr>
<td>Fric 14</td>
<td>0.05</td>
<td>121.1</td>
<td>0.44</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 1 the surface roughness of the 6061-T6 Al and the 1018 steel plates was Rq ~ 0.10 μm and is referred to as the smooth–smooth case. The average value for the coefficient of kinetic friction is 0.15. Some of the large undulations observed in the frictional stress are because of the difficulty in measuring relatively small levels of friction stress obtained for the smooth–smooth tribo-pair condition. Curves B and C correspond to experiments Fric 4 and 5. These experiments represent the smooth–smooth tribo-pair condition. Curves B and C correspond to experiments Fric 4 and 5. These experiments represent the smooth–rough case with the 1018 steel specimen having an average roughness of Rq = 0.20, which is twice that of 1018 steel specimen employed in Fric 6. In both experiments, on arrival of the torsional loading pulse the coefficient of kinetic friction rises to a level of approximately 0.52 and remains at this level for the entire duration of the experiment. It is important to note that for experiments represented by Fric 4 and 5 the surface roughness of the tribo-pair are very similar. Since the levels of the coefficient of kinetic friction obtained in these two experiments are also very similar, it shows that reproducible results can be obtained by using the modified torsional Kolsky bar apparatus. The small difference in the level of the slip velocity obtained for the two experiments is a consequence of the difference in the input torque employed in experiments Fric 4 and 5. Curve D (Fric 7) represents the dynamic friction experiment for which both the tribo-pair surfaces are rough. The coefficient of kinetic friction rises to an average level of approximately 0.65, which is the highest amongst the four experiments.

Fig. 4(b) shows the variation of the interfacial slip velocity as a function of the slip distance for the four experiments discussed above. The highest slip-speed is obtained for the smooth–smooth case (Curve A) and has an average value of 10 m/s. For the smooth–rough case (Curves B and C) slipping speeds of approximately 7.0 m/s are obtained. For the rough–rough case (Curve D) the average slip speed is 5 m/s, and thus has the smallest accumulated slip. The results of these experiments indicate that, for similar input torque levels, by systematically changing the surface roughness of the tribo-pair surfaces the slip condition at the frictional interface can be varied from high to relatively low slip speeds. As expected, the smoother interface transmits a lower level of friction stress and slips at a much higher average slip speed.

Figs. 5 and 6 show the experimental results obtained from the second series of dynamic friction experiments. Fig. 5(a) and (b) represent the experimental results obtained by employing tribo-pairs in which the surface roughness of the

6. Experimental results and discussion

Fig. 4(a) and (b) summarizes the experimental results for the four experiments (i.e. Fric 4–7) representing the first series of experiments. Fig. 4(a) presents the variation of the coefficient of kinetic friction with the interfacial slip distance. Curve A represents the measured coefficient of kinetic friction curve for experiment Fric 6. As shown in pressure and the input torque were kept nearly constant at 35 MPa and 65 N m, respectively.

The second series of experiments was designed to investigate the effect of surface roughness of the harder material in the tribo-pair on the frictional behavior of the tribo-pair interface. The tribo-pair used for the investigation was Carpenter Hampden steel/7075-T6 Al. Experiments Fric 8–11 represent the experiments conducted in this series. In all the experiments a nearly constant normal pressure (90–100 MPa) was employed. The input torque varied from 50 to 80 N m, while the roughness of the harder material in the tribo-pair was varied from Rq = 0.03 to 0.10 μm.

The third series of experiments was designed to study the slip velocity versus friction stress relationship for a Carpenter Hampden steel/7075-T6 Al tribo-pair. This series involves three experiments, i.e. Fric 10, 13, and 14. In order to achieve the objectives of this series of experiments the roughness combination of the tribo-pair material was kept nearly constant at Rq = 0.06 μm for the Carpenter Hampden steel, and Rq = 0.42 μm for the 7075-T6 Al. Different levels of interfacial velocity were obtained by employing different levels of input torque.

As discussed in Section 4, the torsional Kolsky bar experimental configuration allows the investigation of dynamic friction resistance during reverse slip on a region on which forward slip has occurred before. In view of this, experiments conducted in the Series 2 and 3, i.e. Fric 8–11, 13, and 14, were analyzed up to the time when the second loading wave reflects from the tribo-pair interface and reaches the strain gage location A. In this series of experiments the applied normal pressure varied between 95–120 MPa, while the input torque level varied from 50 to 100 N m. The surface roughness of the Carpenter Hampden steel varied from Rq = 0.03 to 0.10 μm, while the surface roughness of the 7075-T6 Al was varied from Rq = 0.05 to 0.45 μm.
CH tool-steel plate is changed from 0.1 to 0.03 while the surface roughness of the 7075-T6 Al (soft) plate is kept the same. The experimental results indicate that the coefficient of kinetic friction changes from approximately 0.2 to 0.1 as the surface roughness of harder material is changed from 0.1 to 0.03. Fig. 6(a) and (b) represent the experimental results for tribo-pairs in which the surface roughness of the softer material, i.e. 7075-T6 Al, is changed from 0.45 to 0.05 while maintaining the same surface roughness for the CH tool-steel plate. It is interesting to note that coefficient of kinetic friction obtained by employing the two different surface roughness of the softer material is essentially the same. This is an important result and shows that under the conditions of the present experiments, it is the surface roughness of the harder plate that governs the friction stress at the sliding interface. It should also be noted that the slip speeds for the two experiments are 5 and 3 m/s, respectively. This difference in slip speed levels is due to the much higher input torque used in conducting experiment Fric 10.

Fig. 7 shows the experimental results for the third series of experiments. In Fig. 7(a), the coefficient of kinetic friction is shown as a function of slip distance. As mentioned earlier, for this series of experiments the surface roughness of the tribo-pair surfaces was maintained nearly the
same while the input torque was the highest for Fric 13 and smallest for Fric 14. It is interesting to note that the coefficient of kinetic friction is nearly constant at a level of \( \mu_k \sim 0.22 \) for the three experiments. The small undulations observed in the coefficient of kinetic friction profile are due to oscillations carried by the input torque. Fig. 7(b) shows the interfacial slip velocity as a function slip distance for experiments reported in Fig. 7(a). The slip speed is highest for Fric 13 at approximately 6 m/s and the lowest for Fric 14 at 3 m/s. These levels of slip speeds are consistent with the input torques employed in these experiments. For Fric 13 the input torque was 0.98 kN.m whereas for Fric 14 the input torque was only 0.5 kN.m. In view of these experimental results it can be concluded that for the CH tool-steel/7075-T6 Al tribo-pair the friction stress is nearly constant for interfacial slip speeds in the range of 3–6 m/s. This result is consistent with the experimental results obtained from plate-impact pressure-shear friction experiments conducted by Irfan and Prakash [10] which clearly show that large changes in the interfacial slip speeds lead to only small changes in steady-state friction stress levels.

The fourth series of experiments was designed to study dynamic friction resistance of sliding interfaces in situations which involve reverse slip on a region on which slip has occurred before. The total time during which both the forward and reverse slip occurs is approximately 1.5 ms. The
Frictional characteristics during reverse slip were analyzed in all experiments that were conducted using Carpenter Hampden tool-steel/7075-T6 Al tribo-pair, i.e., experiments Fric 8–14. Table 2 summarizes the interfacial conditions for these seven experiments. Fig. 8(a) and (b) represent the experimental results obtained from the analysis of Fric 11. From the t–x diagram of the modified torsional Kolsky bar (Fig. 2), it is seen that there are two loading pulses. The first loading pulse, represented by State 1, is generated by the sudden release of the stored torque when the pre-notched bolt in the clamp is fractured. The second loading pulse, represented in Fig. 2 by State 8, is generated by reflection of the first loading torsional wave by the pulley. Fig. 8(a) shows the two loading pulses for experiment Fric 11; the solid-line represents the first loading pulse (State 1) and the dashed-line represents the second loading pulse (State 8). It is to be noted that the shape of the incident loading pulse $T_8$, is governed by the frictional characteristics of the tribo-pair interface during the first loading. The magnitude of $T_8$ (30 N m) is less than that for the incident pulse $T_1$ (54 N m) as part of the incident pulse is used in overcoming the frictional resistance. Fig. 8(b) shows the dynamic friction results for Fric 11. The solid lines show the variation of the coefficient of kinetic friction with time for States 1 and 8, and the dash-dot lines represent the variation in interfacial slip velocity with time. For both States 1 and 8, the coefficient of kinetic friction rises to a steady-state level and oscillates in the vicinity of this level.
The coefficient of kinetic friction $\mu_{k1} \sim 0.24$ for the first loading. The corresponding slip velocity is approximately 3.0 m/s. Since the second torsional loading pulse is generated by reflection of the first loading pulse from the pulley end (rigid end) the frictional slip in State 8 is opposite to the slip which occurred during the first loading pulse. This results in the 7075-T6 Al tubular specimen to retrace part of its slip path on the Carpenter Hampden steel disk. From the experimental results shown in Fig. 8(b), it is seen that the coefficient of kinetic friction $\mu_{k2}$ for the second loading is much higher ($\mu_{k2} \sim 0.45$) as compared to the steady-state coefficient of kinetic friction measured during the first loading. The frictional properties of unlubricated metals are greatly affected by the presence of surface layers on the metal [16]. When in contact with the air, the main constituent of the adsorbed layer at the surface of the sliding metal are generally molecules of water vapor and oxygen. As a result an oxide layer is produced by reaction of oxygen from the air with all metals (except with noble metals). The work hardened layer results from the heavy deformation of the metal due to the mechanical preparation of the surface. Bowden and Tabor [17] lay great stress on the
properties of oxide films at the interface, arguing that these films reduce the friction and wear and that the mechanical properties of these oxides are of primary importance. In a series of experiments conducted by Whitehead [18] on copper, it was shown that the thin film of oxide present on the metal at room temperature behaves in a protective manner at light loads. At higher levels of normal loads the friction stress is higher and correspond to the breakdown and penetration of the oxide film. Similar mechanisms are expected to play a role in the C–H tool-steel/7075-T6 Al alloy tribo-pair employed in the present experiments. During the reverse sliding of the tribo-pair surfaces, it is possible that the oxide layer breaks up occurs which exposes fresh metallic surfaces leading to a much higher coefficient of kinetic friction. Moreover, the higher levels of $\mu_{k2}$ can also be attributed to the development of slip anisotropy that is introduced during the forward slip in the first loading pulse.

As mentioned earlier, the dash-dot lines in Fig. 8(b) represent the variation in interfacial slip velocity with time. During the first loading pulse the slip velocity attains a steady-state of 3.0 m/s. During the second loading a slip velocity of approximately 1 m/s is obtained. This lower slip velocity can be attributed to: (a) the higher value of the coefficient of kinetic friction ($\mu_{k2} \sim 0.45$) during reverse slip when compared to $\mu_{k1} \sim 0.24$) during forward slip; and (b) the lower level of input torque available for the reverse/second loading when compared to the first loading.

Fig. 9(a) and (b) summarize the experimental results for experiment Fric 14. Fig. 9(a) shows the input torque levels for experiment Fric 14. The solid line represents the input torque for the first loading (State 1), the magnitude of

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**Fig. 8.** (a) Input torque profiles for forward and reverse loading for experiment FRIC 11; (b) coefficient of kinetic friction and the corresponding slip speed during forward and reverse loading.

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**Fig. 9.** (a) Input torque profiles for forward and reverse loading for experiment FRIC 13; (b) coefficient of kinetic friction and the corresponding slip speed during forward and reverse loading.
which is approximately 50 N m. The dashed line represents the input profile for the second loading. From Fig. 9(b) it is observed that the coefficient of kinetic friction, \( \mu_{k1} \), during forward slip has an average level of 0.25. The corresponding slip velocity is represented by the dash-dot line and is approximately 3 m/s. Again, the coefficient of kinetic friction during the reverse loading pulse is much higher (approximately 0.45) than that obtained during the first loading pulse. The corresponding slip velocity is 0.8 m/s.

In all experiments investigated in the fourth series of experiments it is observed that the dynamic friction stress required to sustain reverse slip is much higher (almost twice as large) when compared to the dynamic friction stress required to sustain dynamic slip in the forward direction. During the first loading the coefficient of kinetic friction, \( \mu_{k1} \), varies from 0.24 to 0.14 as the roughness of the harder material is changed from 0.1 to 0.03 m. The coefficient of kinetic friction during the second loading, \( \mu_{k2} \), is observed to be between 0.45 and 0.6. This increase in friction stress can be attributed to the anisotropy in frictional surfaces generated during forward slip and to frictional contact of fresh metallic surfaces due to the breakdown of oxide and other surface films.

7. Surface micrographs

In this section, scanning electron microscope photo-micrographs of the sliding surfaces of the C–H tool-steel/7075-T6 Al alloy tribo-pair are presented. Photo-micrographs were taken from tribo-pairs employed in experiments Fric 8 and 12. For experiment Fric 8, the surface roughness of the Carpenter Hampden steel specimen was \( R_q = 0.10 \mu m \) and the surface roughness of the 7075-T6 Al specimen was \( R_q = 0.40 \mu m \). The magnitude of the input torque used to conduct the experiment was 60 Nm, while the normal pressure was 97.6 MPa. For experiment Fric 12, the magnitude of the input torque (54 Nm) was nearly the same as that used in Fric 8 (60 Nm). However, the normal pressure for experiment Fric 12 (108.5 MPa) was higher than that employed in experiment Fric 8 (97.6 MPa). Moreover, the surface roughness of the tribo-pair surfaces employed in Fric 12 were smoother when compared to those employed in Fric 8. The surface roughness of the Carpenter Hampden steel specimen was \( R_q = 0.06 \mu m \) while the surface roughness of the 7075-T6 Al specimen was \( R_q = 0.11 \mu m \).

Fig. 10 shows typical micrographs taken from the slip surface of the 7075-T6 Al specimen used in experiment Fric 8. It should be noted that these micro-graphs represent wear surfaces of 7075-T6 Al specimens on which both forward and reverse slip have occurred. The direction of the initial slip is from top to bottom. Several parallel grooves can be observed on the slip surface. These grooves which are long scratches are formed by the “plowing” of the hard asperi-

Fig. 10. Post test micrograph of the sliding surface (7075-T6 Al) employed in experiment FRIC 8. Sliding direction is from top to bottom.

Fig. 11. (a) and (b) Post test micrographs of the sliding surface (7075-T6 Al) employed in experiment FRIC 12. Sliding direction is from top to bottom.
ties of the Carpenter Hampden steel specimen through the softer aluminum alloy. Also, long finger like extrusions are visible in the direction of slip. These extruded fingers are formed by the smearing of the oxide and other surface layers present on the aluminum specimen. Moreover, a series of parallel lips or tears are observed along the wear scar. The raised “lips” are not evidence of delamination but are more related to “chatter marks” or surface damage which accompanies the formation of a built-up edge on tools machining ductile materials at high cutting speeds [19]. It is significant that these features appear because they indicate new surface formation and considerable plastic flow in a short period of time [20].

Fig. 11(a) and (b) are surface micrographs of the 7075-T6 Al specimen used in experiment Fric 12. The direction of sliding is from top to bottom. The grooves seen in the micrograph are more distinct than those present on the surface of the aluminum specimen used in experiment Fric 8. This is probably due to the larger plastic deformation and smearing of the aluminum surface in the direction of slip caused by higher surface roughness of the tribo-pair surfaces employed in experiment Fric 8. The higher normal pressure employed in experiment Fric 12 may also have resulted in deeper grooves.

The extent of plasticity observed on the contact surfaces is a function of the mechanical properties of the surfaces in contact, e.g. surface hardness and shear strength of the tribo-pair materials in contact. In the softer material plastic deformation manifests itself as deep scratches/grooves generated by the plowing action of the C–H tool-steel asperities in the softer 7075-T6 Al alloy along the sliding direction. As observed from the micrographs of the sliding surfaces of the tested samples the harder Carpenter Hampden tool-steel

![Fig. 11(a) and (b) are surface micrographs of the 7075-T6 Al specimen used in experiment Fric 12.](image)

![Fig. 12. (a) Post test micrographs of the sliding surface (CH tool-steel) employed in experiment Fric 12. The figure shows the wear track developed due to frictional slip on the surface. (b) A magnified view of a crater created by the pull out of an inclusion from the CH tool-steel surface.](image)

![Fig. 13. (a) Post test micrographs of the sliding surface (CH tool-steel) employed in experiment Fric 12. Figure shows the formation of various pits on the specimen surface. (b) A magnified view of the grooves developed on the slip surface during the frictional loading process.](image)
shows significantly lower levels of plastic deformation when compared to the softer 7075-T6 Al alloy. Figs. 12(a and b) and 13(a and b) are photo-micrographs of the sliding surface of the Carpenter Hampden steel specimen used in Fig. 12. In Fig. 12(a), the scuffed track on the surface of the Carpenter Hampden steel specimen created during dynamic slip of the tubular aluminum specimen is clearly visible. The track starting at the right top corner of the micrograph has a width of approximately 1 mm. The dark smear in the center of the micrograph is probably debris and smeared metal transferred from the aluminum specimen. The photo-micrograph also reveals several craters on the surface of the steel specimen. Fig. 12(b) shows a highly magnified view of one of the several craters observed in Fig. 12(a). This crater was created by tearing out of a large impurity during dynamic slip. Fig. 13(a) also shows the surface damage that has occurred on the steel specimen. Uneven surface with craters and pits confirm that material removal from the steel specimen occurred during the dynamic slip process. Fig. 13(b) reveals slip marks on the surface of the steel specimen. Note that the direction of slip is from top to bottom.

8. Conclusions

The conventional torsional Kolsky bar was modified to study time-resolved frictional characteristics of sliding interfaces at normal pressures up to 150 MPa, slip speeds up to 15 m/s and slip distances of approximately 10 mm. The usefulness of the device is illustrated by studying the dynamic frictional characteristics of sliding interfaces comprising 1018 steel/6061-T6 Al and Carpenter Hampden steel/7075-T6 Al tribo-pairs. The experimental results indicate that

1. In all experiments a steady frictional state is achieved immediately after the arrival of the torsional wave at the tribo-pair interface.
2. The coefficient of kinetic friction for the 6061-T6 Al/1018 steel tribo-pair increases with surface roughness of the tribo-pair interface. Coefficient of kinetic friction ranging from 0.1 to 0.65 was measured for interface condition varying from rough–rough to smooth–smooth condition.
3. The coefficient of kinetic friction for the Carpenter Hampden steel/7075-T6 Al tribo-pair is observed to increase with the surface roughness. Coefficient of kinetic friction values ranging from 0.1 to 0.5 were measured.
4. For the Carpenter Hampden steel/7075-T6 Al tribo-pair the surface roughness of the harder material is observed to govern the friction stress and slip velocity at the frictional interface.
5. Large changes in the interfacial slip speeds are observed to lead to relatively small changes in the steady-state friction stress levels.

6. For the Carpenter Hampden steel/7075-T6 Al tribo-pair it was observed that the dynamic friction stress required to sustain reverse slip is much higher as compared to frictional stress required to sustain dynamic slip in the forward direction.

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References