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Temperature Rise When Rubber Slides

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It is of practical importance to know the temperature rise through the length of the contact zone when rubber slides on various substrates. Model experiments have been carried out with rubber pads sliding on wood. Temperature measurements were made and compared with theoretical estimates which were derived, allowing for heat conduction, from the frictional work done during sliding. The agreement was often excellent, suggesting that the theoretical expressions can be applied with confidence. Experiments were extended to the sliding of rubber on ice. Agreement between the measured and theoretical temperature rise was again satisfactory.

The importance of frictional temperature rise on the performance of rubber goods is well-known[1]. Attempts have been made to measure the temperature rise[2,3]. Various theoretical studies have been published for the case of skidding tyres[4,5] and it has been noted that the heat generated is confined to a thin surface layer of the rubber[6]. Radiation pyrometry has been used to sense the temperature of a tyre surface after leaving the contact zone[7].

In one study the frictional heating of elastomer sliders was analysed[8] and measurements made of the rise of temperature in the contact zone by embedding a thermocouple in a rubber slider at about 0.1 mm from the rubbing surface. It has also been noted by many that the temperature rise produced at high sliding speeds directly influences the observed level of friction which, being viscoelastic dependent, is temperature sensitive. It is also recognised that heat generation during sliding can damage the rubber surface[9,10]; equally the substrate surface may be changed and that is relevant to some of the studies described here. It is of direct interest to rubber/ice friction studies to know by how much the temperature rises through the length of the contact zone during steady state sliding.

Carslaw and Jaeger[11] have derived heat conduction expressions needed to estimate how much the temperature might rise. The object of the present work was to compare predictions with model experiments in which, for practical convenience, rubber pads were slid over wood and the temperature rise measured with an infra-red thermometer.

The analysis of frictional heating was also extended to the case of rubber sliding on smooth-surfaced ice. Whereas any temperature change on wood was detected with an infra-red thermometer, in the case of ice miniature thermocouples were used. Results suggest that a fair prediction of temperature rise can be made.

The various experiments carried out are reported here and the findings related to the practical uses of rubber.

THEORY

Consider a rubber pad sliding over a flat wood substrate *(Figure 1)*. Heat is generated by friction which gives rise to a boundary condition of *constant heat flux* (the rate at which heat is transferred across any surface at a given point per unit area per unit time). Suppose the constant heat flux is F_o. According to Carslaw and Jaeger, after heat has flowed for a time t into the substrate (zero initial temperature) the

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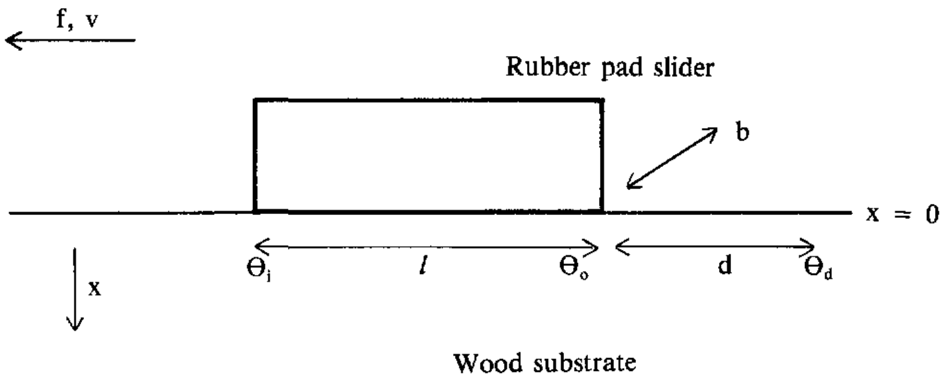

Figure 1. Heat generation by friction. Isothermal surfaces are planes parallel to x = *0 and the flow of heat is linear, the flow lines being parallel to the* x *axis. The solid which is bounded by the plane* x = *0 and extends to infinity in the positive* x *direction is termed the semi-infinite solid. Thermal properties are assumed to be independent of position and temperature. The heat flux at* x = *0 is a prescribed function of time, the initial temperature being zero.*

temperature at a point in the substrate plane $x = 0$ is given by

$$\Theta = \frac{2F_o}{K}\left(\frac{kt}{\pi}\right)^{1/2} \qquad \ldots 1$$

where K is the thermal conductivity of the substrate of diffusivity k ($k = K/\rho c$; c = specific heat and ρ = density). This expression assumes there is negligible heat flow into the rubber slider. This may be the practical case if the slider has a much smaller heat conductivity than the substrate. It is assumed, also, that there is negligible heat flow parallel to the substrate surface.

Suppose the rubber pad moves at a sliding speed v under a frictional force f, then the rate of doing work per unit area of contact is

$$\frac{fv}{lb} = F_o \qquad \ldots 2$$

where l is the length of the rubber pad and b its breadth. This work appears as heat which can raise the surface temperature of the substrate from Θ_i on going into the contact region to Θ_o on coming out. This temperature rise, $(\Delta\Theta)_o = \Theta_o - \Theta_i$, can be calculated using *Equation 1,* noting that heat has flowed for time $t = l/v$. Thus

$$(\Delta\Theta)_o = \frac{2f}{b}\left(\frac{v}{\rho c\,\pi K l}\right)^{1/2} \qquad \ldots 3$$

A practical difficulty arises in precisely measuring the temperature Θ_o at the exit edge. To overcome this, measurements were made using an infra-red thermometer positioned at different distances d away from the exit edge. Carslaw and Jaeger provide an expression for the fall-off in temperature with distance which can be written as

$$(\Delta\Theta)_d = (\Delta\Theta)_o, \left(\frac{l+d}{l}\right)^{1/2}. \left[1 - \left(1 - \frac{l}{l+d}\right)^{1/2}\right] \qquad \ldots 4$$

where $(\Delta\Theta)_d = \Theta_d - \Theta_i$.

If the slider's test conductivity is about the same as the substrate's, and if it cannot be assumed that a steady state temperature has been reached in the slider, then the value of $(\Delta\Theta)_o$ found from *Equation 3* would be halved if the slider is semi-infinite due to the equally shared heat flow into the substrate and into the slider. If the slider has a different heat conductivity K_2 to that of the substrate K_1 then *Equation 1* is modified to

$$\Theta' = \frac{2F_o}{K_1 k_2^{1/2} + K_2 k_1^{1/2}}\left(\frac{k_1 k_2 t}{\pi}\right)^{1/2} \qquad \ldots 5$$

EXPERIMENTAL

Procedure for Sliding on Wood

The arrangement of apparatus used to test the above predictions is shown in *Figure 2.* The rubber slider was stuck to the underside of the carriage and an infra-red thermometer mounted on the topside of the carriage. The thermometer (Heimann GmbH, type S3A66) was fitted with a short focus lens (type B KT 13/1). The thermometer was operated as per the manufacturer's recommendations with the emissivity adjustment control set for wood ($\epsilon = 0.83$). Its temperature resolution was about $\pm 0.2°C$ with a quoted accuracy of $\pm 1.5\%$ at fsd and response time, according to temperature range, of 0.2 s to 1.0 s for 90% of final reading. The carriage was either pulled by hand or by an electric motor (by hand gave the highest sliding speeds). The sliding velocity was found from the time taken (stopwatch) for the carriage to travel 1 m over the wood substrate (bench top). The carriage was loaded with metal plates as weights to provide a high normal stress at the rubber/wood interface. The friction force was measured with a calibrated spring. Signals from the IR thermometer were either read directly as temperature off the meter display unit or passed *via* a 'backing-off' circuit into a pen recorder. Voltage backing-off allowed small temperature changes to be followed more accurately.

The rubber slider used was a natural rubber sulphur vulcanisate containing 14% carbon *(Formulation A, Table 1).* Its density was 1050 kg m^{-3}. By reference to standard tables its specific heat was taken to be 1675 J kg^{-1} K^{-1} and its thermal conductivity to be 0.21 W m^{-1} K^{-1}.

The laboratory bench top over which the slider was run was made of African teak. Its density was 730 kg m^{-3} and by reference to standard tables its specific heat was taken to be 1382 J kg^{-1} K^{-1} and thermal conductivity to be 0.16 W m^{-1} K^{-1}.

A spring balance was found adequate to measure the tangential force f necessary to initiate sliding of the rubber pad over the wood surface. From this force the friction coefficient could be calculated by dividing by the normal load acting on the pad. For a rubber pad, freshly cleaned with alcohol, and run dry over dust-free wood the friction coefficient was generally 0.8–1.4. If the rubber surface was deliberately powdered lightly with French chalk the value fell to 0.4–0.6. When the friction was high it was difficult to pull the pad over the wood in a uniform manner — severe stickslip sometimes arose leading to an erratic temperature reading. For this reason chalk powder was often used to reduce friction and give smoother travel.

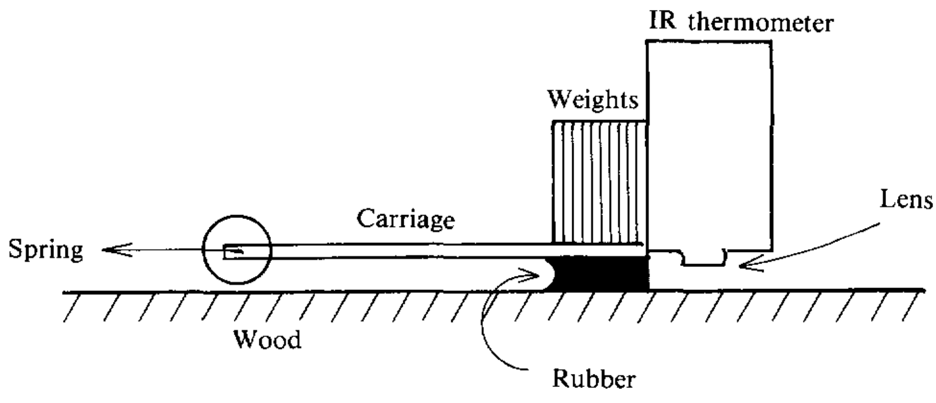

Figure 2. Arrangement of apparatus for measuring temperature rise on wood substrate using an IR thermometer.

TABLE 1. RUBBER COMPOUND FORMULATIONS

Item	Parts by weight		
	A	B	C
Natural rubber, SMR L	100	100	100
Carbon black, HAF	20		
Zinc Oxide	5	5	
Stearic acid	2	2	
Nonox ZA	1	1	
Sulphur	2.5	2.5	
Santocure CBS	0.6		
Sundex 8125	11.1		
Dicumyl peroxide			2
Santocure NS		0.5	
Cure time/temp. (min/°C)	40/140	40/140	60/160
Hardness (IRHD)	48	43	35

Procedure for Sliding on Ice

An attempt was made to measure the temperature rise of an ice track in high speed sliding contact with a rubber pad *(Formulation B, Table 1)* using an infra-red thermometer, all contained in a fridge *(Figure 3)*. It sensed the temperature of the ice surface after passing under the rubber. The sensing point was at some distance behind the rubber pad (see *Figure 3*) but a correction can be made for this, so that the temperature at the pad's exit edge can be calculated *(Equation 4)*.

To pursue the measurement and analysis of temperature rise in rubber/ice contacts in more detail an alternative experimental technique was adopted. Miniature thermocouples (Comark K76 P2) were employed to sense the temperature of the ice surface both just before and after rubbing contact with a hemisphere sample of a particular rubber under test. The temperature rise through the length of the contact zone was found in this way and displayed on a differential electronic thermometer (Comark 1606 BS).

The arrangement of thermocouples is shown in *Figure 3*. They were held in place with Sellotape and pressed against the ice surface, being positioned far enough away as to not distort the contact region made by the rubber against the ice. A smooth-surfaced, circular ice track was supported on a driven turntable housed in a closed refrigerator[12] with ambient temperatures within it controlled to 0.5°C by a mercury contact thermometer. Rubber samples were optically transparent in order to view the sliding interface *(Formulation C, Table 1)*. The friction force was measured with a load cell.

The temperature difference across the contact zone was measured simultaneously with the friction force and the two were displayed on a twin channel pen recorder (Telsec T/T/S1142). Upon the start of sliding it was clear from the recorder that the temperature rise followed the increase in friction force. However, care had to be taken to bring the thermocouples to thermal equilibrium before the start of each run. The temperature measurements made at a certain distance behind the contact zone were corrected to give the temperature at the rear edge of the contact zone. For this optical observations were made through the transparent rubber testpieces of the distance between the contact periphery and the trailing thermocouple. The leading thermocouple sensed the ice surface temperature before the contact zone, and this

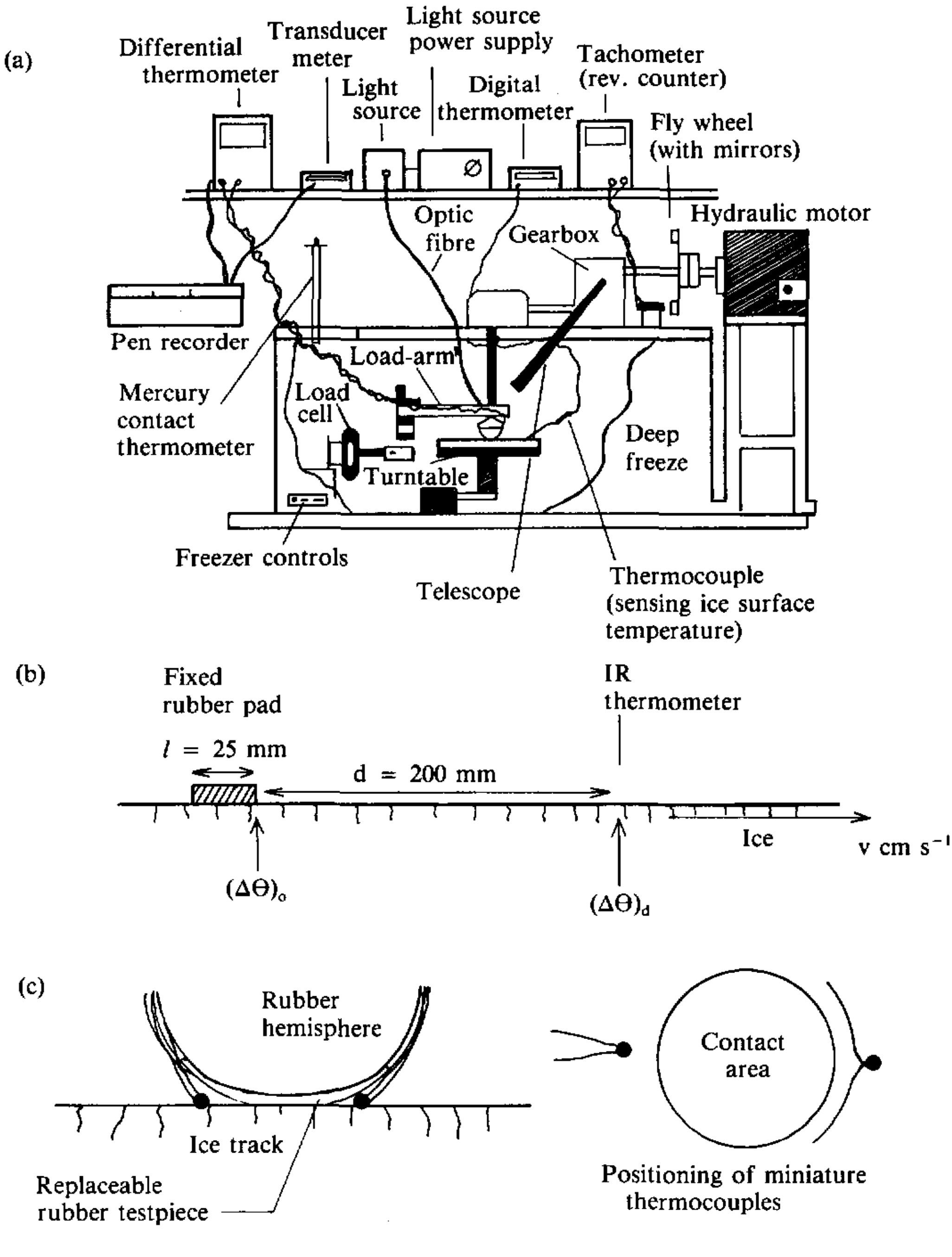

Figure 3. Ice friction apparatus contained in deep freeze.

temperature was assumed to be constant over the short distance between the thermocouple and the front edge of the contact. Thermal quantities used in calculations were the ice thermal conductivity (2.2 $Wm^{-1}K^{-1}$), the ice density (916 kg m^{-3}) and the ice specific heat 2090 J kg^{-1} K^{-1}).

RESULTS

Preliminary Temperature Rise Measurements on Wood

To start investigations, a rubber pad of large rectangular dimensions (l = 225 mm, b = 153 mm) was used. Its thickness, as in all subsequent experiments was 5 millimetres. The IR thermometer lens centre was 15 mm from the contact exit. The thermometer reading increase during sliding was simply compared with the temperature rise predicted by *Equations 3* and *4*. The results at two sliding speeds were near to prediction (first two lines, *Table 2)*.

In order to obtain greater rises in temperature the pad width was halved, then quartered *(Table 2)*. For the smallest width useful measurements could only be obtained at low sliding speeds. At higher speeds the carriage tended to twist from side to side and sliding contact became non-uniform along the length of the rubber pad. It is noted that the theory *(Equation 3)* assumes no heat flow into the rubber slider and the closeness of some of the observations to the theory would appear to confirm this (see later discussion). Other combinations of load (5.4 kg to 12.8 kg) sliding speed (0.08 ms^{-1} to 1.33 ms^{-1}) and friction (μ = 0.4 to 0.7) were examined for the rubber pad of length l = 225 mm and widths b = 153 mm, 72 mm and 36 millimetres. The results are too numerous to show in *Table 2,* but the same general level of agreement between

TABLE 2. PRELIMINARY TEMPERATURE RISE RESULTS

Pad width b (mm)	Pad load (kg)	Speed (ms^{-1})	Friction coefficient	Observed temp. $(\Delta\Theta)_d$ Rise (°C)	From Equations 3 and 4
Rubber pad length l = 225 mm, ambient temp. 22°C, d = 15 mm					
153	12.8	0.35	0.5	1.0 ± 0.2	1.1
		0.66		1.7 ± 0.2	1.5
72	12.5	0.66	0.4	2.5 ± 0.5	2.5
36	12.5	0.16	0.7	4.0 ± 0.5	4.3
Rubber pad length l = 40 mm					
36	9.4	0.33	0.5	5.0 ± 0.3	4.7
	13.1	0.50		9.0 ± 0.5	9.9
Rubber pad length l = 22 mm					
15	11.5	0.40	1.3	17 ± 1	29

Ambient temp. 22°C, d = 15 mm

theory (*Equations 3* and *4*) and observation was found. To obtain temperature rises of 10°C to 20°C a smaller rubber pad (l = 40 mm, b = 36 mm, same compound) was employed. Typical results *(Table 2, last three lines)* showed good agreement with theory when the friction coefficient was low (0.5, chalked pad) but poor when the friction was high (1.3, solvent cleaned pad). Stickslip motion encountered at the higher friction may be the reason. In calculating the average rate of doing work at the sliding interface something like two-thirds of the maximum sliding friction appeared to be a more suitable figure upon which to base heat generation estimates. For chalked surfaces the uncertainty did not arise because the friction was always at a steady level. For this reason most measurements were made with chalked surfaces.

Consideration of Heat Flow into Rubber Slider

The following is an approximate treatment to assess heat flow into the rubber slider relative to total heat generation, the object being to see whether the heat flow into the rubber has become negligible towards the end of its pass over the wood substrate. It was towards the end of a pass that temperature measurements with the infra-red thermometer were made.

Suppose after sliding some distance over the wood substrate the rubber surface has acquired a temperature Θ. After Carslaw and Jaeger[11] the temperature gradient at any point is

$$\frac{\partial \Theta}{\partial x} = \left(\frac{\Theta_r}{\sqrt{(\pi k t)}}\right) e^{-x^2/4kt} \qquad \ldots 6$$

Wood in interfacial contact with the rubber is assumed to be at the same temperature, but the temperature gradient into the wood will be greater than that into the rubber because the rubber hinterland has already been warmed. The heat flux required to maintain Θ_r in the rubber surface at x = 0 is

$$F_r = K_r \left[\frac{\partial \Theta}{\partial x}\right]_{x=0} = \frac{K_r \Theta_r}{\sqrt{(\pi k_r T)}} \qquad \ldots 7$$

where T is the total time of heat flow for one complete pass of the rubber over the wood *(Figure 4)*. The value of Θ_r is approximately determined by the thermal properties of the wood substrate and from *Equation 1* is given, assuming $F_r << F_o$, as

$$\Theta_r = \frac{2F_o}{K_w} \left(\frac{k_w t_c}{\pi}\right)^{1/2} \qquad \ldots 8$$

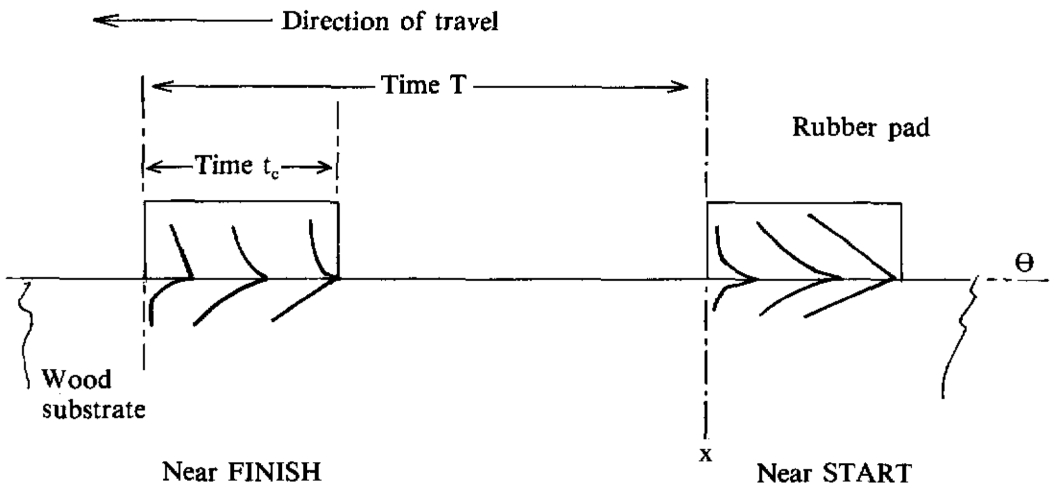

Figure 4. Relative heat flow into slider and substrate. Diagram illustrates temperature profiles (θ against x*) in slider and substrate at the start and finish of a single pass.*

where t_c is the time any point in the wood surface is in contact with the rubber slider and it is assumed that after some distance of sliding all of the heat flow is into the wood. F_o is the total heat flux being generated. Thus from *Equations 7* and *8* the relative flow of heat into the rubber slider is given as

$$\frac{F_r}{F_o} = \frac{2K_r}{\pi K_w} \left(\frac{k_w t_c}{k_r T} \right)^{1/2} \quad \ldots 9$$

The thermal conductivities of rubber and wood are nearly the same, as are the diffusivities. Inserting their values gives

$$\frac{F_r}{F_o} = 0.96 \left(\frac{t_c}{T} \right)^{1/2} \quad \ldots 10$$

which can be written to a good approximation as

$$\frac{F_r}{F_o} = \left(\frac{l}{L} \right)^{1/2} \quad \ldots 11$$

where l is the length of the rubber slider (in direction of travel) in contact with the wood substrate and L is the total distance the slider travels over the wood. Provided the ratio *(l/L)* is small, then the assumptions leading to *Equation 11* are valid, but as the ratio increases the assumptions no longer hold and the above analysis breaks down. In the experimental tests the rubber slider was drawn over the wood bench for a measured distance of 1 m with a run-in distance of 0.25–0.5 m prior to the measured metre. The sliding velocity was taken from the time to travel the measured metre, but temperature rise observations were only made over the second half of the measured metre. For a slider of length 40 mm *(Table 2)* travelling at least 1 m over the wood the ratio *(l/L)* is 0.2 and to the accuracy of the experiments it would appear reasonable to assume that F_r is small.

It is noted that this analysis presents the worst case because of the chosen step rise in temperature in the slider surface. In practice the temperature rise will be rounded with less heat flow into the slider than assumed here. For shorter sliders than 40 mm thermal equilibrium is even more certain, but for the slider of length 225 mm *(Table 2)* there is some doubt, though the experimental results suggest that thermal equilibrium was attained.

Investigation of Temperature Fall-off Behind Slider

The object was to confirm that *Equation 4* could be reliably used to correct for sampling the wood substrate temperature at some distance behind the exit edge of the slider. A short slider pad of length l = 14 mm was used. Its breadth was 26 mm so that at the highest applied loads frictional stresses could be raised to the order of 400 KNm^{-2} to produce temperature rises of tens of degrees through the contact length. The IR thermometer was positioned at five different distances, *d*, between 5 mm and 185 mm behind the slider. In all tests the slider was drawn over the wood at the same speed and under the same load. These were arranged to give a theoretical temperature rise of about 30°C. Because of small differences in friction and sliding speed from one pass to another, inevitably there was scatter in the observed temperatures behind the slider. At each distance *d* the average temperature was found. Averaged temperatures, together with an indication of scatter, are compared with *Equation 4* in *Figure 5*. This suggests that *Equation 4* can confidently be used to find $(\Delta\Theta)_o$ value from the measured $(\Delta\Theta)_d$ value.

Influence of Frictional Stress

Equation 3 can be written as

$$(\Delta\Theta)_o = 2\sigma \left(\frac{vl}{\pi K \rho c} \right)^{1/2} \quad \ldots 12$$

where σ is the frictional stress. Variation in this stress would be predicted to exert the most influence on changes in the temperature rise $(\Delta\Theta)_o$. This was studied using different sized sliders operated under a range of loads. Observed temperature rises, corrected by *Equation 4* for measurement position, are compared with expectation in *Figure 6*. This plots the temperature rise $(\Delta\Theta)_o$ at the slider's exit edge against the parameter vl for different stresses σ. Theory and experiment compare favourably, though at high sliding speeds measurements fell short of expectation. This may be associated with the response time of the infra-red thermo-

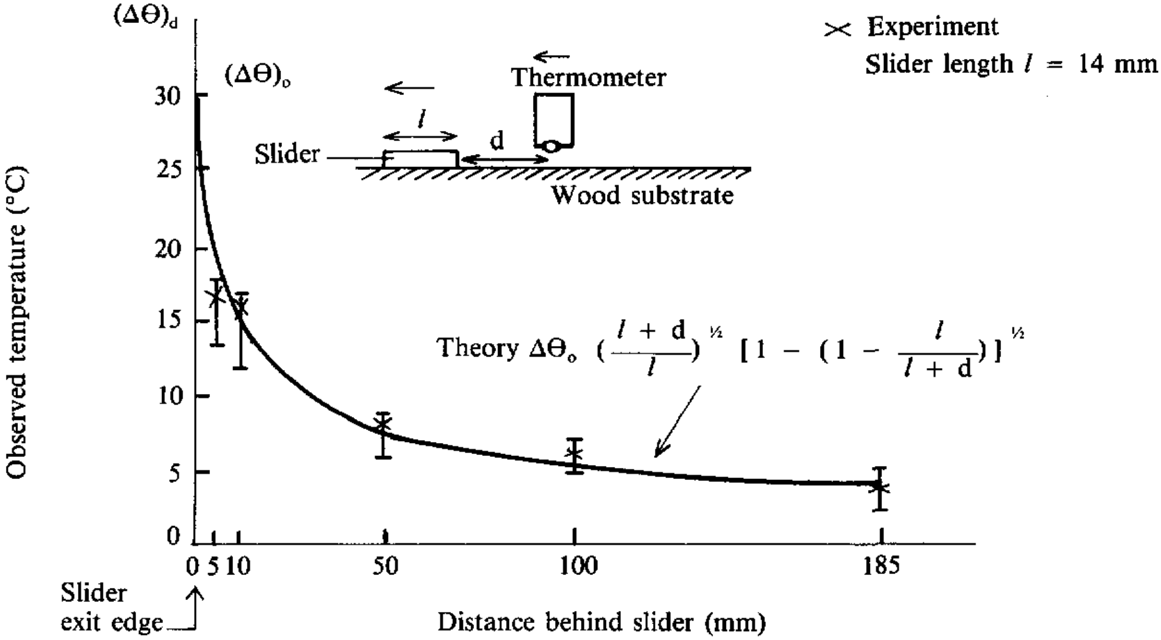

Figure 5. Observed temperatures behind slider compared with theoretical estimate.

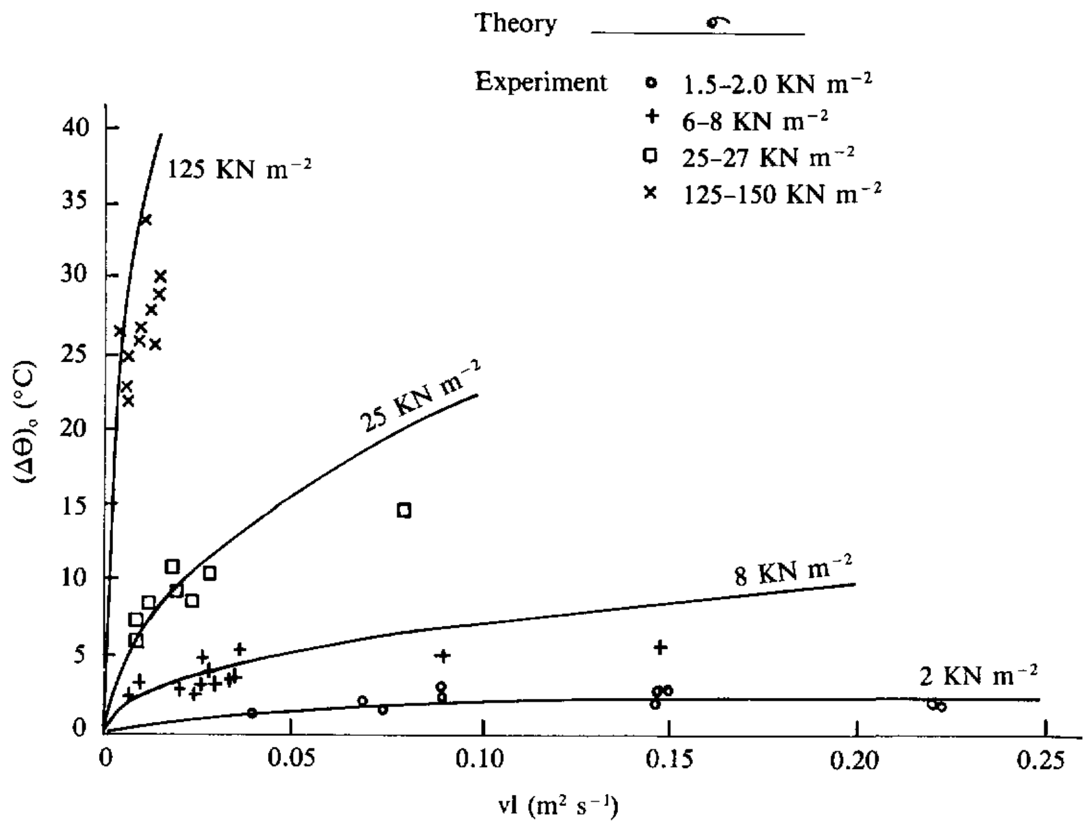

Figure 6. Influence of frictional stress.

meter. At high speeds pass times over 1 m length of wood are of the order 1 s, which borders on the response time of the thermometer.

Comparison of Theory and Experiment for Sliding on Wood

For different sized sliders operated under a range of loads over a decade of sliding speed all the results are compared with prediction in *Figure 7.* Measured temperatures were corrected to $(\Delta\Theta)_o$ using *Equation 4* and compared with that predicted by *Equation 12.* Agreement is good for temperature rises up to about 10°C. At higher temperatures results increasingly fall short of prediction. This may, in part, be due to the slow response of the IR thermometer, as discussed above, and also perhaps due to less frictional work being done than anticipated due to only partial contact over the sliding interface with increased severity of operating conditions. It cannot be overlooked that at speeds of 1 ms^{-1} in the absence of stickslip there will be a tendency to air entrainment by elastohydrodynamic action.

Measurement of Temperature Rise when Rubber Slides on Ice

For a 25 mm square rubber pad sliding on a smooth-surfaced ice track, temperatures at the exit edge for different sliding speeds are displayed in *Table 3.* The results are based on sensing the ice track temperature a short distance behind the pad using an infra-red thermometer. There is clear correspondence between melting and fall in friction.

The analysis of frictional heating when rubber slides on smooth-surfaced ice has been carried out for temperatures ranging from the

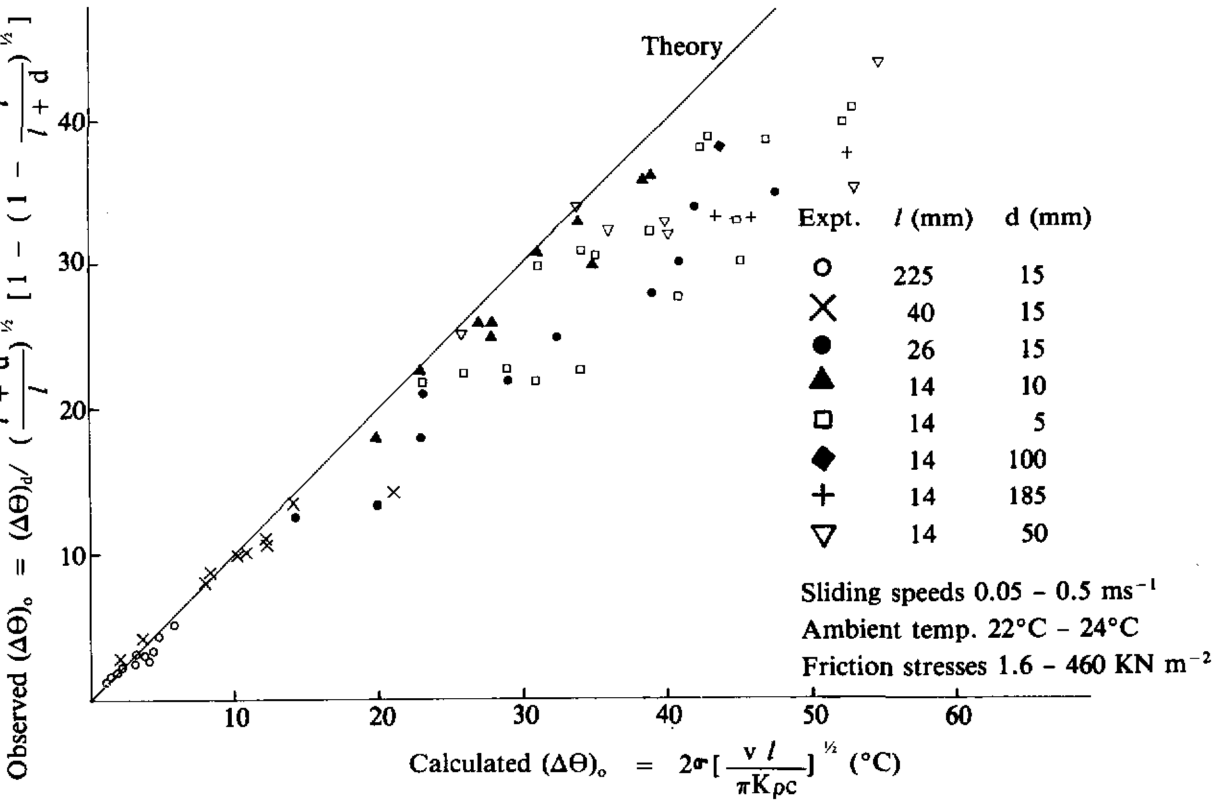

Figure 7. Theory and experiment.

TABLE 3. ICE TRACK TEMPERATURE RISE RESULTS

Sliding speed v (ms^{-1})	*Measured* $(\Delta\Theta)_d$ (°C)	*Corrected* $(\Delta\Theta)_o$ (°C)	*Whether* melting	Measured friction coefficient
1.79	1.25	7	No	0.48
4.47	2.5	15	Just	0.23
8.94	3.5	21	Yes, before back edge	0.13

Ambient temperature −15°C

melting point of ice down to −30°C. For this miniature thermocouples were used. The ice track was prepared as smooth as possible by skimming with a sharp razor blade. The speed of the ice was continuously varied during the test to produce several results in the range 0.01 ms^{-1} to 1 ms^{-1}. The theoretical and experimental temperature rise at the contact exit, $(\Delta\Theta)_o$, was compared. Below −5°C there is a satisfactory agreement *(Figure 8)*.

DISCUSSION

Experiments confirmed that increasing the frictional stress has the largest effect on raising the contact temperature. When the friction is high

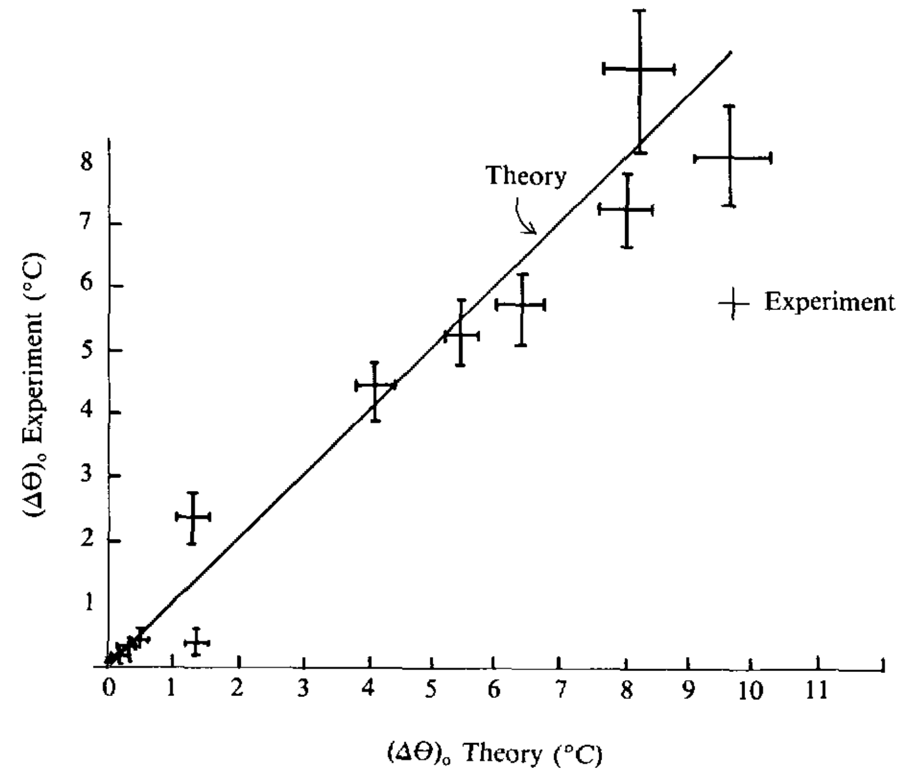

Figure 8a. 2% dicup NR hemisphere sliding at speeds from 0.01 − 1 ms^{-1} on polished ice at −25°C ± 2°C under applied load of 4.9 N.

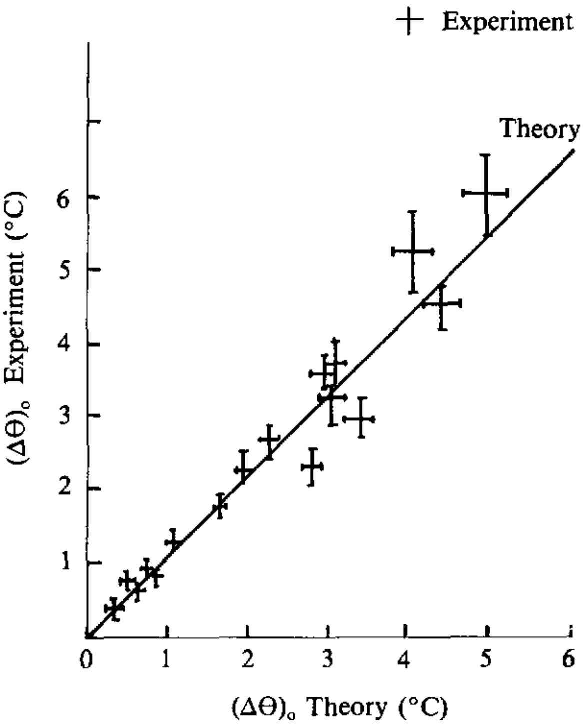

Figure 8b. 2% dicup NR hemisphere sliding at speeds from 0.01 – 1 ms^{-1} on polished ice at −5°C to −6°C under applied load of 4.9 N.

there is a tendency to stickslip motion. This was particularly noted for clean rubber sliding on wood, and also sometimes found on well-polished ice at low temperatures. Under circumstances of stickslip the measured temperature rise was very erratic. It raises the question of how normal stress might be distributed in the contact zone and whether there are 'hot-spot' regions.

From time to time highway authorities have noted that the friction coefficient of tyre on road has been lower than anticipated. It seems particularly prevalent on roads freshly dressed with Tarmacadam. Perhaps this is not so surprising when it is realised that for a car skidding (locked wheel) at speeds greater than 50 km per hour the temperature rise in the tyre contact areas can be in excess of 200°C. This melts the tar, hence skidding on a molten surface. The action, of course, leaves behind the well-known skid marks — often thought to be transferred rubber, but more likely to be refrozen tar! Apparently on a worn road the skid resistance is improved because the Tarmacadam has been worn off the tops of incorporated road stones, so surface melting at points of asperity contact is no longer possible.

In the case of ice friction there has been debate[13] about the 'hot-spots' and their association with melt-water. A paradoxical argument runs thus: frictional heat produces melt-water, but does not the presence of water mean less friction? The paradox is resolved by appreciating that only part of the frictional heat produces melt-water, the rest being conducted away through the slider and the ice. The greater the conduction losses the greater the friction.

The idea that temperature rise leading to interface melting can limit frictional grip is taken a stage further in a recent study by Ettles[14]. He proposes that tyre-roadway friction is controlled by thermal rather than by hysteresis and viscoelastic effects. The basis of this is that the maximum friction attainable is limited by the decomposition temperature T_d of the rubber. *Equation 3* can be rearranged to give

$$f = (\Delta\Theta)_o \frac{b\,(\rho\, c\, \pi\, K\, l)^{1/2}}{2v^{1/2}} \qquad \ldots 13$$

Ettles suggests that T_d be substituted for $(\Delta\Theta)_o$, the decomposition temperature of the rubber compound relative to ambient.

Whilst the principal object of the present work was to examine experimentally the temperature rise caused by sliding rubber contacts, it is of interest to see how well *Equation 13* predicts the level of friction for the sliding of rubber on ice for conditions where the ice can melt. A comparison between this frictional melting theory and experiment is shown in *Figure 9*. The experiments were carried out at a temperature of −5°C, so the value of $(\Delta\Theta)_o$ was set at 5. Direct optical observations of the sliding contact interface (through the transparent rubber) provided values of b and l, both of which vary a little with speed. The divergence of theory and experiment for speeds less than

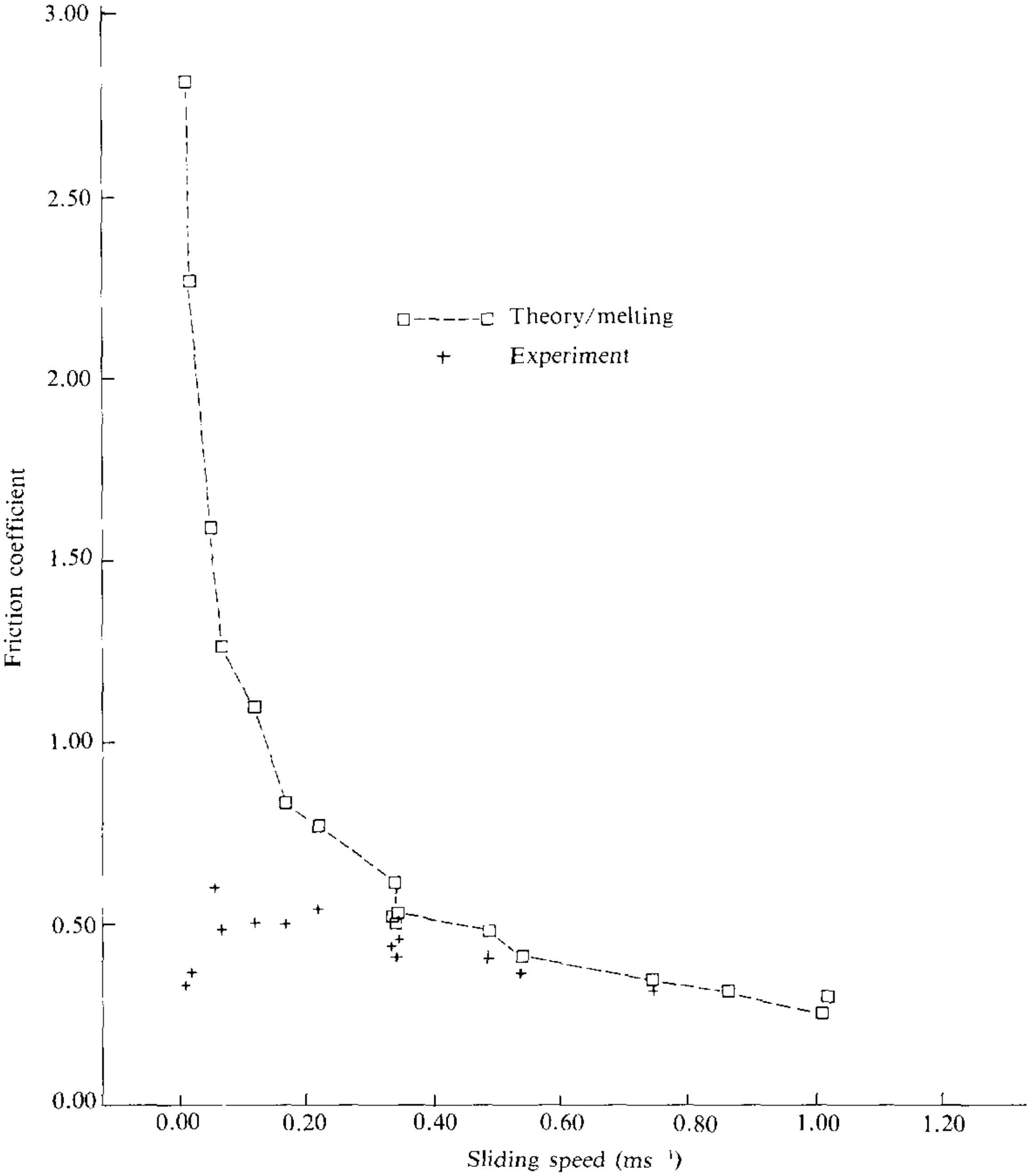

Figure 9. Comparison between frictional melting theory and experiment for 2% dicup cured NR hemisphere sliding on ice at −5°C under an applied load of 17.7 N.

0.3 ms^{-1} are due to $(\Delta\Theta)_o$ itself being a function of speed (not allowed for in *Equation 13*), and due to the surface properties of ice[15]. The surprisingly good prediction of the sliding friction for speeds greater than 0.3 ms^{-1} owes much to being able to determine b and l fairly reliably. It was found, however, that as the normal load was decreased, or the temperature lowered, the prediction became poorer. This may be because b and l are less reliable in a contact situation where the real area of contact is appreciably less than the geometric, and also because $(\Delta\Theta)_o$ is speed dependent.

As the equations above indicate, a numerical value of the rubber-ice friction coefficient can be calculated fairly well by considering only the heat losses. This requires no detail of the friction mechanism. Yet the fact that it gives results agreeing with experiments strongly supports the Bowden and Hughes frictional melting idea[16]. Water films do seem to be present, though they may be discontinuous.

It is often asked whether pressure melting explains, for example, the low friction of ice skates. There's no dispute with the physical idea that the all-important lubricant water film might be produced by pressure melting as Reynolds first thought in 1901 — it is just a question of numbers. The melting point depression/pressure index of ice is about $-0.007°C$ per atmosphere. This means that for ice colder than $-3°C$ there would usually be insufficient contact pressure to cause melting, even for the sharp edge of a skate (150 atmospheres) and certainly not for the broad sole of a ski, nor the tread of a tyre, yet at high speed all slips easily on much colder ice or snow.

If the water film produced by heat generation in 'dry' sliding is thin, a micron or less, its shear resistance at high speeds is not small. Frictional melting thus appears even less paradoxical because significant heat is generated by shear in the water film itself — enough to prevent it re-freezing whilst in the contact region. This leads to the picture, albeit simplified, of an area of dry friction at the leading edge where the ice temperature is rapidly rising to the melting point followed by a thin water film that may or may not be continuous, depending on surface roughness and heat generation.

The difficulty with the frictional melting hypothesis has been in obtaining direct experimental evidence of the water film. When F.P. Bowden and T.P. Hughes proposed the idea in 1939, they inferred the existence of water by electrical conductivity measurements. In recent investigations[17,18] its existence is assumed in order to calculate friction. The good agreements found strongly infer the presence of a melt water film.

Rubber can slide easily on ice, yet the contact pressures (e.g. tyre tread, 1 — 10 atmospheres) are unlikely to induce pressure melting, except close to 0°C. By looking through transparent rubber sliding on ice, we find it is possible to associate a loss of grip at the interface with the disappearance of solid-solid contact, and to see streaks of water issue from under the trail edge of the rubber and quickly re-freeze[19]. This happens at temperatures well below zero provided the speed is high enough. If the speed is too low there is good grip and no water is obvious. Here then are some direct observations of frictional melting.

CONCLUSION

The experimental results obtained in this investigation would appear to indicate that the assumptions made in using the theoretical expressions of Carslaw and Jaeger can be applied with confidence to sliding rubber contacts in order to predict temperature rise through the length of the contact zone. The actual temperature rise can be surprisingly large. When rubber slides on ice, both direct contact area observations and ice track temperature rise measurements give an indication of ice melting due to frictional heating. The rubber-ice friction coefficient at high sliding speeds can be calculated fairly well using the heat conduction equations.

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