PM6

FRICTION

At midnight in the museum hall
The fossils gathered for a ball.
There were no drums or saxophones
but just the clatter of their bones,
A rolling, rattling, carefree circus
Of mammoth polkas and mazurkas.
Pterodactyls and brontosauruses
Sang ghostly prehistoric choruses.
Amid the mastodonic wassail
I caught the eye of one small fossil.
Cheer up, sad world, he said, and winked -
it's kind of fun to be extinct.

OBJECTIVES

Aims

In this chapter you will study the phenomena of friction, determine the laws of friction and consider the explanation of these laws in terms of a microscopic model. The effects of naturally occluding surface layers on of lubricants on friction are discussed.

Minimum Learning Goals

When you have finished studying this chapter you should be able to do all of the following.

1 Explain and use the following terms : *friction, normal force, real area of contact, coefficient of friction, adhesion, cold-welding, lubrication, hydrodynamic lubrication, boundary lubrication, elasto-hydrodynamic lubrication.*

2 (i) Recall the experimental laws of sliding friction.

(ii) Do simple calculations based on the second of these laws.

(iii) Describe an experiment to verify these laws.

3 (i) Using a microscope model, explain the laws of friction.

(ii) Describe how electrical measurements and radioactivity measurements can (separately) be used to confirm parts of this explanation.

4 Describe and explain how surface layers alter the value of the coefficient of friction.

5 Describe the process of polishing and explain how it is based on the fact that frictional forces are non-conservative.

6 State the differences among three types of lubrication (hydrodynamic, boundary and elasto-hydrodynamic) and give one example of each type.

PRE-LECTURE

1. Remind yourself of the concept of a shear stress (Chapter PM1).
2. Recall that when a metal is subjected to increasing stress it normally goes through an elastic regime where the stress is proportional to strain and then into a plastic regime where there is flow of the metal at essentially a constant stress (Chapter PM1).
3. Remind yourself of the basic concepts of the flow of a viscous liquid and in particular of Newton's law of viscosity (Chapter PM4).

LECTURE

6-1 OUR EVERYDAY EXPERIENCE OF FRICTION

Demonstration

To **slide** heavy objects requires considerable effort. The heavier the object the greater the effort.

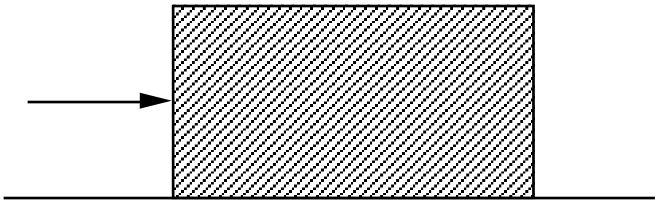

Fig 6.1 Sliding an object

Demonstration

It is a lot easier to move a heavy object by **rolling** it than by sliding it.

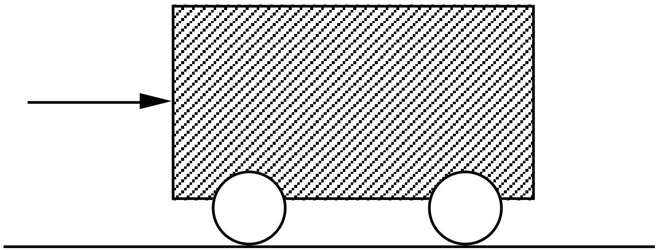

Fig 6.2 Rolling an object

We can express these facts by saying that there is a **friction force** resisting the motion. The force for rolling friction is less than for sliding friction.

Demonstrations

The force of sliding friction depends markedly on the surfaces involved. Friction is very small in skating and skiing.

Friction plagues us in many contexts.

Demonstration

Considerable power is lost in overcoming friction in engines. Even more important than the power loss is the wear which results from friction.

Lubricants can be used to reduce friction and wear. Early applications were the use of animal fats to lubricate chariot wheels.

Though friction plagues us a lot, it is of considerable advantage in many contexts.

Demonstrations

Friction of a rope on something or on itself as in a knot enables large loads to be easily controlled.

Friction enables the braking of moving vehicles.

Traction of cars, bikes, trains etc. depends on friction.

Traction in walking depends on friction.

6-2 LAWS OF SLIDING FRICTION

The laws of sliding friction were first formulated by Leonardo da Vinci and re-discovered in 1699 by Admontons. They are **empirical laws** which give the dependence of the friction force on the relevant parameters.

Demonstration

One apparatus which can be used to find these laws is a tilting board on which an object is placed. The board is tilted until the object slides. From the measured angle the friction force, the tangential force resisting the motion, can be deduced. (See post lecture material.)

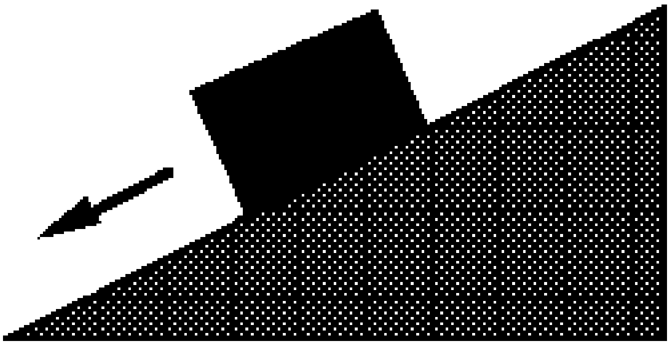

Fig 6.3 Sliding down an incline

The laws were, however, determined using the following apparatus:

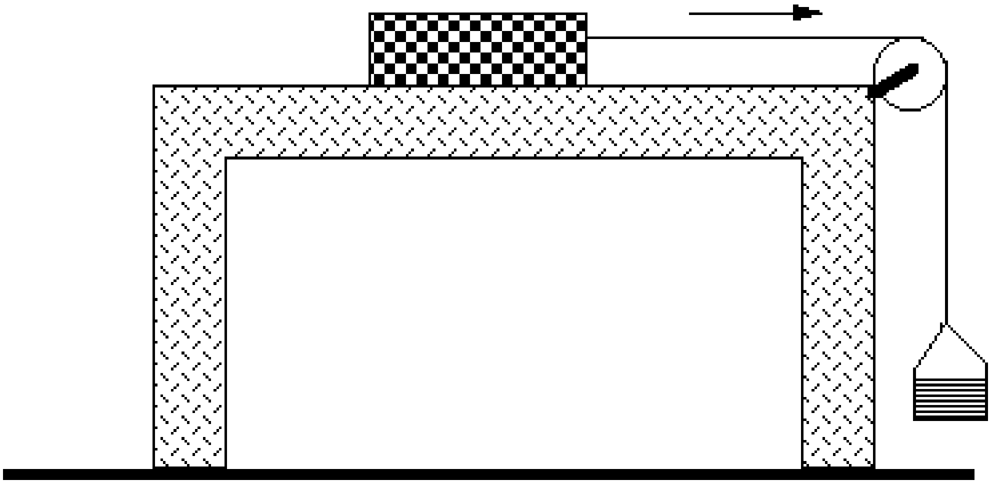

Fig 6.4 An experiment to determine the laws of friction

A steel block was placed on a horizontal sheet of steel and connected via a string which passed over a pulley to a weight-carrier which hung vertically. Weights were added to the carrier until the block was just on the point of sliding. The weight was recorded, this being the friction force.

Friction force with 1 block = 4.5 N (steel on steel)

The block was then turned over onto another face of smaller area and the measurement repeated. The weight was the same as before.

Thus we have:

First Law of Friction.

The friction force F_r is independent of the area of contact.

The experiment was then repeated with 2 and 3 blocks of the same weight with the following results:

Friction force with 2 blocks = 10 N (steel on steel)

Friction force with 3 blocks = 15 N (steel on steel)

Thus we have:

Second Law of Friction.

The friction force F is proportional to the normal component of the contact force N.

Thus $F \propto N$ and so $F = \mu N$, where μ is a constant known as the **coefficient of friction**. Often two values of this coefficient are given. One is called the static coefficient and corresponds to the force required to just get the object moving. The other is called the kinetic coefficient and corresponds to the force required to keep the object sliding at a constant velocity.

The coefficient of friction depends on the surfaces involved.

Demonstration

This was shown by repeating the measurement for 3 blocks on a sheet of aluminium.

Friction force with 3 blocks = 20 *N* (steel on aluminium)

The laws stated are crude laws, the sort obtained with crude apparatus. Even with this apparatus, complications are evident - the tendency of the object to stick again after it has started to slide. With more refined apparatus, these complications can be examined. As well, the dependence of friction on velocity can be investigated.

Demonstration

In a simple apparatus of this type, an object connected to a horizontal spring balance rests on a table which can be rotated underneath it. The spring balance measures the friction force.

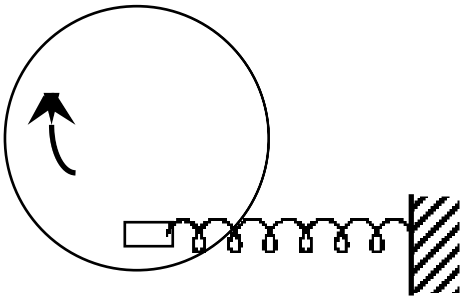

Fig 6.5 Using a spring balance to measure the frictional force

This apparatus made evident the fluctuations which occur in the friction force and showed that whereas at low velocities the friction force was essentially independent of the velocity, it did decrease when the velocity became high.

6-3 EXPLANATION OF THE LAWS OF SLIDING FRICTION FOR METALS

To explain the laws of friction, it is necessary to introduce additional experimental information.

Firstly, a variety of techniques show that even when the surfaces look smooth, they are **microscopically rough**. This is shown by:

Demonstrations

Photographs taken with electron microscopes.

The oblique sectional technique. If cuts at small angles to a surface are made, surface irregularities are magnified.

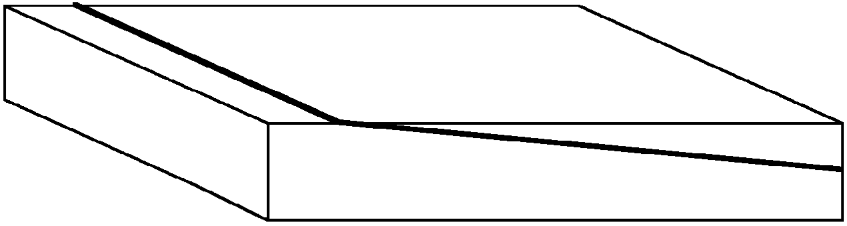

Fig 6.6 An oblique section

Since the surfaces are rough, it is tempting to think that the friction must be due to the intermeshing of the surfaces. But the sliding of such surfaces over each other is non-dissipative. That this cannot be the explanation is also shown by the fact that after a certain degree of polishing, further polishing results in an increase of the friction.

Once it is realised the surfaces are rough, it is apparent however that the real area of contact must be small - the surfaces must only touch at a few points.

Demonstration

This was shown by placing two irregular lead plates in contact with each other. It was further shown that the real area of contact increased as the load increased.

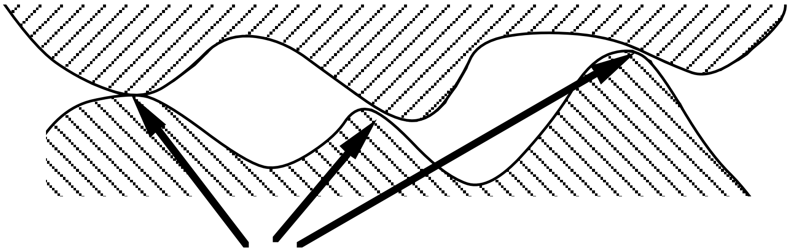

Fig 6.7 The "contact" between two plates, viewed at a microscopic level

Demonstration

The increase in area of contact with load was also shown by measuring the voltage drop across two surfaces in contact in the following circuit. The voltage drop depends on the resistance of the path; this resistance decreases as the (real) area of contact increases.

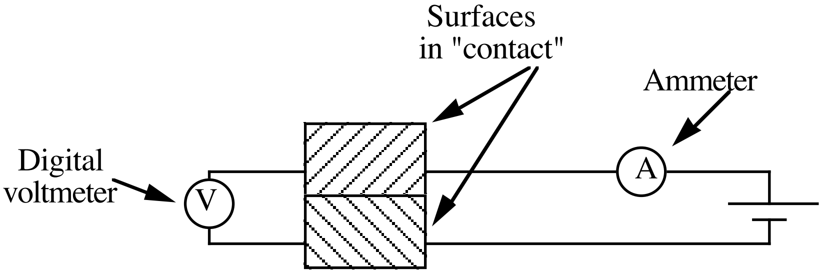

Fig 6.8 Experimental arrangement to measure the potential drop between the surfaces

If precise experiments of this nature are made, it is found that the real area of contact increases proportionately with the load. This is so since even at the smallest loads the stresses at the contact points are large enough to make the metals deform plastically.

The final important piece of experimental information is that strong adhesion occurs at the points of contact. The points of contact are in effect cold-welded forming a continuous solid. If the materials are to be slid over each other, these junctions have to be sheared.

Demonstrations

That strong junctions are formed can be shown by oblique sections of the friction tracks formed when one material is slid on another. These show that material is transferred from one surface to the other.

This transfer can also be shown by sliding a radio-active metal on a non-radioactive metal. After sliding, radioactivity is detected on the non-radioactive metal.

[As an aside, it should be noted that the transfer of metal which occurs when one metal is slid on another (which can occur in screwing or hammering) is of relevance in bone surgery. Since transfer can occur, it is very important to use tools of the same material as the metal plates etc. used to repair the bones. Otherwise, contact EMFs are set up which result in corrosion.]

Bringing the various pieces of experimental information together, an explanation of the laws of friction can be given. If we assume the friction force is just that required to shear all the junctions then since the real area of contact increases with the load, then so must the friction force. This is the second law (see post-lecture material for further details).

Further, since the real area of contact depends only on the load and not on the apparent areas of contact, the friction force is independent of the apparent areas of contact. This is the first law.

Actually the friction force is not only that required to shear the junctions. There is also a contribution associated with the "**ploughing**" of the hills of one surface through the other surface. This is small unless one surface is very much harder than the other.

6-4 OTHER FRICTIONAL BEHAVIOUR

The above picture of sliding friction for metals is incomplete. Invariably, **surface layers** exist on the metals and these play a major part in determining the frictional behaviour. Indeed, it is only because surface layers exist that metals can be slid on each other. If the surfaces are cleaned in a vacuum and the metals slid on each other in the vacuum, it is found the surfaces bond together so that it is not only impossible to slide one on the other but it is impossible to pull them apart.

Demonstration

The existence of these strong forces was shown using two accurately plane gauge blocks which were first slid on each other to break down the surface layers.

The presence of surface layers can result in a breakdown of the $F = \mu N$ relationship - the coefficient of friction μ can vary with the load N.

This can happen if the layers are such that they remain intact at low loads but break down at higher loads. The coefficient of friction then changes from that for surface layer sliding on surface layer to that of metal on metal or metal on surface layer.

Layers of soft metal are placed on the surfaces of bearings to reduce friction.

The **sliding of non-metals** on each is explainable in much the same way as it is for metals. Generally, however, the coefficient of friction is much more load-dependent. For some materials such as **rubber** this results from the materials deforming **elastically** rather than plastically at the points of contact. For other materials such as **plastics** this behaviour arises because they are **visco-elastic**.

Demonstration

An important non-metal as regards its frictional behaviour is **teflon**. This has a very low coefficient of friction of 0.05 - 0.1 arising from the nature of its molecular structure which is 'streamlined".

Teflon is an important bearing material being used for example as one of the surfaces in artificial hip joints.

Finally, a few words about **rolling friction**. One form of this is the traction type as in a car wheel on the road where frictional grip is essential. The other is "free" rolling.

Demonstration

"Free" rolling is typified by a ball-race.

In "free" rolling, the coefficient of friction is very low, less than 0.001, which is much less than any coefficient for sliding friction. The mechanism for frictional energy loss is quite different from that for sliding friction.

6-5 HEATING EFFECTS

Friction is a non-conservative force. When objects slide on each other, kinetic energy is converted to heat resulting in increase in the temperature of the surfaces.

Demonstrations

An abrasive saw cutting a pipe produces sparks.

Fire can be produced by the high speed rubbing of one piece of wood on another.

Refined experiments show that very localised temperature increases of up to 2000 K for 10^{-4} seconds or less are produced.

Demonstration

These local hot spots are basic to the polishing process. When a metal such as a denture casting is polished, local thermal softening of the metal leads to flow and filling up of gaps. Obviously, a high melting point polishing agent is necessary for efficient polishing.

It is the heating of the surfaces which causes the coefficient of friction to decrease at high velocities. The high temperature enhances the plastic flow, and if it is high enough a layer of essentially liquid metal is produced which acts as a lubricant.

Demonstration

The heating of the surfaces is basic to skiing. A lubricating layer of water is produced. As the ambient temperature decreases, it is harder to produce and maintain this layer and the skis stick.

6-6 LUBRICATION

The reduction of friction between two surfaces by placing another material between them is known as **lubrication**.

Demonstration

A block will slide much easier on a table if a layer of oil is spread on it.

Hydrodynamic lubrication

The type of lubrication in which the surfaces are completely separated by a thin film of fluid is known as **hydrodynamic lubrication.** It results in very low coefficients of friction, of the order of 0.001 and completely eliminates wear.

Demonstration

This type of lubrication is used in journal bearings. A complete film is formed if the load is not too high and the speed of the rotating shaft is great enough.

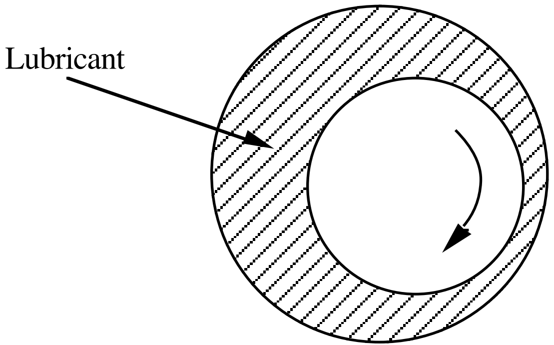

Fig 6.9 Lubricant squeezed between a rotating shaft and its bearing (hydrodynamic lubrication)

In this type of lubrication, the frictional energy loss is due only to the viscous forces in the lubricant (see post-lecture material). The viscosity cannot be reduced indefinitely, however, since the separation between the surfaces decreases as the viscosity decreases and eventually the surfaces come into contact.

Boundary lubrication

When metal contact begins to occur as can happen if the speed of the journal is decreased, a continuous film of fluid no longer exists. If the journal speed is further decreased, the lubricant is reduced to localised patches a few molecules thick. Lubrication under these conditions is known as **boundary lubrication.**

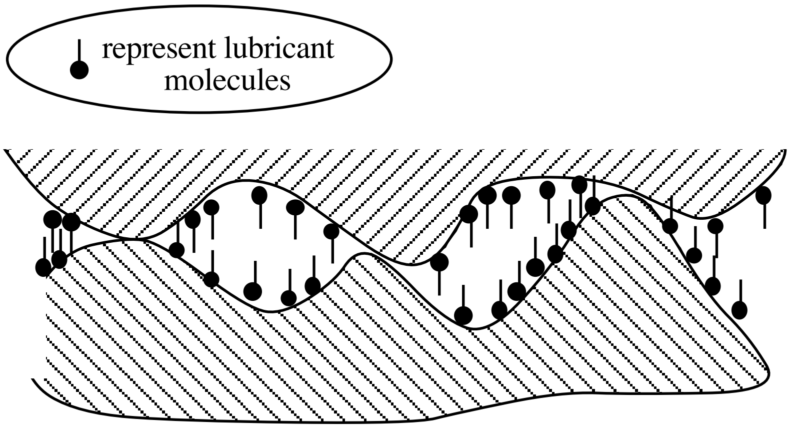

Fig 6.10 A very thin film of lubricant, with molecules illustrated (boundary lubrication)

In this type of lubrication, the coefficient of friction does not depend on the viscosity of the lubricant but rather on its chemical nature. A good boundary lubricant is one which will attach itself firmly to the clean metal surfaces formed as the cold-welded junctions are sheared. A layer is then formed which acts as a lubricating film, and if it can be easily sheared than the friction is low. Typically coefficients of friction of the order of 0.1 are obtained and the wear is slight.

Elastohydrodynamic lubrication

Of considerable interest is the lubrication of synovial joints in animals, such as the hip joint. This can be explained neither in terms of hydrodynamic nor boundary layer lubrication. Rather it seems that the lubrication is of another type known as **elastohydrodynamic lubrication** in which the surfaces deform appreciably, the elastic deformations being comparable with the lubricating film thickness so that it is maintained. In the synovial joints the cartilage elasticity is such as to allow this process. The rheological properties of the synovial fluid are also important; in particular the synovial fluid is thixotropic. This theory of synovial joint lubrication is supported by the fact that synovial fluid from rheumatoid arthritis cases is newtonian, and that wear in the joint occurs when hard calcifying material is deposited on the cartilage. (This decreases the cartilage elasticity.)

POST LECTURE

6-7 PROBLEMS

Q 6.1 In the inclined plane apparatus used for measuring the coefficient of friction ,(shown in the diagram below) the block starts to move down the plane when the angle of the plane is θ.

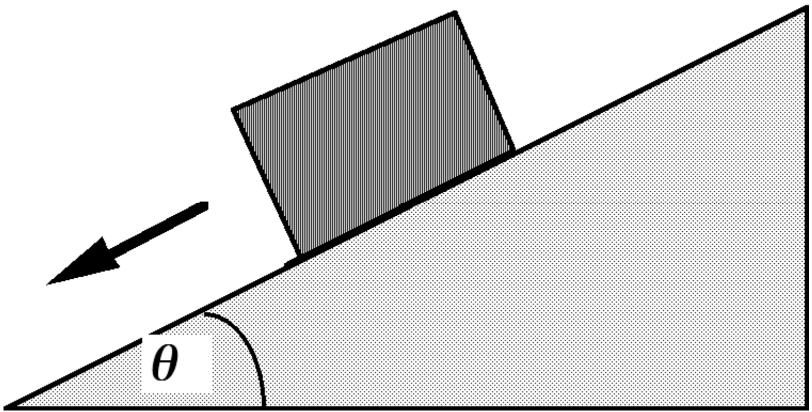

Fig 6.11 Diagram for Q6.1

Derive an expression for the coefficient of friction in terms of this angle θ.

Q6.2. Friction is a dissipative force. Thus it has been stated in the lecture that friction cannot be understood in terms of intermeshing surfaces sliding over each other since this is a non-dissipative process.

Explain why this sort of process is non-dissipative.

6-8 AN EXPLANATION OF THE SECOND LAW OF FRICTION

The second law of friction can be explained in terms of the shearing of cold-welded junctions. If s is the shear strength of the junctions and A the total real area of contact, then the frictional force F is given by

$$F = A s.$$

Further, since plastic flow occurs at the junctions the normal force N is related to the area of contact by the expression

$$N = Ap$$

where p is the yield pressure, the stress at which plastic flow occurs.

Thus $$F = \frac{s}{p} N$$

and so $$\mu = \frac{s}{p}.$$

If s and p are taken as those of the softer material, this expression predicts reasonable values for μ. Really good agreement is not obtained because of the influence of surface layers.

6-9 MORE PROBLEMS

Q6.3 Since friction is a dissipative force, the model which explains it in terms of the shearing of cold-welded junctions must involve energy dissipation. Explain how this energy dissipation occurs.

Q6.4 A shaft of radius *r* is rotating with angular velocity □ in a bearing. Assume that a thin film of lubricant of uniform thickness *d* exists between the shaft and the bearing and that the length of shaft supported by the bearing is Ú✎

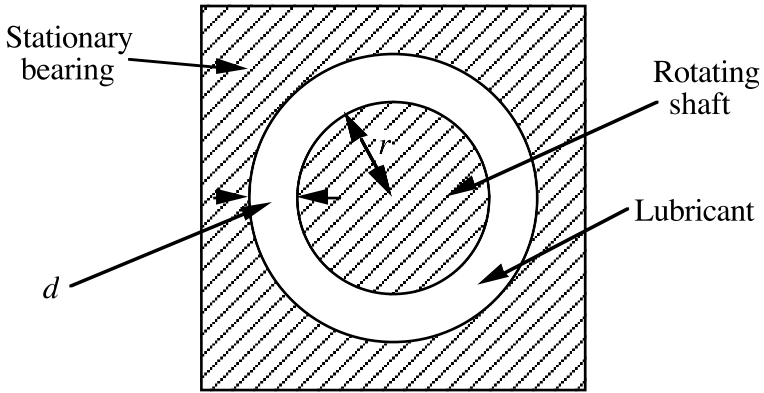

Fig 6.12 Diagram for Q6.4

(a) What is the velocity gradient in the film assuming that this gradient is uniform throughout the thickness of the film?

(b) Determine the shear stress in the lubricant using Newton's law of viscosity.

(c) Hence obtain an expression for the friction force at the surface of the shaft, the force at the surface of the shaft, the force which is resisting its rotation.

(This result shows, as mentioned in the lecture, that to reduce the resistance to motion, the coefficient of viscosity has to be decreased. You should also note that the theory given here is that pertaining to the torsional viscometer which was described in chapter PM4.)