3.1 Introduction

The technical and economic advantages of epoxy concrete as a material for machine tool structures have been discussed qualitatively in Chapter 2. Similarly, the use of PTFE based thermoplastics such as Turcite-B, Fluon VB-60, Fluon VX-2, Teflon and epoxy based thermosetting plastics such as Diamant Moglice and SKC-3 as slideway materials in plain slideways have also been discussed in Chapter 2.

In this chapter a review of research work with regard to the dynamic behaviour of epoxy concrete, and the investigations carried out with regard to the friction and wear characteristics plastic materials widely used in slideways of CNC machine tools are presented.

3.2 REVIEW ON EPOXY CONCRETE

A research programme aimed to establish the technical advantage offered by epoxy concrete has been conducted at the Institute of Mechanical Technology, Turin Poly-Technic, Italy by De Filippi et al. [7]. In their investigation, the cast iron bed on an existing lathe was replaced by an epoxy one, using the same mechanical units, so that the dynamic behaviour of the two lathes and the part played by the different structures could be compared. Cutting tests were performed on these two lathes under identical conditions and the radial acceleration on the tool shank in the horizontal plane was measured when cutting.
was done near the tailstock. Figure 3.1 shows the tool vibration amplitude near the tailstock. It is clear that the lathe with epoxy concrete bed performs better.

Koji Takada and Ikuo Tanabe [8] have investigated the thermal deformation of machine tool structure composed of epoxy resin concrete and cast iron. According to their investigation the composite structure of a lathe which has epoxy resin concrete plate between the bed and the head stock showed that the change of parallelism between the spindle centre line and the longitudinal guideway is much smaller than that of a conventional lathe totally made of cast iron. The composite structure, therefore, may be able to reduce the form error of a machined work piece such as cylindricity which is difficult to correct in the machining process.

Epoxy concrete is known as Granitan S-100 at Fritz Studer AG, a company where the material was first developed and used in their grinding machine. The material structure of Granitan S-100 is a mixture of a reactive resin (epoxy resin) as the bonding agent and stone as an aggregate. Several investigations regarding this material such as comparison of energy use, damping properties and the main characteristics which make them suitable for machine structures have been reported in the company's technical information brochure.

3.3 REVIEW ON FRICTION CHARACTERISTICS OF THERMO-PLASTICS FOR SLIDEWAYS

3.3.1 Coefficient of Friction and Friction Forces

More accurate displacement and stable positioning of the slide can be achieved by reducing friction, eliminating clearances and increasing
1. S = 0.06 mm/Rev
2. S = 0.12 mm/Rev

V = 229 m/min

FIG. 3.1 TOOL VIBRATION AMPLITUDE NEAR THE TAILSTOCK
(AFTER DE FILIPPI et al.) (7)
the stiffness of slideways. By reducing friction forces in slideways, it is possible to reduce misalignments in the follower system resulting from deformation of the drive elements caused by friction forces. The insensitivity zone and positioning error of the slide are also reduced with reduction in friction forces. It has been reported that the average static coefficient of friction in cast iron slideways is 0.25 [20]. For medium machines with drive stiffness ranging from 100-150 N/μm, the deformation of the drive as a result of friction forces is 0.05 - 0.07 mm, which is unacceptable in CNC machines [20].

The static coefficient of friction for slideways faced with plastic materials (special polymer) 0.04 - 0.06, while that of anti-friction slideways is 0.002 - 0.003 and that of hydrostatic and aerostatic slideways is even lower [20]. In all these cases deformation of the drive is of the order of micrometres or fraction of a micrometre.

3.3.2 The Slide Positioning Error

The slide positioning error $\varepsilon$ is an important performance parameter of CNC machine tools. This is defined as

$$\varepsilon = F \cdot \frac{\Delta T}{K} [20]$$

where

- $F$ = a constant varying between 1 and 2
- $K$ = stiffness of the drive
- $\Delta T = \Delta f \cdot N$
- $\Delta f$ = the difference between the static and dynamic coefficient of friction
- $N$ = the normal load in Newtons
with conventional materials steel and cast iron $\Delta f$ averages 0.09. The positioning error of slide weighing 5 - 10 kN with a drive stiffness of 100 - 150 N/μm can then be as high as 0.01 - 0.02 mm. Whereas with special slideway polymer materials, the static coefficient of friction is equal to or even slightly less than the dynamic coefficient of friction, so that good positioning accuracy and uniform motion are ensured. If a high-stiffness, clearance-free feed drive with a low friction coefficient is used in combination with slideways of special polymer materials for which is $\Delta f$ is practically zero; it is possible to have a minimum positioning error not exceeding 1-3 μm.

3.3.3 Misalignment

By eliminating clearances in slideways, it is possible to prevent misalignment of the slide on reversal of motion. Such misalignment is approximately equal to the clearance in plain slideways and many range from 0.02 to 0.03 mm [20]. With considerable distance between the slideways and the cutting zone, these misalignments measured in the cutting zone are greatly magnified. In anti-friction slideways clearance are eliminated or reduced by preloading to a level of 1-2 μm. Such a possibility may not be practicable in slideways faced with special polymer materials. However, this may not be construed as a major drawback for employing the polymer materials in slideways.

3.3.4 Stiffness of the Slideway

The stiffness of the slideway determines the misalignment of the slide under load. It is reported [20] that for a given slideway configuration, anti-friction slideways with a slideway length of 700-800
mm, the stiffness of preloaded anti-friction slideways is 4000-6000 N/μm whereas the stiffness of the plain slideways and closed loop hydrostatic slideways is 2000-3000 N/μm.

As far as static stiffness of slideways bonded with polymer material is concerned, it was generally believed that the thickness of about 1.5 to 3.0 mm of such material on steel or cast iron surface may not significantly affect its value. An experimental investigation to arrive at an optimum minimum thickness for which the normal vibration amplitude is the lowest is presented in Chapter 10.

3.3.5 Stick-Slip Motion and Damping

Irregularities in slow displacements are determined mainly by the difference between the static and dynamic coefficient of friction, stiffness of the drive and to a large extent damping of vibrations. The greater the difference in coefficients of friction and less the vibration damping, the wider the range of stick-slip motion, all other things being equal.

Damping of vibrations in the direction of motion along the slideways depends on the rate of displacement. Friction forces in the slideways have a damping effect on vibration only if vibration velocity is greater than the speed of motion. If not, the overall velocity does not change its sign in the presence of vibration, and the overall friction forces does not have a damping effect. This conclusion has been confirmed by Levina [21] and Kudinov [22] in their theoretical and experimental work.
Another vibration direction which has significant influence in the machining process is the normal vibration of the slide which indirectly affect the surface finish of the component being machined. Therefore, the major part of the present work is devoted to the experimental investigation of normal vibration response of plastic slideway materials used in CNC machine tools.

3.3.6 Friction Characteristics of PTFE and PTFE-Metal Composites

The friction mechanism of a plastic surface sliding over a metal surface has been reported by Huggington [1]. Steijn [23] showed that there is a decrease in coefficient of friction with an increase in normal load. The coefficient of friction of most plastics increases as the sliding speed increased [16]. The explanation for the initial rise and the subsequent fall of friction with increasing speed is that it is the combined effect of stick slip and shearing [24]. The contribution of sticking to friction is more at very low speeds. The rate of shearing increases as well if the speed increases within the low speed range resulting an increase in the total friction. At high speeds, the contribution of static friction and dynamic friction to the total friction are nearly equal which eventually results in levelling off or decrease in friction.

In plastics, which have negative slopes in their friction-velocity curves, the effect of increase in shearing on the total friction is negligible at low speeds. As the speed increases, the contribution of slip is larger than the contribution of stick to the total friction which leads to a decrease in the coefficient of friction.

The steady state friction characteristics on a scraped cup ground
cast iron to cast iron surface and PTFE to steel surface have been reported by Bell and Burdekin [25] and is reproduced in Fig. 3.2. The results obtained indicate that unlubricated surfaces and surfaces lubricated with mineral oils tend to exhibit negative slope characteristics at low sliding speed causing stick-slip motion. But there is a change in friction-velocity curve from negative to positive slope for the same cast iron surface lubricated with boundary additive lubricant at low sliding velocity. Hence, stick-slip was eliminated. On the other hand unlubricated PTFE surface exhibits an increase in coefficient of friction which results in a positive slope characteristics over a much wider range of speed. It is this property of PTFE based material which is considered advantageous and primarily responsible for eliminating the undesirable stick-slip motion on slideways. Similar investigations were also reported by Patil and De [3].

The report published by a Russian investigator [26] for different plastics materials are also in agreement with the above results. The friction-velocity characteristics reported for different plastic materials which are presented in Fig. 3.3. Fluor plast (PTFE) quickly increases with increase in sliding speed, when compared to Kaprone (Nylon).

With sliding speeds less than 1 m/min Fluorplast has a low coefficient of friction of the order of 0.1 to 0.15. But, the coefficient of friction of Stirakril (Acrylic resin) remains constant with increase in sliding speed. It is also reported [26] that after several hundred hours of testing with dry lubrication neither wear nor scoring of the lower metallic test pieces was observed.
FIG. 3.2. STEADY STATE FRICTION CHARACTERISTICS OF CAST IRON AND PTFE SLIDEWAYS (AFTER BELL AND BURDEKIN) (2)
FIG. 3.3. COEFFICIENT OF FRICTION PLOTTED AGAINST SLIDING SPEED [15]  
SPECIFIC PRESSURE = 200 N/cm²  
NO LUBRICATION
Aniagan and Bell [4] have investigated the frictional characteristics of PTFE-metal composites sliding over a ground cast iron surface. Dry sliding characteristics as well as the effect of lubricant type and viscosity have been reported for different PTFE-metal compositions, such as Trucite-B, Fluon VB-60 and Fluon VX-2. The test results reveal that all the PTFE based composites exhibited positive slope friction characteristics under dry sliding condition. Lubricants of lower and higher viscosity exhibited positive slope friction velocity characteristics. However, no significant difference was observed between lower and higher viscosity lubricants for sliding speeds above 2.5 mm/sec.

3.4 REVIEW ON THERMOSETTING PLASTICS FOR SLIDEWAYS

3.4.1 Moglice

The friction characteristics of Moglice slide coating system, a thermosetting antifriction composite and cast iron when sliding over steel surface have been presented in Fig. 3.4. The friction velocity curves are drawn for three different grades of Moglice, i.e., Moglice hard, Moglice FL and Moglice WL-B and compared with that of cast iron. For all the grades of Moglice, it is seen that the dynamic coefficient of friction increases initially with increasing sliding speed, then remains nearly constant up to the region of mixed friction. This increase in friction eliminates stick-slip in driving elements during setting up and permits accurate positioning in micrometers.

On the other hand, it is observed that the coefficient of friction of cast iron decreases with increasing slide speed resulting in stick-slip motion in slideways. Another advantage of Moglice coating is that
FIG. 3.4. FRICTION OF MOGLICE, MOGLICE FL, MOGLICE W1-B AND CAST IRON WITH STEEL
(FROM THE MANUFACTURER'S CATALOGUE)
its coefficient of friction is very low and hence the starting force and elastic pre-load are small.

3.4.2 SKC-3

As mentioned earlier SKC-3 is also a popular brand of epoxy material increasingly used for slideway coatings. This material also exhibits very low coefficient of friction when paired with ground cast iron or steel.

The friction-velocity characteristics of this material has been presented in Fig. 3.5. This also provides a comparison between the frictional characteristics of the sliding pairs SKC-3 cast iron and cast-iron, cast iron. The plot shows that the static coefficient of friction is very low, being approximately one seventh of the corresponding value for cast iron-cast iron pair. This suggests very low starting forces or torque and therefore much reduced loads in the drive prior to movement and correspondingly less lost motion due to the drive compliance.

The dynamic friction rises initially as speed of sliding increases and then remains virtually constant until the region of mixed conditions is reached. This particular behaviour of the material is responsible for providing stick-slip free movement to the sliding table. The difference in friction which occur when SKC-3 is paired with either ordinary cast iron, hardened cast iron, ordinary steel or hardened steel is very small and can be ignored.

It has been reported that an SKC-3 cast iron slide combination will display not only a considerable ease of movement, but also is free
**Fig. 3.5. Friction Characteristics of Cast Iron with Cast Iron & SKC-3 with Cast Iron**

(From the Manufacturer's Catalogue)
from stick-slip, which is of vital importance for machine tool builders in view of the increasingly stringent demands by modern positioning control system of CNC machines [14].

3.5 WEAR CHARACTERISTICS OF PTFE AND PTFE-METAL COMPOSITES

The description of the basic mechanism of wear on slideways with several aspects relating to it have been reported by Burdekin et al. [27]. The effects of various factors such as sliding time, sliding velocity and contact pressure on wear and wear rate of PTFE slideways have been investigated by Patil and De [3].

Anlagan and Bell [28] investigated the wear characteristics of PTFE-metal composites when sliding over cast iron. A typical linear wear versus sliding distance curve for Turcite-B is shown in Fig. 3.6. The curve shows two regions of wear, representing running-in-wear and steady-state wear. The running-in-wear which is taking place at a rapid rate ceases within the first kilometre of sliding where the steady state wear begins.

An index for comparing the wear performance of various PTFE-metal slideway composites is the wear factor \( K_w \). This can be evaluated from the slope of the steady-state wear versus sliding distance curve, and is given by the formula

\[
K_w = \frac{h_w}{P X} \text{ (\( \mu \text{m} / \text{N/mm}^2 \cdot \text{km} \))}
\]

Where \( h_w \) is linear wear in \( \mu \text{m} \)

\( P \) is interface pressure in \( \text{N/mm}^2 \)

\( X \) is sliding distance in km
FIG. 3.6. A TYPICAL LINEAR WEAR Vs SLIDING DISTANCE CURVE (AFTER ANLAGAN AND BELL) FOR DRY TURCITE-B
(V = 50 mm/sec, P = 40 N/cm²)
A comparison between the wear factors of dry and lubricated Turcite-B revealed that the introduction of even traces of lubricant reduces the wear factor drastically. As per the test result the wear factor of lubricated Turcite-B roughly one-twentieth of the wear-factor of dry Turcite-B.

According to a study conducted by Domros [29] the wear factor of dry cast iron is 0.47, which is approximately two times as high as the wear factor of dry Turcite-B. When lubricated with traces of oil, the wear factor for cast iron is found to be approximately 10 times as high as the wear factor of Turcite-B. These comparisons suggest that the slideways with PTFE-metal composites offer good wear resistance even under dry conditions and that the use of a lubricant has a substantial influence on the wear characteristics of slideways.

An assessment of the wear behaviour of epoxy based thermosetting reson composites has been reported by Rubenstein [30]. Investigations on wear characteristics of plastic materials also indicate that under clean lubrication conditions, Ferobestos and SKC-3 exhibit high wear resistance than Turcite-B. Whereas under trace lubrication conditions, Turcite-B and SKC-3 exhibit higher wear resistance than Ferobestos. This can be attributed to the fact that Turcite-B and SKC-3 can readily embed the foreign matter eliminating the possibility of abrasion or scoring of slideway interfaces.

Quantitative measurement of wear by analysing the samples of the wear generated during operation by a technique called ferrography has been documented by Roylance and others [31, 32, 33]
The investigations reported so far are mainly concerned with the friction and wear characteristics of various plastic slideway materials. Another important aspect pertaining to the behaviour of slideway materials is the response to vibration and their damping characteristics. Not much investigation work in this area has been reported. Hence adequate experimental data required for the design are not available. This work is therefore devoted to the experimental investigation of vibration response of plastic slideway materials which are widely used in modern CNC machines.