2.1 CAST IRON

Traditionally grey cast iron (Flake graphite) and steel have been used as materials for structures of machine tools. One of the important reasons of using grey cast iron as a material for beds, bases or columns of machine tools is its inherent vibration damping property. The possibility of making castings of almost any shape, good machinability and lower cost in volume production are the other reasons for choosing cast iron as the material for the construction of machine tools. Later, it was considered necessary to grade the cast iron based on its composition and mechanical properties to enable the user to have a fairly wider choice to meet the specific functional requirements. The functional requirements may be in terms of more hardness, more strength, high wear resistance etc. Several grades of cast iron are available to meet the specific requirements of different types of machine tool structures.

The deciding factor in selecting the proper grade of cast iron is whether the slideways are to be cast integral with the bed. The slideways should possess high hardness to offer adequate resistance to wear. On the other hand a grade of cast iron with a pearlitic structure having high strength is to be selected for heavily loaded beds.

There are also other types of cast iron being used to some extent. They are modular graphite cast iron or SG Iron (Spheroidal Graphite iron) having high tensile strength and special patented types called meehanite.
2.2 DRAWBACKS OF CAST IRON

Though cast iron has got certain favourable properties which make it suitable for machine tool structures, it is not free from few drawbacks [9] which are discussed below.

a) More lead time

Casting of bed using cast iron involves number of processes like making a pattern, core boxes, preparation of sand mould, melting and pouring, cleaning and fettling the casting and artificial stress relieving or ageing to relieve the internal stresses after machining. Hence considerable time is required for getting a structure ready for assembly and this time is termed as lead time. In a factory engaged in large scale production of machine tools, this large lead time will result in substantial work-in-progress inventory.

b) Large scrap rate

Sound castings can be produced only if proper casting procedure is strictly followed. Defects of minor nature may be made good but certain major defects which will be revealed only during machining cannot be rectified. Such castings are to be necessarily rejected as scrap. Hence, there is a need to reduce or completely eliminate such rejections as they will contribute to increase the production cost.

c) Machining allowance

Some surfaces of the casting are to be necessarily machined. The allowances provided on such surfaces are called machining allowances. In the case of cast iron considerably large machining allowances are to be provided to obtain a true machined surface owing to the unevenness
of the cast surface and surface defects. The large machining allowance increases machining time and hence machining cost. The machining allowance, therefore, should be as little as possible.

d) More material content of the machine tool

In a machine tool, the material cost alone accounts for about 35-45 percent of the total cost of the machine tool. Hence measures to reduce the material content without compromising the strength and the rigidity are to be examined and explored. Since the factor of safety used in the case of cast iron is comparatively high, and the modulus of elasticity of cast iron is lower than steel, the volume of material consumed is also higher.

e) More production cost for one-off machine

Sometimes there may be the necessity to build and supply one or two machine tools to cater to the customer's specific requirements. In such cases the expenditure involved in the manufacture of pattern and core box will increase the production cost of the machine tool. Hence production of machine tools in small quantities with cast iron bed is highly uneconomical. Many special purpose CNC machines fall under this category.

2.3 STEEL

The manufacturing and economic problems in using cast iron have been discussed in section 1.2. Some of these drawbacks can be eliminated by replacing cast structure by steel structure.

Structures can be fabricated from the previously cut pieces of
rolled steel by welding, bolting or sometimes bonding. The rolled steel is free from the defects associated with castings.

The slideways may be welded or bolted to the bed. Hence the bed can be made of comparatively cheap carbon steels.

The elastic limit and modulus of elasticity and other mechanical properties of steel are higher than those of cast iron and therefore much less material is required for a welded steel structure than for an equivalent cast iron structure subject to the same forces and torques if the factor of safety and rigidity of the two beds are taken to be equal. For equivalent rigidity, the weight of a steel structure will be about 0.5 to 0.75 of that of a cast iron structure, i.e., the savings of metal ranges from 50 to 25 per cent. The actual economy in design in replacing cast iron with steel depends to a great extent upon the design of the two versions.

In making a choice between cast iron and steel as the material for the bed, base or column of the machine tool, it is necessary to bear in mind all the engineering and economic factors of each option. It is prudent to go for cast iron in the case of mass production, while fabricated steel structure is preferable when it is necessary to make one or a two machine tools in a short time.

With regard to vibration damping properties, welded steel beds are not generally inferior to cast iron beds, inspite of the fact that the cast iron as a material is more capable of damping vibrations than steel. The measurement of damping in machine tool structures and their parts have shown that the damping due to internal friction of the material
is small, compared to the damping present in joints, fixed or movable. It has been reported [10] that damping of an assembled structure is about 30 to 50 times higher than that of its individual parts.

Fig. 2.1 shows [10] damping ratios for a lathe bed alone, the same with slide mounted, then head stock added and finally with tail stock added. Damping ratio is seen to be increased by a factor of about 8.

In the case of beds of welded steel construction, the total length of welds has got considerable influence on the damping level of the structure.

Welded beds for machine tools can be made of plate steel of a thickness $\delta > 3$ mm. If the walls are thin ($\delta < 8$ mm) the required rigidity can be provided by adding sufficient number of ribs in a suitable arrangement.

2.4 CONCRETE

Reinforced concrete has been used to some extent, for making beds of heavy machine tools. A reinforced concrete bed was constructed by the Kramatorsk Heavy Machine Tool Plant, USSR [9] for a heavy duty lathe for turning work upto 1250 mm in diameter, 6300 mm long and weighing upto 30 tons. This bed was designed and constructed in place of the cast iron bed. To compare the rigidity of the reinforced concrete bed with the cast iron bed, both were subjected to a horizontal force of 6.5 tonnes at three places. The total deflections of the beds measured at these three places showed that the deflections for the reinforced concrete bed is less by 36 to 45 per cent. The use of reinforced
FIG. 2.1. INFLUENCE OF JOINTS ON DAMPING [10]
concrete bed in the place of cast iron bed is thus technically justified. Subsequently reinforced concrete was used as a bed material by several machine tool builders. Many commercial machine tools feature such beds in the early 1970s both in US and in Europe [11]. A number of such machines were exhibited in the European World Machine Tool Shows in Paris in 1975. Concrete was also extensively used in the design of profile milling machines, heavy lathes and horizontal boring mills.

2.4.1 ADVANTAGES OF CONCRETE

The reinforced concrete was chosen in the place of cast iron and steel particularly for heavy machine tools because of its suitability and availability. It can be cast easily and cured in a shorter time comparable to the best delivery times for castings and steel fabrication.

Another important factor is the cost. It is a fact that the material itself is relatively inexpensive. However, the material cost is only a small part of the total price of the design. A drilling machine company which made its first concrete based machine tool back in 1972, has enumerated costs such as building frames, making moulds, designing each frame for a specific component and engineering the reinforcing structures [11]. But even early machines were estimated as costing 25 per cent less than a comparable structure made of cast iron and steel fabrication.

Yet another favourable reason for considering the reinforced concrete is the material's vibration damping capability characteristics. This was perhaps the primary reason why it was used in early designs. However, the fact that vibration also has deleterious effect on concrete to the extent of breaking it cannot be ignored. Hence the use of concrete in
machines like punch presses is not advisable where the machine is subjected to severe vibrations.

2.5 EPOXY CONCRETE

In spite of the advantages offered by the reinforced concrete, it has not found wide applications in machine tools due to a number of reasons. These include problems associated with materials, equipment required to prestress the reinforcement and the lack of expertise in using this material for machine tools.

However, with development of CNC machine tools, a need was felt for using new materials for machine structures with the aim of reducing vibration which will improve tool life and surface finish. In order to meet these requirements, Epoxy concrete as a material for machine tool construction came into being. Epoxy concrete is a mixture of about 93% crushed granite and 7% epoxy binder. This castable material was developed by Dr. Jorge Renker, Technical Director of Swiss Grinding Machine builder Fritz Studer AG, which was the first machine-tool builder known to offer it [11]. The technology was latter transferred to other machine-tool builders in the U.S. Cincinnati Milacron and Brown and Sharpe were the early licencees before the technology gained wider acceptance. Today many machine tool builders have started using or experimenting with this material.

Although the 93/7 formulation is fairly standard, the composition, which uses Araldite as its epoxy base, can be modified to impart special properties. The physical and mechanical characteristics of Epoxy concrete depend on its resin percentage and the type of aggregate. The work
concerning this aspect have been reported elsewhere [12]. The commercial name of this material was 'Synthetic Granite'. Because an epoxy material, Araldite is used as the binder, the resulting mixture is called epoxy concrete. As with concrete, internal sections can be cored to reduce weight or to provide for hydraulic, electrical or coolant connections.

It has been reported that the material has exhibited exceptional vibration damping characteristics which is revealed from Fig. 2.2. It possesses high rigidity to weight ratio, thermal stability and good environmental resistance. As cast and unreinforced, the material has a low specific weight (specific weight = 0.025 N/mm$^3$) making it lighter than aluminium (specific weight = 0.027 N/mm$^3$) when compared with cast iron, epoxy concrete is only one-third as heavy (specific weight = 0.072 N/mm$^3$).

Table 2.1 shows that epoxy concrete falls short of cast iron in tensile strength, compressive strength and modulus of elasticity. Experimental investigations [11] show that it is superior to most grey irons in modulus-to-weight ratio whereas in strength-to-weight it is not as effective as cast iron. Hence thicker sections are necessary to meet the requirement regarding strength.

2.5.1 Advantages of Epoxy Concrete

This material offers both technical and economic advantages. On the technical side, epoxy concrete has a damping capacity that is several times higher than that of cast iron, as noticed from Fig. 2.2. Owing to this there will be an improvement in the dynamic behaviour of the machine tool.
FIG. 2.2. DAMPING CHARACTERISTICS OF CAST IRON, STEEL AND EPOXY CONCRETE [11]
<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus of elasticity N/mm$^2$</th>
<th>Specific gravity N/mm$^2$</th>
<th>Specific stiffness</th>
<th>Coefficient of thermal expansion $^\circ$C$^{-1}$</th>
<th>Thermal conductivity Wm$^{-1}$K$^{-1}$</th>
<th>Tensile strength N/mm$^2$</th>
<th>Compressive strength N/mm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI (FG 260)</td>
<td>$1.17 \times 10^5$</td>
<td>7.21</td>
<td>16,000</td>
<td>$12 \times 10^{-6}$</td>
<td>75</td>
<td>260</td>
<td>800 approx.</td>
</tr>
<tr>
<td>Mild Steel C 15</td>
<td>$2.07 \times 10^5$</td>
<td>7.93</td>
<td>26,000</td>
<td>$12 \times 10^{-6}$</td>
<td>80</td>
<td>460</td>
<td></td>
</tr>
<tr>
<td>Reinforced concrete 1 : 1.5 : 3</td>
<td>$2.4 \times 10^4$</td>
<td>2.29</td>
<td>10,000</td>
<td>$9 \times 10^{-6}$</td>
<td>0.1</td>
<td>4</td>
<td>270</td>
</tr>
<tr>
<td>Epoxy concrete</td>
<td>$3.3 \times 10^4$</td>
<td>2.50</td>
<td>14,000</td>
<td>$12 \times 10^{-6}$</td>
<td>0.5</td>
<td>25</td>
<td>80</td>
</tr>
</tbody>
</table>
The economic advantage is obtained from substantially reducing the need to tie up the capital by minimizing the build up of stocks of structures. The considerable lead time mentioned as a drawback in the use of cast iron can be drastically reduced. Due to the easy adaptability, machines can be built to the customer's specific requirements. Since casting takes place more or less at room temperature and the increase in temperature due to the mixing of resin and hardener in the resin polymerisation process is only marginal, and cheap material can be used to obtain the mould cavity. Wood serves the purpose well for small volume production.

No waste by-products are formed during fabrication and hence it is not harmful to the environment. Energy consumption in manufacturing is lower than that for other materials. These materials harden very quickly without shrinkage. No measurable changes in dimensions occur due to the humidity changes. Mineral oils and mineral emulsions do not affect the material.

2.6 ACRYLIC CONCRETE

The growing acceptance of epoxy concrete, however led to the development of other castable composites. The more recent entry is an acrylic concrete used as a material for machine-tool base. Here the resin used for binding is called acrylic and hence it is termed acrylic concrete. The proprietary formulation, called Motema-acrylic concrete [11] uses crystalling quality with a purity of 99.5% SiO₂ in combination with a matrix of calcite and polymethyl methacrylate.
According to a presentation [11], methacrylates, unlike other reaction resins, permit production of resins with different viscosities. This, in turn, eases the use of the material in sandwich form of construction in combination with cast iron.

Sanwich construction with acrylic concrete has been used by Berthold Hermle GmbH (FRG) [11] in their tool room milling machines. The machines incorporate the acrylic concrete not only for the base of the machine but also for the transverse slide.

In the preceding sections (2.1 to 2.6), the conventional and unconventional materials used for structures of machine tools are discussed.

2.7 REQUIREMENTS OF MACHINE TOOL SLIDEWAYS

The other area where the present study has concentrated is the design of slideways. The slideways or guideways play a vital role in the operation of machine tools. The factors which affect the operation and performance of machine tool slideways include the following:

i) the accuracy of manufacture

ii) alignment

iii) surface texture

iv) load on slideway

v) speed of traverse of slide

vi) stiffness

vii) hardness

viii) lubrication, friction, wear rate, damping characteristics and environmental conditions
The factor, accuracy of manufacture refers to the accuracy with which slideways are machined to conform to their required geometrical features. The alignment of the slideway refers to proper relative positioning of the mating surfaces when they are assembled. Any misalignment will affect the dimensional and form accuracy of the component, machined on the machine. The factors, surface texture, friction and wear are interrelated. For example, a smooth surface provides a lower friction and reduced wear. Wear is also affected by the surface hardness. During the operation, the shape of the stationary slideways (bed ways) is usually copied by the moving unit. It is better to use harder material for the stationary slideways and the softer material for the moving unit. It is more difficult and expensive to repair the bedways rather than replacing the moving unit.

The stiffness refers to the resistance to deformation of slideways and is denoted by the ratio of normal load and elastic displacements due to contact. Proper lubrication between the mating surfaces is essential to reduce the frictional forces and to minimize the wear substantially. Damping is characterised by its ability to resist vibrations produced or transmitted to the machine while in operation.

However, the functional requirement of present day high precision CNC machine tool slideways is high positioning accuracy in the order of micrometers. This important requirement cannot normally be achieved in a plain metal to metal contact slideways due to the presence of stick-slip motion at low feed rates. Hence, CNC machine tool builders have developed alternative slideway systems to meet this specific requirement.
2.8 TYPES OF SLIDEWAY SYSTEMS

A machine tool can be designed with any one of the following slideway systems. They are:

i) Plain slideway
ii) Rolling-friction slideway
iii) Externally pressurised hydrostatic or aerostatic slideway

The choice of a particular slideway system to a machine tool is discussed elsewhere [13]. A brief description on each slideway system is given in the following paragraphs.

2.8.1 Plain Slideways

Of the three slideway systems, plain slideway system is comparatively cheaper and simple in construction with metal-to-metal surface contact. But it offers a high static coefficient of friction and a low dynamic coefficient of friction causing negative slope for friction-velocity which contribute to stick-slip motion at low sliding velocities. The occurrence of stick-slip motion has an adverse effect on the positioning accuracy of the slide. However, plain slideways exhibit high stiffness and damping [14]. A typical plain slideway system is shown in Fig. 2.3.

2.8.2 Rolling Friction Slideway

Rolling friction slideway system makes use of balls, or rollers as rolling elements which result in a very low coefficient of friction of the order of 0.005 [14]. This ensures highly sensitive precision movements and uniform slow motion. In addition, rolling friction slideways have a considerably longer service life than plain slideways. Though, the stiff-
CAST IRON MATING SURFACES

FIG. 2.3. PLAIN SLIDEWAY SYSTEM (14)
ness of this slideway system is quite high, it often fails to provide a satisfactory level of damping. Moreover, the cost is comparatively high. Figure 2.4 shows a rolling friction slideway used in CNC machining centres.

2.8.3 Hydrostatic Slideway

An externally pressurised hydrostatic or aerostatic slideway system makes use of a thin film of pressurised oil or air. Wear is totally eliminated in this system because there is no metal-to-metal contact. In addition, this system offers low friction, high stiffness and good damping. Despite of these advantages, the machine tool builders rarely opt for this system because of the initial cost and maintenance problems. The hydrostatic slideway system is very complex and highly expensive. Figure 2.5 shows the arrangement of a hydrostatic slideway system.

2.8.4 Plain Slideways with Anti-friction Plastic Inserts

Comparing the technical and economic advantages of the slideways systems discussed above, it is seen that the plain slideway system is the best alternative to other systems, provided the problem of stick-slip motion is either eliminated or minimised by suitable means. The stick-slip motion normally present in metal-to-metal contact plain slideways can be eliminated if one of the mating surfaces (normally the shorter sliding surface) is made of a material which exhibits a very low coefficient of friction. Different plastic materials known for their low-friction property can be serve this purpose. A typical slideway arrangement using this type of slideway is shown in Fig. 2.6.

2.9 THERMOPLASTICS FOR SLIDEWAYS

Experimental investigations reported already on three groups of plastics, namely phenolic resin, nylon and teflon
FIG. 2.4. ROLLING FRICTION SLIDEWAY SYSTEM USING THK LM ROLLER (REPRODUCED FROM THE CATALOGUE OF THK Co.LTD. TOKYO, JAPAN)
FIG. 2.5. HYDROSTATIC SLIDEWAY SYSTEM (14)
FIG. 2.6. PLAIN SLIDEWAY WITH ANTI-FRICTION PLASTIC INSERTS [14]
(polytetra fluoroethylene - PTFE) have revealed that Teflon has exceptionally good frictional characteristics than the phenolic resin, nylon [6,15,16,17,18]. It is also reported [16] that apart from its having the lowest coefficient of friction than all other materials, the sliding surface was free of stick-slip even under dry conditions. However, the practical application of pure Teflon as a slideway material was not recommended due to its having very low wear resistance. Phenolic resin and nylon though exhibit good wear resistance against cast iron or steel surfaces, have frictional characteristics which are unsatisfactory. Hence, the effort was to combine the good wear resistance of resins and nylon with the excellent friction characteristics of Teflon to obtain a good slideway material. According to Russian Scientist Pronikov [19] the best method to evolve a satisfactory slideway material is to combine PTFE and Nylon which results in a material having requisite friction and wear properties.

Another approach to the problem is to use some filler materials in plastics to increase the wear resistance, and reduce creep and thermal expansion properties. Some of the commonly used fillers are asbestos, glass fibre, graphite, bronze and lead. The new materials thus obtained are generally called anti-friction composites.

Some of the commercially available PTFE based antifriction composites and their properties are discussed below [4].

i) TURCITE-B : This is a 22% by volume bronze filled PTFE. This thermoplastic material produced by W.S.Shamban and Company of Denmark. This can be machined by any conventional machining process after it is bonded to the sliding surface by a suitable adhesive. It is
available in the form of sheets of different standard thickness (0.794 mm, 1.588 mm, 3.175 mm). This is used extensively as slideway material in CNC machine tools because it enhances positioning accuracy through elimination of stick-slip. Owing to its low friction the power requirement for moving slides is also less.

ii) FLUON VB-60: This is a bronze-filled 27% by volume PTFE. This thermoplastic material is produced by the Imperial Chemical Industries. It is generally recommended as a good bearing material and hence can be used as slideway material in machine tools too. The thermal conductivity of this material is higher than that for Turcite-B. This can be machined by any conventional machining operation.

iii) FLUON VX-2: This is a 40% by volume bronze-and graphite-filled PTFE, a thermoplastic material produced by the Imperial Chemical Industries. It is also recommended for bearing applications, under dry conditions at low speeds. Thermal conductivity is nearly twice that of Turcite-B. This material can also be ground.

The thermoplastic anti-friction composites discussed in preceding paragraphs are available in strips of different standard thicknesses. All plain slideway is built either by bonding the required strip of composite to the sliding surface with a suitable adhesive or mechanically fastened it to the surface by means of screws. These methods are illustrated in Fig.2.6. Ground or scraped cast iron or steel against ground or scraped plastic composite are the commonly used pairs.

2.10 THERMOSETTING EPOXY MATERIALS FOR SLIDEWAYS

Instead of thermoplastics, thermosetting plastics can be used. These
anti-friction composites are available in the form of paste, called anti-friction coatings. These coatings consist of a two-component plastic material, based on an epoxy resin incorporating high grade fillers. They also exhibit similar properties like low friction, high wear resistance and good damping action which make them suitable for slideway application on par with thermoplastic antifriction composites. A few such anti-friction coatings have been developed and are commercially available for application to machine tool slideways. The most commonly used thermosetting anti-friction composites are Diamant Moglice and SKC-3.

2.10.1 Diamant Moglice

M/s. Diamant Metal Plastic GmbH (FRG) offers a series of products called Moglice (the word is a contraction whose roots which include moly disulfide and the German word for glaze). Diamant had been formulating metallic-filled epoxy materials since the late 1940s mostly for application in foundries to plug blow holes. In 1964, they were asked by West German Machine Tool Builder Froriep to develop a non-shrink low-friction slideway material. A moglice compound in putty form saw its first application form years later [11].

It is reported [11] that most users of this material are machine tool builders particularly interested in streamlining the assembly. The compound may be used for filling screw holes, for positioning bearing surfaces, to connect the steel ways and bases, for casting low-friction surfaces in place. Primarily the material is most commonly used as slideway material between mating surfaces. Hence it is known as Moglice slide coating system.
Moglice is reported to have the following characteristics:

1) Dimensionally accurate moulding is achieved by non-shrink hardening

ii) High dimensional stability because of its having good resistance against moisture

iii) Good adhesion to metal surfaces or moglice surfaces

iv) Resistance to abrasion by means of its special fillers

v) Good damping

vi) Working safety due to its excellent dry running properties

vii) Anti stick-slip properties.

2.10.2 SKC-3

Another popular brand of epoxy material is thermosetting anti-friction composite SKC-3. This material is known as anti-friction coating and is exclusively suitable for slideways because of its very low coefficient of friction.

Investigations on the performance of this material reveal that it can withstand operating temperatures upto 80°C and is chemically inert except when exposed for prolonged periods to acetone, benzene or toluol. Other favourable properties are good damping, high resistance to wear and virtual impossibility of seizure. Moisture has no effect because SKC-3 is non-absorbent and the material can be machined if necessary.

The foregoing survey in epoxy materials clearly establish the ground for widespread application of epoxy concrete as material for machine tool beds and columns replacing the conventional cast iron. With regard to the construction of slideways, the application of plastic
materials (both thermoplastic and thermosetting) as an interface material in plain slideways is recommended as the best alternative to the rolling friction and hydrostatic slideway systems which are costlier and complex in construction.