Precision Machine Design-Mechanical Contact Bearings

(Source: Slocums' precision machine design)

Bearing surfaces play key roles in motion's accuracy and precision, load carrying capacity, lifetime, energy loss, heat generation, etc. Sliding contact bearings and rolling bearings are critically important for most precision machine design.

Factors affecting bearing design: applied load, accuracy/precision, preload, stiffness, vibration/shock resistance, damping capability, friction, and thermal performance

1. Sliding contact bearing

The sliding contact bearing has been the oldest, simplest, and least expensive bearing technology in a wide range of application such as; from coarse construction machinery to ultra-high precision machines of atomic resolution. The stick-slip is commonly observed in most sliding bearings, as it depends on the material, surface finish, and lubricants. In order to minimize the static friction coefficient, various types of lubricants are utilized: light oil, grease, and solid lubricant such as graphite or PTFE(Poly-Tetra-Fluoro-Ethylene) polymer.

Followings are typical examples and guidelines for the materials of sliding bearing and guideway

1) Cast Iron on Cast Iron

This combination has been traditionally used in wide range of application for sliding bearings, because the lubrication can be inherently obtained by the graphite in cast iron, and it can be hand-scraped to a high degree of accuracy. It is a good practice that one surface is harder than the other surface, in order to strengthen wear characteristics, and to refinish on only one surface when it is needed.

2) Cast Iron on steel

By introduction of precision grinding machines and high strength steel, the practice of one surface being harder than the other surface has been implemented conveniently. Thus this cast iron on steel largely replaced the cast iron on cast iron. Many machine tool carriages are still using this combination, particularly where high stiffness and high load capacity are required.

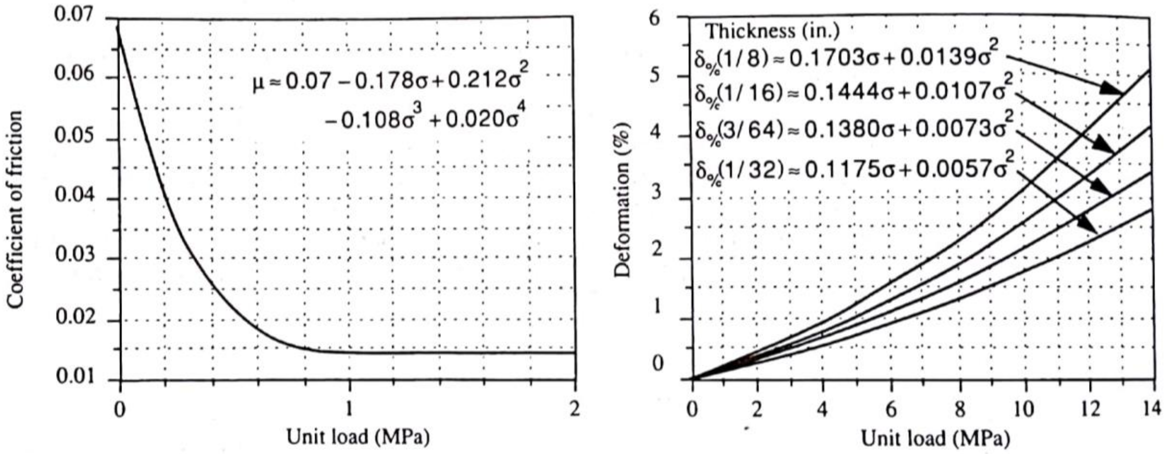
3) Brass on Steel

Brass has inherent lubrication capability especially when in contact to steel. When the brass parts can be manufactured as porous structure by the power metallurgy process, a reservoir can be formed for the lubricant. When the bearing surface is heated up, the lubricant is coming out to the surface, thus it can reduce friction and heat generation from the surfaces. This has been used in very high speed reciprocating machines, acceptable to dirt environment, and can be used in articulated joints of non-precision machinery such as backhoe.

4) Polymers on most materials

The PTFE based bearings have very low static friction coefficient such as about 10-20% of dynamic friction coefficient, thus have very good bearing performance for most machine tool applications, replacing traditional metal on metal bearings. Turcite®, for example, being in frequently use for polymer based bearings, is used in the form of thin sheet a few millimeter thick bonded to the machine carriage. After bonding, the bearing surfaces are scraped to achieve maximum accuracy and to have good oil retention characteristics into the surface. The bond usually lasts for the life of machine tools, but the bonded sliding surfaces should be kept from dirts or particles, because the dirts and particles can tear the bonded layer to fail seriously. Typical material properties are shown in the following.

(Source from Slocum's precision machine design)



Maximum load	14 MPa
Limiting pressure x velocity (PV)	53 Mpa x m/min (25,000 psi x fpm)
Minimum operating temperature	-200℃
Maximum operating temperature	280℃
Coefficient of friction	From 0.02 to 0.2 (depending on unit load and lubrication)

Figure 8.2.1 Properties of Turcite® sliding bearing material. (Courtesy of W. S. Shamban & Co.)

Maximum load	
Normal	140 N/mm^2
Special circumstances	250 N/mm^2
Compressive yield strength	310 N/mm^2
Maximum rubbing velocity	2.5 m/s
Specific load x rubbing velocity (PV factor)	
Continuous	1.75 N/mm^2 x m/s
Short periods	3.5 N/mm^2 x m/s
Minimum operating temperature	-200℃
Maximum operating temperature	280℃
Coefficient of friction (unlubricated)	From 0.02 to 0.2, depending on load
Electrical resistance	1 to 10 ohms/cm^2
Nuclear radiation resistance	Unaffected by gamma-ray dose of 10^8 rad

Table 8.2.1 Properties of Glacier DU® bearing material available as bushings or in sheet form. (Courtesy of The Glacier Metal Company Ltd.)

Compressive strength	96.5 MPa
Shear strength	31.7 MPa
Compressive modulus	4.0 GPa
Shear modulus	0.8 GPa
Shrinkage	400 micron/m
Coefficient of thermal expansion	42.5 micron/m/C°
Lubricated static coefficient of friction	Approx. 0.11
Lubricated dynamic coefficient of friction	Approx. 0.09
Density	2.1 g/cm^3
Pot life	45 minutes
Cure time	40 hours

Table 8.2.2 Properties of a typical castable high lubricity polymer. (Courtesy of ITW-Philadelphia Resins.)

Specific weight	1.6 g/cm^3
Dynamic strength	1450 N/cm^2
Static strength	14,000 N/cm^2
Minimum operating temperature	-40°C
Maximum operating temperature	125°C
Shrinkage	About 1/4%
Moisture absorption	Very good resistance

Table 8.2.3 Properties of Moglice™ high lubricity castable bearing replication material. (Courtesy of "DIAMANT" Metallplastic GmbH.)

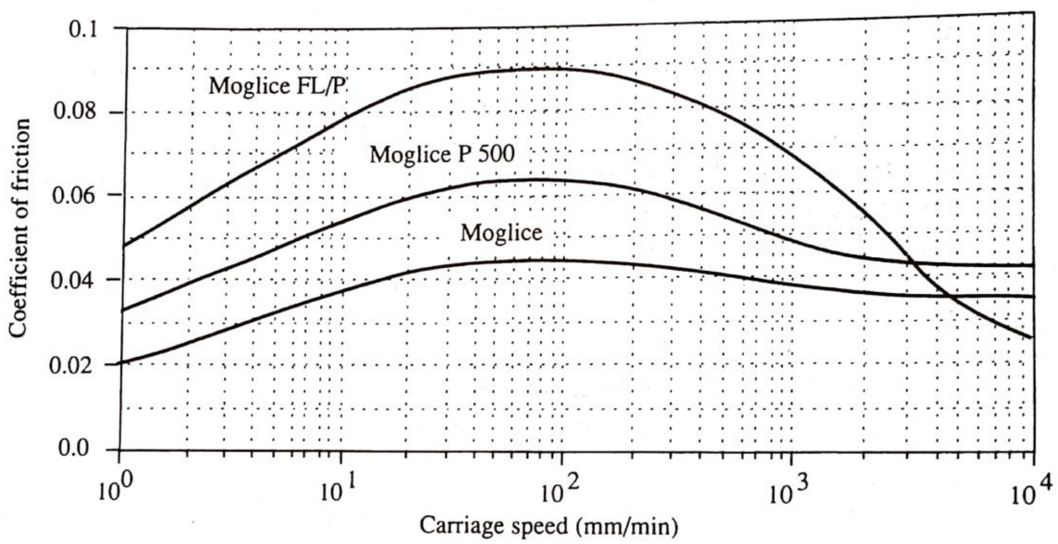


Figure 8.2.2 Frictional properties of Moglice™ castable bearing material: contact pressure 5 daN/cm^2 with mineral oil having a viscosity of 25 centistokes at 50°C. (Courtesy of "DIAMANT" Metallplastic GmbH.)

(Source from Slocum's precision machine design)

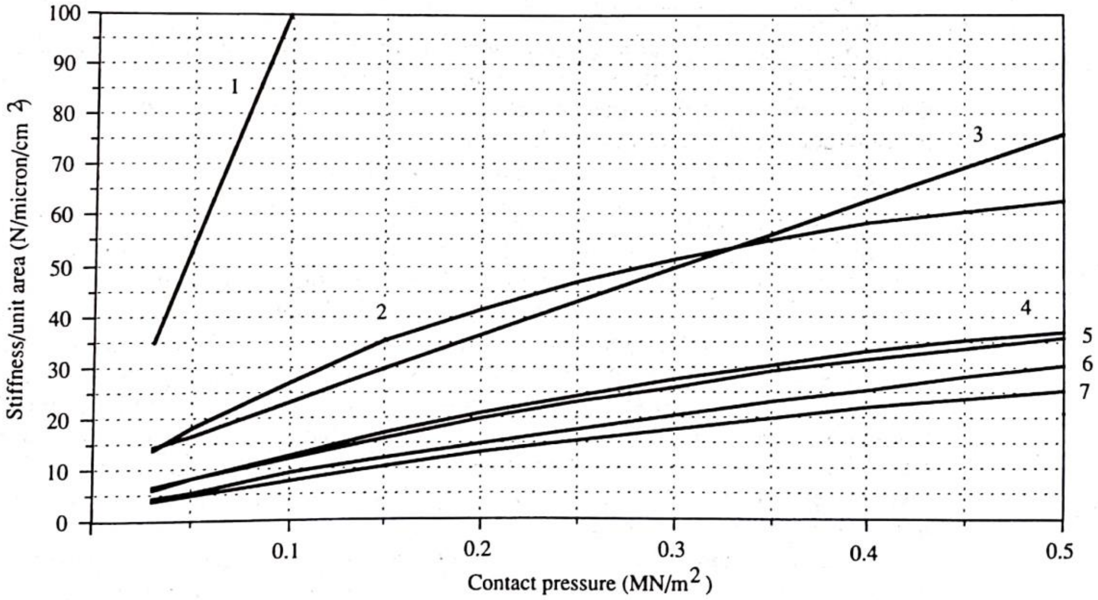
5) Most materials on ceramics

Ceramics can be harder than any materials and also can be finished to higher precision without any surface degradation due to oxidation, and typical ceramic bearing materials are aluminum oxide, silicone nitride, silicon carbide, and Zerodur™.

Materials sliding on the ceramic surfaces have inherent lubrication capability like the polymer bearing. Ceramics surface can have the negative skewness after surface finishing due to brittleness, thus it can have very good high loading capacity with negligible wear and low friction. Also, residual stresses are not easily built up during the finishing process, hence it is easier to grind or lap the ceramic bearing rail than the steel one. Manufacturing difficulty in ceramic elements and the related high material cost are, however, main drawbacks.

6) Contact stiffness vs preload for sliding bearing

The sliding contact bearing can have very high stiffness due to the large sliding surface, and higher stiffness can be achieved with the bearing worn-in. The following fig. shows typical stiffness curve for various sliding bearing types.



#	Way	Bearing	Stiffness/unit area (k/a) as a function of contact pressure P
1	Lapped cast iron	Ground cast iron	k/A = 6.2105 + 9.5583e-4P
2	Ground cast iron	Ground cast iron	k/A = 7.2247 + 2.3291e-4P - 3.4428e-10P^2 + 2.0422e-16P^3
3	Ground cast iron	Scraped cast iron	k/A = 10.129 + 1.3275e-4P
4	Ground cast iron	Ground ferobestos	k/A = 3.4536 + 9.7855e-5P - 5.5217e-11P^2 - 1.0544e-17P^3
5	Ground cast iron	Ground plain DX	k/A = 3.8624 + 8.7409e-5P - 3.7974e-11P^2 - 1.8380e-17P^3
6	Ground cast iron	Ground dimpled DX	k/A = 2.1344 + 7.5302e-5P - 5.8759e-11P^2 + 4.2540e-17P^3
7	Ground cast iron	DU as received	k/A = 2.1064 + 6.1535e-5P - 3.0397e-11P^2 + 2.2446e-18P^3

Figure 8.2.3 Constant stiffness of various sliding contact bearings lubricated with light oil and after wear-in. (After Dolbey and Bell.)

(Source from Slocum's precision machine design)

The preloading should be sufficient so that all parts of bearing pads are in contact with the mating surfaces.

For the PTFE based bearings, the static friction coefficient can decrease from about 0.3 to 0.03-0.1, after worn-in period of few hundred to few thousands cycles. The dynamic coefficient would be 0.02-0.1 after worn-in. For some PTFE bearings, preload can help to lower the friction coefficient, typically preloading of about 10% of maximum load will give significant reduction in the friction coefficients from 0.07 to 0.015, as shown in fig. This will greatly help for especially for contouring accuracy of machines, where the direction of motion is changing four times along the circular path, thus crossing the zero point 4 times for X,Y axis for one complete contour path.

Sliding bearing design detail

1) Bearing sizing

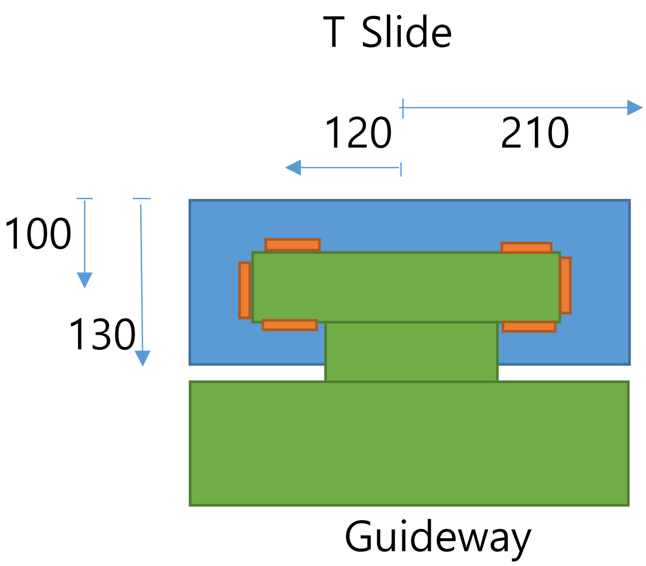
In order to prevent the sliding bearing system from 'walking' (yawing or pitching) during low velocity, the ratio of length to width for a bearing pad will be better around between 2:1 and 1:1. A rule of thumb is to use the *ratio of golden rectangle of Greek architecture*, that is 1.618:1 (≒1:0.618)

Higher speed gives higher friction forces, and higher moment loads to the bearing system, thus higher length to width ratio is preferable.

For large machines such as moving bridge type machines where this sizing cannot be applied, two drive system is recommended; one is master drive and the other is slave drive.

Ex) Sizing for T slide bearing pads, where the carriage rides on the sliding contact bearings, and another identical bearing set located a distance 480mm into the page

(Source from Slocum's precision machine design)



Cast Iron T slide on DUⓡ(PTFE based) sliding bearing

Preload of 1000N will be applied to achieve 1.75GN/m bearing stiffness in the vertical direction.

In order to determine the size of bearing pad;

From the stiffness curve of DUⓡ

K_{pad}/A_{pad} [N/um/cm^2]

$=2.1064+6.1535e\text{-}5*(F_{pad}/A_{pad})$ [N/m^2]

$K_{pad}=K_{desired}/8=1.75/8$ [GN/m]

=0.21875[GN/m]=218.75[N/um]

$F_{pad}=F_{preload}/4=250$[N], thus

218.75/A [N/um/cm^2]=2.1064+0.01538375/A [N/m^2]

∴ 0.021875/A [N/um/m^2]=2.1064+0.01538375/A [N/m^2]

∴A=(0.021875-0.01538375)/2.1064=0.00324 [m^2]≒32[cm^2]

Thus the pad size is 8cm by 4cm (if 2:1 ratio)

2) Oil distribution groove

For precision machines when large load of about more than 100N, lubrication is to be considered, thus the lubrication groove is better to be formed in the form of '/' or 'X' by cutting on the inner part of bearing pads, making periodic oil/grease injection possible without disassembly.

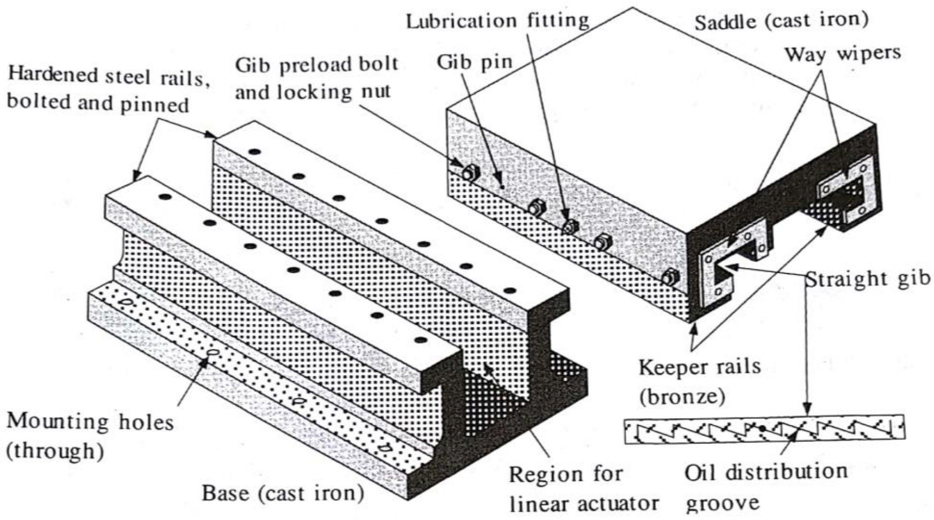


Figure 8.2.5 Components of a tee-shaped slide. Note the straight gib and way wipers. (Courtesy of Setco Industries Inc.)

(Source from Slocum's precision machine design)

3) Gib design

Because sliding contact bearings are quite stiff, and friction coefficient is relatively high when compared to rolling bearings, the preload forces are usually kept low, thus slight amount of wear or material relaxation can make the preload lost, because the amount of preload is only a few microns in the structure. Therefore, inserting a gib in to the bearing system is a very good practice to give or adjust the preload, rather than making all parts with the precision interference. Fig shows common types of gibs.

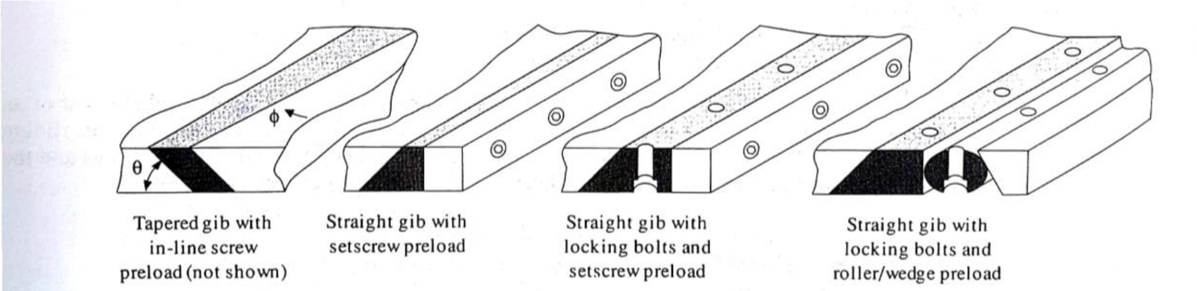


Figure 8.2.4 Some of the many types of gibs that can be used to preload bearings.

(Source from Slocum's precision machine design)

The thickness of the t_{gib} can be chosen such that the deflection is one-half of the desired repeatability, δ, of the system.

$t_{gib}=[2\alpha\eta ab^3P_{max}/(\delta E)]^{1/3}$

where a,b are dimension of the gib, E is Young's modulus, and all other parameters are shown in the fig.

Ex) Brass gib of 0.01m by 0.05m size under P_{max}=0.5MPa (≒5Kgf/cm^2≒5bar), E=110GPa, δ=1um=10^{-6}m;

Then t_{gib}=0.0183m=18.3mm

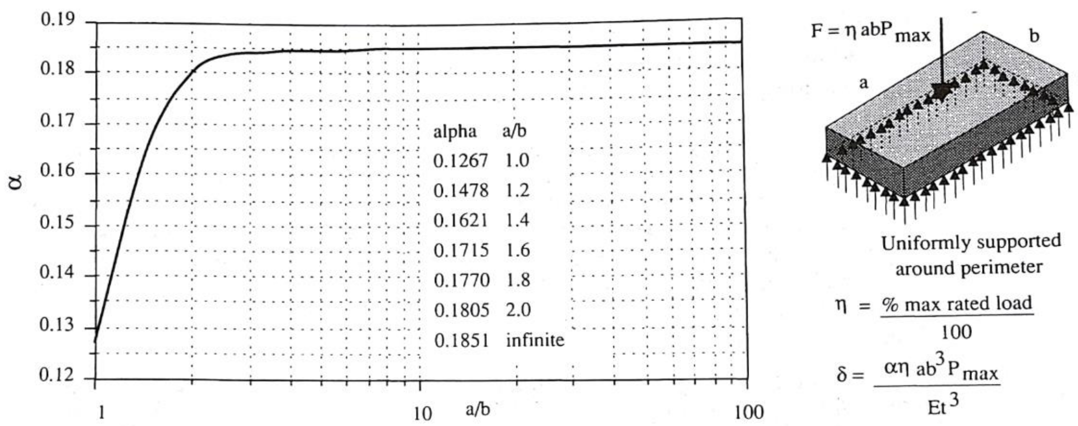


Figure 8.2.6 Model for calculating straight gib thicknesses.

(Source from Slocum's precision machine design)

4) Various slider design including commercial modular slider

There are variety of slider designs, and some designs are modular design which are commercially available.

T slider, Dove-tail slider, Rectangular slider, and Double V slider are typical examples.

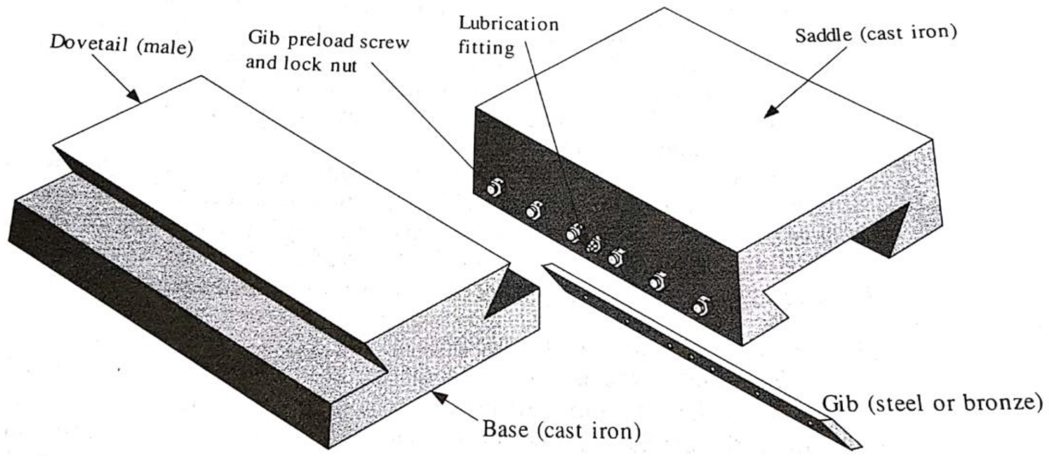


Figure 8.2.13 Construction of a modular dovetail slide assembly. (Courtesy of *Russell T. Gilman, Inc.*)

(Source from Slocum's precision machine design)

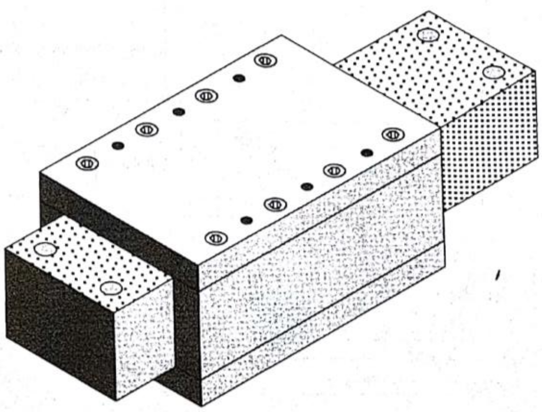


Figure 8.2.9 General configuration of a rectangular linear motion sliding contact bearing. Bearing surface may be composed of pads or be the entire interface (use of gibs not shown).

(Source from Slocum's precision machine design)

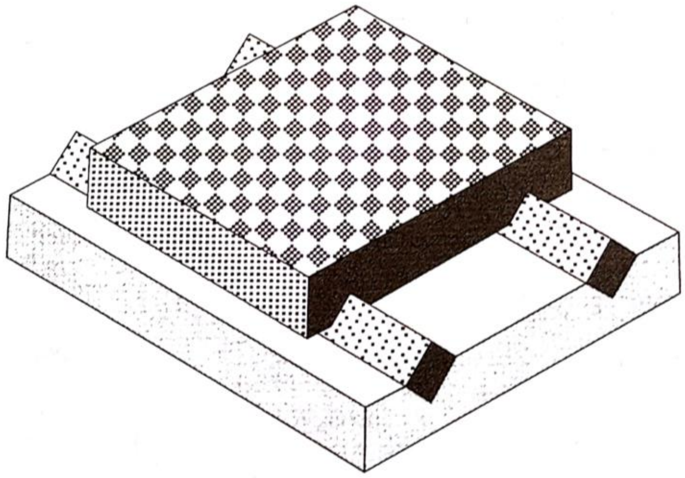


Figure 8.2.15 General configuration for a double-vee linear motion sliding beari
Bearing surfaces may be composed of two bearing pads on each side of the vees (ei
pads total), three pads per vee (six pads total), or pads covering the entire interface w
the vees.

(Source from Slocum's precision machine design)

The Nanosurf-2 of the NPL(National physical laboratory, UK) has shown the best performance of sliding bearing in this kind as in the fig. About 2-3um PTFE based film is deposited on to the convex bearing pads, and the heat generated by friction during the motion can be quickly transferred to the backing metal. The bearing rail is lapped to have a surface finish in nanometer range. The motion accuracy is depending on the shape and surface finish of the bearing rail, while the repeatability and resolution depend on the surface finish.

The vertical error of motion, or smoothness of motion, δ, can be approximately as follows;

$\delta = [R_a^3 / D_{contact}]^{1/2}$

where R_a is the surface roughness of bearing rail, and $D_{contact}$ is the diameter of circular contact region from the Hertz stress. This indicates that better surface finish and larger contact area due to higher contact pressure will give smoother motion of slider, by the averaging effects.

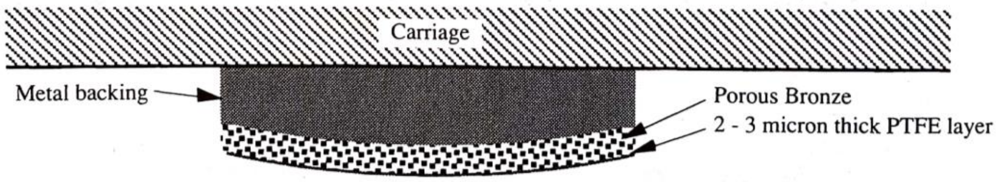


Figure 8.2.18 Cross-section of the sliding bearing pad design for the Nanosurf 2. (Courtesy of the National Physical Laboratory.)

(Source from Slocum's precision machine design)