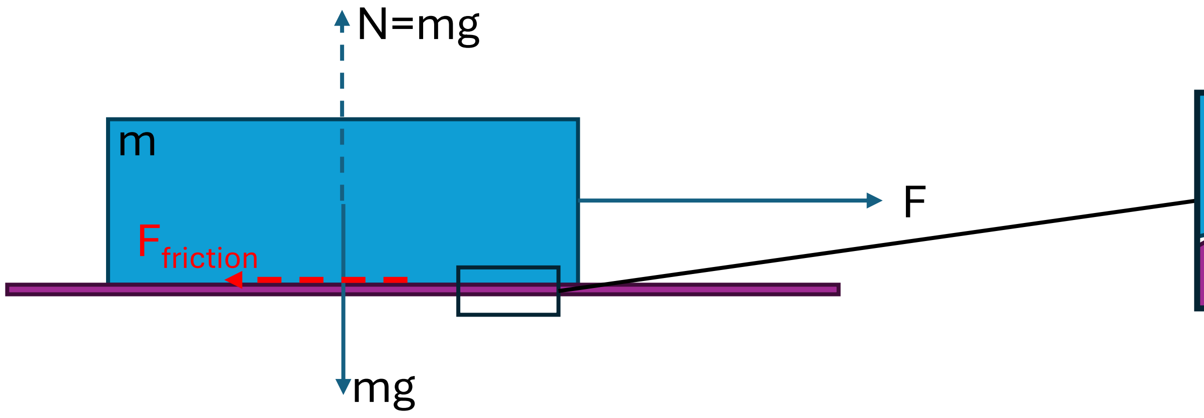
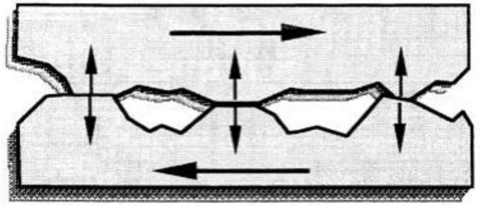
The friction is the resistance to relative motion between two surfaces in contact (sliding motion, rolling motion, static w/o moving)

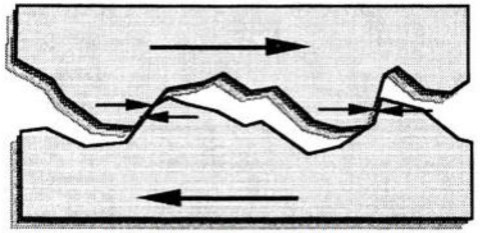
The amount of friction is primarily determined by two factors:

- Nature of the Surfaces: function of the material and its Surface finish. Rough surfaces tend to have higher friction than smooth surfaces because irregularities in the surface create more contact points and stronger intermolecular interactions between the atoms or molecules of the two surfaces.

- Normal Force or Pressure: The force pressing the two surfaces together, known as the normal force, is crucial in determining friction. Frictional force is directly proportional to the normal force. As the normal force increases, so does the frictional force and vice-versa.




Adhesive forces impede relative movement


Repulsive forces impede relative movement

The amount of friction is not directly dependent on the area of contact!
However, the area of contact can indirectly affect friction under certain conditions. For example, for very soft materials, increasing the area of contact can distribute the force over a larger surface area, potentially reducing the pressure at any individual point of contact and, in turn, affect the frictional force. Note that this effect is of a secondary order.

The surface topographies of the PMMA (with different nanocomposite films) observed using scanning electron microscopy (JEOL-JSM-5600LV, JEOL Ltd, Tokyo, Japan) and surface profilometry (Talyscan 150, Taylor Hobson Ltd, Leicester, UK) with a diamond stylus of 4 μm in diameter. From: *DOI:10.1515/polyeng-2014-0346*

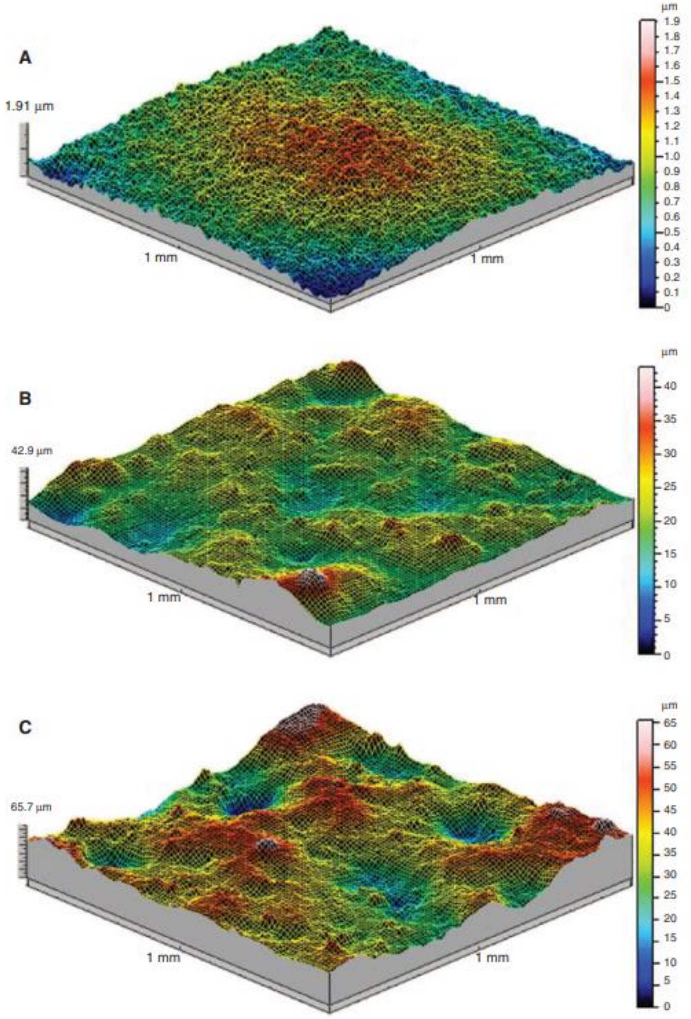
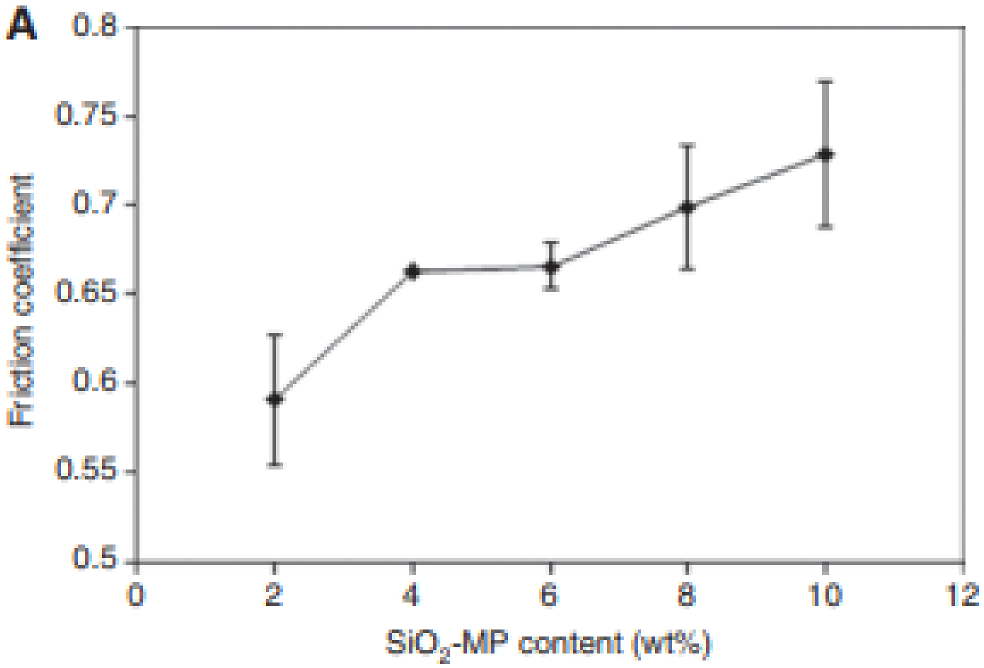


Figure 4: Surface topographies of (A) poly(methyl methacrylate) (PMMA) film and PMMA/multiwalled carbon nanotube silicon dioxide microparticle (MWCNT-SiO_2-MP) nanocomposite films co-incorporated with (B) 4 wt% MWCNTs and 2 wt% SiO_2-MPs and (C) 4 wt% MWCNTs and 10 wt% SiO_2-MPs.



The <u>coefficient of friction</u> **μ** measures the amount of interaction between two surfaces related to the friction between the two surfaces as they slide over another, rolls over another, are in contact (but not moving)

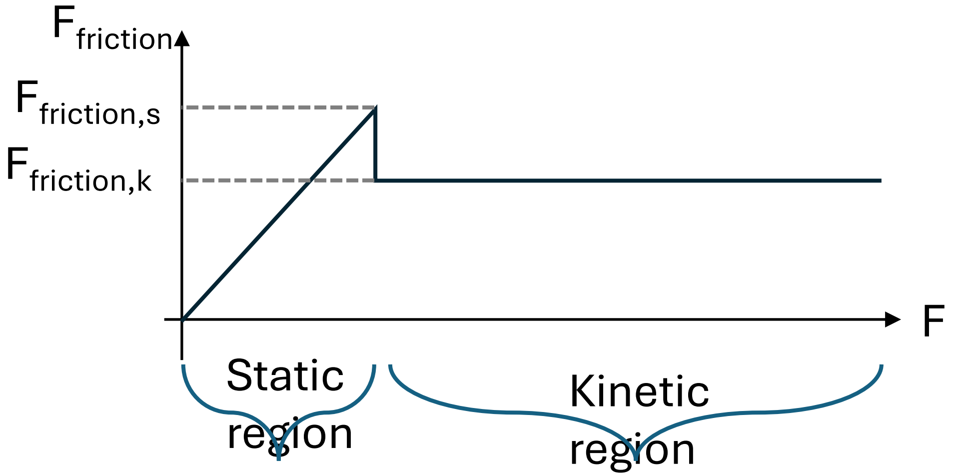
$$0 < \mu \leq 1^{*}$$ (μ =0 no friction; *not always, as for sticky materials etc.)

$$F_{friction} = \mu\, mg$$

- The static coefficient of friction $\boldsymbol{\mu_s}$ represents the frictional force between two surfaces when they are stationary or not moving relative to each other.
- The kinetic coefficient of friction $\boldsymbol{\mu_k}$ represents the frictional force between two surfaces when they are in motion relative to each other.

$\boldsymbol{\mu_s}$ is generally higher than $\boldsymbol{\mu_k}$ because it accounts for the additional force required to overcome the initial resistance to motion between stationary surfaces (when there is much more inter-molecular attraction between the objects)

$F \leq F_{friction,s}$ = no relative movement
$F > F_{friction,s}$ (and by definition $F > F_{friction,k}$) = relative movement



Effect of Temperature on Static Coefficient of Friction (μ_s):

Generally, as temperature increases, μ_s tends to decrease with respect to Room Temp. This is often attributed to changes in the surface properties of materials. For example, at higher temperatures, materials may become softer or exhibit different surface interactions, leading to reduced friction between them.

Effect of Temperature on Kinetic Coefficient of Friction (μ_k):

The effect of temperature on μ_k can vary depending on the materials involved and the specific conditions.
With respect to Room Temp., μ_k may decrease or increase with temperature because the materials experience changes in surface properties and/or lubricants become more/less effective at higher temperatures (it can evaporate at higher temperatures).

Friction at cryogenic temperatures:

Friction between surfaces typically decreases at cryogenic temperatures due to reduced molecular motion, changes in material properties, and potentially increased effectiveness of lubricants. In some studies, were stipulates the existence of two mechanisms: i) thermal and hydrodynamic, which are responsible of the decrease in the friction coefficient under cryogenic conditions. The thermal effect induces a gain in hardness of the antagonistic surfaces and attenuates the adhesion between the two bodies in contact; ii) The second hydrodynamic effect of lubrication is the formation of a gas phase film between asperities.

Overall, the relationship between temperature and **μ** is complex and can depend on various factors. Experimental testing and analysis are often required to determine the effects of those factors on friction coefficients.

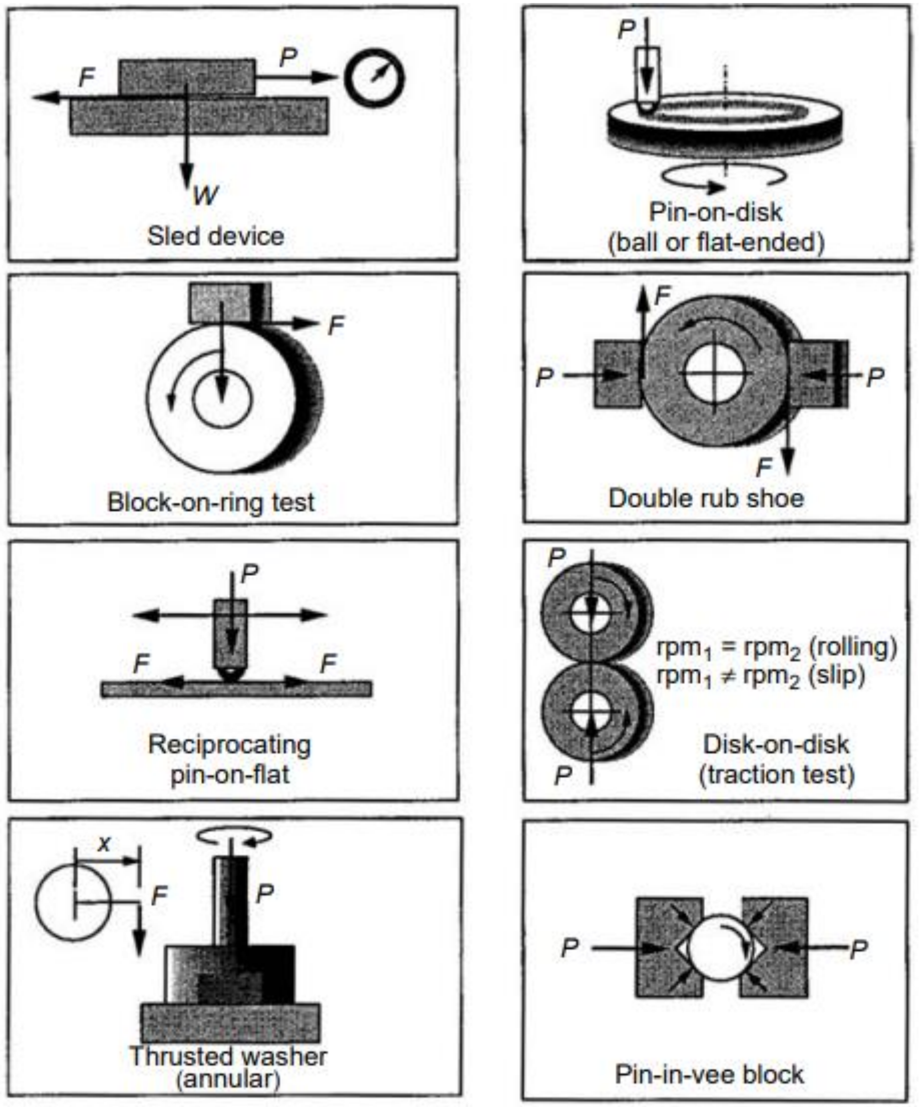
...from a CERN study:

Stainless steel (304 L) on stainless steel (304 L): the coefficient of friction is almost constant from room temperature down to 1.8 K and approximately equal to 0.4.

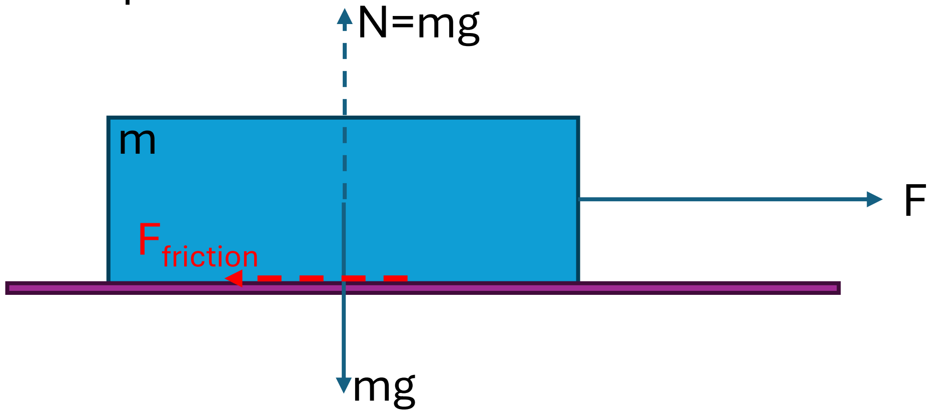
	Temperature:	300 K	77 K	4.2 K	1.8 K
Stainless steel / mild steel	CERN	0.57	0.52	0.5	0.61
Stainless steel / vetronite	CERN	0.23	0.46	0.11	0.36
Stainless steel / vetronite	FBMNL	0.32	0.51	0.21	-
Aluminium / vetronite	CERN	0.43	0.52	0.46	0.38
Aluminium / vetronite	FBMNL	0.47	0.60	0.51	-

Friction Science and Technology- From Concepts to Applications-CRC Press (2008):

https://ia801004.us.archive.org/11/items/dekkermechanicalengineeringpeterj.blaufrictionscienceandtechnologyfromconceptsto/%28Dekker%20Mechanical%20Engineering%29%20Peter%20J.%20Blau%20-%20Friction%20Science%20and%20Technology_%20From%20Concepts%20to%20Applications-CRC%20Press%20%282008%29.pdf



Example 1.



NOT MOVING

m=100kg

μs=0.5

mg=981N

$F_{friction,s}$=0.5*981N=490N

$|F| \leq F_{friction,s}$=no sliding movem.

or

$|F| > F_{friction,s}$=sliding movem. →

MOVING

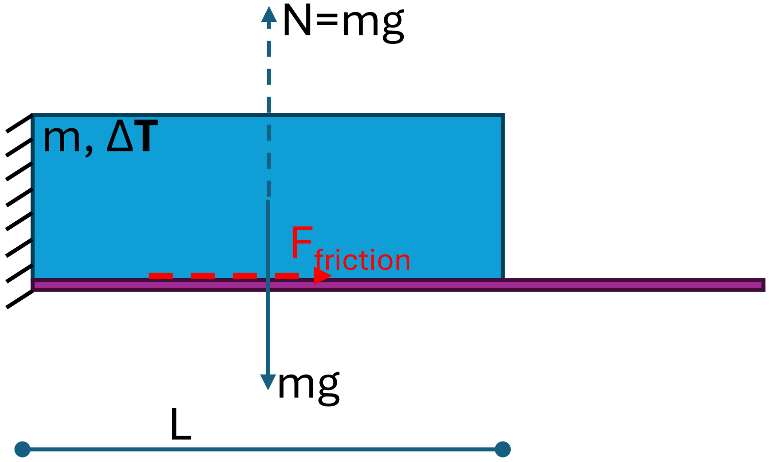
m=100kg

μk=0.2

mg=981N

$F_{friction,k}$=0.2*981N=196N

Example 2.



m=100kg
L=500mm
$A=2500mm^2$
Ti=20°C
Tf=-120°C
α=20e-06
E=200GPa
μs=0.5

ΔL=500*20e-06*(-140) =-1.4mm

$\varepsilon =$ ΔL/L

$\sigma =$ N/A

$\sigma =$ E*ε

We can compute the equivalent force due to thermal shrinkage:

F=A*E* ΔL/L=2500*200000*(-1.4)/500= -1400kN

$F_{friction,s}$=0.5*981N=490N

$|F| \leq F_{friction,s}$=no sliding movement

$|F| > F_{friction,s}$=sliding movement ←

We should always compare the magnitude of the applied force with the static friction force to understand if there is moving or not!

In the FEAs:
If $F \leq F_{friction,s}$ remember that we do not have relative movements! We can use μs and check/confirm that no sliding occurs. To enhance the reliability of the simulations it is recommended to specify a “shear breaking-weld force” equal to $F_{friction,s}$ (if the software not automatically computes the normal force acting to each mesh node and convert it to the equivalent friction force step-by-step). For expedited analyses, a welded connection can be utilized.

If $F > F_{friction,k}$ we can assume μk (but simulations should be checked also with μs, especially in terms of stress for brittle materials, since we always have transition phase).

For more complex analyses, one common approach is to use the Coulomb friction model, which assumes that the frictional force is proportional to the normal force and is limited by the $\boldsymbol{\mu_s}$ when the surfaces are not sliding. Once sliding occurs, it's limited by $\boldsymbol{\mu_k}$.

https://roymech.org/Useful_Tables/Tribology/co_of_frict.html

Material 1	Material 2	Coefficient Of Friction			
		DRY		Greasy	
		Static	Sliding	Static	Sliding
Steel	Aluminium Bros	0,45			
Steel	Brass	0,35		0,19	
Steel(Mild)	Brass	0,51	0,44		
Steel (Mild)	Cast Iron		0,23	0,183	0,133
Steel	Cast Iron	0,4		0,21	
Steel	Copper Lead Alloy	0,22		0,16	0,145
Steel (Hard)	Graphite	0,21		0,09	
Steel	Graphite	0,1		0,1	
Steel (Mild)	Lead	0,95	0,95	0,5	0,3
Steel (Mild)	Phos. Bros		0,34		0,173
Steel	Phos Bros	0,35			
Steel(Hard)	Polythened	0,2		0,2	
Steel(Hard)	Polystyrene	0,3-0,35		0,3-0,35	
Steel (Mild)	Steel (Mild)	0,74	0,57		0,09-0,19
Steel (Mild)	Steel (Mild)	-	0,62		
Steel(Hard)	Steel (Hard)	0,78	0,42	0,05 -0,11	0,029-,12
Steel	Zinc (Plated on steel)	0,5	0,45	-	-
Teflon	Steel	0,04		0,04	0,04

Barrett, "Fastener Design Manual," NASA Reference Publication 1228, 1990:

Materials	Static		Sliding	
	Dry	Greasy	Dry	Greasy
Hard steel on hard steel	0.78	0.11 (a)	0.42	0.029 (k)
	---	0.23 (b)	---	0.081 (e)
	---	0.15 (c)	---	0.080 (i)
	---	0.11 (d)	---	0.058 (j)
	---	0.0075 (p)	---	0.084 (d)
	---	0.0052 (h)	---	0.105 (k)
	---	---	---	0.096 (l)
	---	---	---	0.108 (m)
	---	---	---	0.12 (a)
Mild steel on mild steel	0.74	---	0.57	0.09 (a)
	---	---	---	0.19 (u)
Teflon on Teflon	0.04	---	---	0.04 (f)
Teflon on steel	0.04	---	---	0.04 (f)

Friction Science and Technology- From Concepts to Applications, 2008:

Material Combination		
Fixed Specimen	Moving Specimen	μ_s
Steel	Cast iron	0.4
Steel, hardened	Steel, hardened	0.78
	Babbitt	0.42, 0.70
	Graphite	0.21
Steel, mild	Steel, mild	0.74
	Lead	0.95
Steel, 1032	Aluminum	0.47
	Copper	0.32
	Steel, 1032	0.31
	Ti-6Al-4V	0.36
Steel, stain. 304	Copper	0.33
PMMA	PMMA	0.80

During the design phase, we should have the flexibility to consider both lower and higher values of the friction coefficient to optimize a particular effect. It cannot be predetermined whether opting for the lower or higher value would result in a more conservative assumption, as it depends on the specific case study.

During the prediction phase, it is crucial to adopt the most accurate value. If a specific experimental value is not available, we can rely on the central value extracted from the comprehensive literature database.

Dry and Room Temperature conditions:

Hard steel – hard steel μ_s **=0.78**; μ_k **=0.42**

Teflon – hard steel μ_s **= 0.04-0.2**; μ_k **=0.04**

Copper – hard steel μ_s **= 0.53**; μ_k **=0.36**

Copper – copper μ_s **= 1-1.6**; μ_k **=1**

PMMA-PMMA μ_s **= 0.8;**

PMMA- hard steel μ_k **= 0.65-0.8;**

Effect of cryogenic friction conditions on surface quality:
https://www.sciencedirect.com/science/article/pii/S221282712200600X/pdf?md5=cf4a0cc0b6271cd199173c8e8e33a6dd&pid=1-s2.0-S221282712200600X-main.pdf

Friction and wear of PTFE composites at cryogenic temperatures:
https://www.tselubes.com/wp-content/uploads/2017/03/Friction-and-Wear-of-PTFE-Comp-at-Cryogenic-Temperatures.pdf

The measurement of Friction coefficient Down to 1.8 K for Large Hadron Collider:
https://cds.cern.ch/record/1019470/files/CM-P00062282.pdf

LUBRICATION MECHANISMS OF LN2 IN ECOLOGICAL CRYOGENIC MACHINING:
https://www.tandfonline.com/doi/abs/10.1080/10910340500534324

Friction and wear behavior of a PMMA-SiO2 coating on hardened steel:
https://link.springer.com/article/10.1557/opl.2014.166

Friction and wear behavior of zirconium oxide reinforced PMMA composites:
https://www.sciencedirect.com/science/article/abs/pii/S135983681300423X?via%3Dihub

Friction and wear behavior of zirconium oxide reinforced PMMA composites:
https://www.sciencedirect.com/science/article/abs/pii/S135983681300423X?via%3Dihub

The effect of temperature on wear and friction of a high strength steel in fretting:
https://doi.org/10.1016/j.wear.2013.03.048

https://www.engineeringtoolbox.com/friction-coefficients-d_778.html

https://engineeringlibrary.org/reference/coefficient-of-friction

https://www.tribonet.org/wiki/friction-coefficients-in-atmosphere-and-vacuum/

https://www.engineersedge.com/coeffients_of_friction.htm

https://roymech.org/Useful_Tables/Tribology/co_of_frict.html

https://nfsi.org/wp-content/uploads/2013/10/Determining.pdf

https://www.schneider-company.com/coefficient-of-friction-reference-chart/