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MATERIAL SELECTION FOR TRIBOLOGICALLY LOADED COMPONENTS

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Abstract: *This paper examines the selection of materials for machine parts subjected to high friction and wear (tribologically loaded components). Three main classes of engineering materials – metals, polymers, and ceramics – are analyzed in terms of tribological properties such as hardness, coefficient of friction, and wear resistance. The importance of these properties for material performance under frictional conditions is discussed. A specific example is used to illustrate the process of selecting an optimal material based on tribological requirements.*

Keywords: *Material selection, Tribology, Metals, Polymers, Ceramics, Hardness, Wear, Sliding bearing*

1. INTRODUCTION

For many engineering components operating under mutual friction conditions, proper material selection is essential for reliability and longevity. Tribologically stressed parts – such as bearings, gears, sliding guides, and seals – endure continuous surface contacts under load, leading to friction (resistance to motion) and progressive wear (material degradation). Inappropriate material choice can result in excessive wear, loss of efficiency due to high friction, and even sudden failure caused by wear. Therefore, selecting materials that optimally balance tribological requirements (e.g., low friction, high wear resistance) with other criteria (such as strength, toughness, corrosion resistance, cost, etc.) is crucial during the design phase.

Modern materials science has developed methodologies to support systematic material selection based on engineering requirements. One of the pioneers of this approach is Michael F. Ashby, whose scientific work contributed greatly to the formalization of the material selection process. Ashby developed the concept of so-called Ashby diagrams – graphical representations where different material classes (metals, polymers, ceramics, composites) are arranged in coordinate systems defined by its specific properties [1]. These diagrams enable designers to identify candidates that satisfy multiple criteria at a glance. Additionally, Ashby (in collaboration with S. C. Lim and others [2]) studied tribological phenomena such as wear mechanisms and developed so-called wear mechanism maps that graphically present different wear regimes based on loading conditions and material properties. Through such approaches, the process of material selection becomes more quantitative and data-driven.

The aim of this paper is to provide an overview of tribologically relevant material properties and compare metals, polymers, and ceramics in this context. The following chapter analyzes each of these material groups, focusing on their advantages and limitations in frictional applications. Subsequently, key tribological characteristics (hardness, friction, and wear) are discussed in more detail, along with a quantitative comparison across materials. Special attention is given to Ashby's results and graphs that link these properties (e.g., the relationship between hardness and wear rate). A case study – the selection of a material for a sliding bearing – illustrates a step-by-step approach to material selection based on tribological and other criteria. [1]

2. ANALYSIS OF MATERIALS FOR TRIBOLOGICAL LOADS

To ensure satisfactory performance under frictional conditions, the material used for a component must possess an appropriate combination of properties. Metals, polymers, and ceramics differ fundamentally in structure and properties, and thus exhibit varied behavior under friction. This section analyzes each of these material categories from a tribological perspective.

2.1 Metals

Metals are widely used for wear-prone components (e.g., steels for gears, bronze for bearings) due to their high strength, toughness, and impact resistance. A key advantage of metals is their relatively high hardness compared to polymers – many engineering steels have hardness values around 200–300 HV, while hardened tool steels can exceed 600 HV [5]. Higher hardness translates to improved scratch resistance and better resistance to abrasive wear. Moreover, metals can undergo thermal or chemical treatments (e.g., hardening, nitriding) to develop hard surface layers that improve wear resistance. However, pure metals with very soft microstructures (such as pure lead or tin) exhibit high wear rates – due to low hardness, large real contact areas are formed, leading to severe wear even under low loads [3]. As a result, soft metals are rarely used alone in tribological pairs; instead, they are commonly used as alloying elements (e.g., alloys with tin, lead, or zinc for sliding bearings) or in combination with harder phases.

Regarding friction, metals sliding against each other under dry conditions typically produce moderate to high coefficients of friction (around $\mu \approx 0.5$) [6]. This relatively high friction results from adhesion between clean metal surfaces: microscopically, rough metallic contacts touch at small asperities rather than across the full nominal area, leading to local bonding (welded or stuck points) that impede relative motion [6]. The presence of lubricants (oils or greases) significantly reduces friction between metal surfaces – the friction coefficient under lubricated conditions can drop below 0.1. Furthermore, metals often form oxide layers on their surfaces during friction, which act as protective barriers that reduce metal-to-metal contact, and thereby friction and wear [3]. For example, mild steel may form a thin Fe_3O_4 layer that mitigates wear, whereas increased load or temperature may destroy this layer and lead to intensified wear [3].

As for wear, metals in contact can exhibit several wear mechanisms: abrasive wear (where a harder material scratches and removes particles from a softer one) and adhesive wear (where two metallic surfaces locally weld together and then break apart, detaching material fragments) are the most common [4]. A well-established rule in practice is that harder metals wear less in contact with softer ones – for example, a hardened steel surface will wear slower in contact with a softer steel, while the latter will suffer accelerated wear due to grooving and material removal. This is why alloyed steels with elements like chromium, molybdenum, or cobalt offer better wear resistance – these alloys form hard carbides or strong solid solutions that enhance hardness and reduce wear [3]. A traditional material for sliding surfaces is gray cast iron, whose lamellar graphite microstructure acts as a solid lubricant and improves tribological behavior. In practice, combinations of metals are often chosen to optimize friction and wear – for instance, steel sliding against bronze or a copper alloy: the hard steel ensures load capacity, while the bronze is soft enough to absorb abrasive particles and form protective films, resulting in acceptable wear rates.

2.2 Polymers

Polymeric materials (plastics) have gained importance in tribological applications due to their unique properties: low coefficients of friction, self-lubricating capabilities, and corrosion resistance. Although polymers are significantly less hard than metals and ceramics (typical hardness values are very low, often below 20 HV – for example, polypropylene is 7 HV, polyoxymethylene (POM) is 18 HV [5]), this softness and elasticity allow for substantial elastic deformation under contact. Under load, polymers partially conform and increase the real contact area, while also adapting more easily to the roughness of the opposing surface, which can result in reduced friction. Many polymers are considered self-lubricating – during sliding, a thin layer of polymer may transfer onto the opposing surface or melt slightly, forming a lubricating film. Consequently, polymers often exhibit lower friction coefficients than dry metals: in general, friction for polymers sliding against metal, another polymer, or ceramics ranges from $\mu \approx 0.1$ to 0.6, with PTFE (Teflon) among the lowest at 0.1 or even lower [7].

In practice, extremely low friction values (around 0.04) have been recorded for combinations like graphite-coated steel sliding against PTFE [6]. Of course, friction also depends on conditions – for polymers, the coefficient of friction may decrease with increasing load (as the polymer deforms and "flows", improving lubrication) until a threshold is reached where overheating or material damage occurs [7].

Despite favorable friction behavior, wear of polymers is a more complex issue. Polymers generally exhibit moderate wear compared to metals, and especially ceramics [3]. The softer polymeric surface tends to lose material more easily under load, especially when sliding against much harder surfaces – typical wear mechanisms include adhesive wear (tearing off polymer fragments that stick to the harder surface) and abrasive wear (when harder surfaces or particles scratch the polymer) [3]. However, polymer wear can be acceptably low if proper modifications are made: polymers are often filled with solid lubricants (graphite, molybdenum disulfide) or fibers to produce composites with reduced wear and increased load capacity. For instance, polyacetals (or polyoxymethylenes, commonly abbreviated as POM) and nylons reinforced with glass fibers or carbon particles demonstrate better tribological performance than pure polymers. During operation, many polymer sliding elements form a transfer film on the counter surface – a thin polymer layer that acts as a protective barrier. This phenomenon can stabilize friction at low levels and slow wear after an initial "running-in" period. Literature suggests that polymers generally have lower friction coefficients but higher wear rates than metals and ceramics under the same conditions [3]. Nevertheless, polymers offer additional advantages: they are lighter, quieter in operation (damping vibrations), and corrosion-resistant. In applications with moderate loads and a preference for dry lubrication (no oil), polymeric bearings and gears (e.g., made from nylon or polyacetals) can successfully replace metallic ones, often achieving longer service life due to lower friction and no need for maintenance.

2.3 Ceramics

Ceramic materials (oxides, carbides, nitrides, etc.) are known for their extremely high hardness and resistance to high temperatures. In the context of tribology, ceramics offer unique advantages: due to their hardness (often above 1000 HV – for example, aluminum oxide 2500 HV, silicon carbide >2000 HV [5]), they exhibit exceptional resistance to abrasive wear. Hard ceramic surfaces are difficult to scratch or plastically deform under the action of other materials.

Moreover, ceramics are chemically inert – many can operate at elevated temperatures and in corrosive environments without significant degradation, maintaining their tribological properties (hardness, surface stability) even where metals would oxidize or soften.

Interestingly, ceramic surfaces in contact often exhibit reduced friction and wear compared to metallic ones, at least in the initial stage. This is because the contact between two very hard and stiff bodies occurs over extremely small real contact areas – asperities touch only at a few points due to minimal elastic deformation. Smaller contact areas mean less adhesion between surfaces, so the coefficient of friction is often moderate or low. For instance, sliding a metallic surface over a finely polished ceramic plate can produce less resistance than metal-on-metal contact, as ceramics don't easily form strong adhesive bonds with metals. However, ceramic friction also depends on surface roughness and operating conditions – rough ceramic surfaces can cause abrasion and increased friction until they are polished through use.

The main challenge with ceramics is their brittleness and low fracture toughness. Ceramics have limited plastic deformation capabilities; rather than bending under load, they tend to fracture. This property also affects wear: if frictional conditions cause surface microcracking, ceramic material may wear via brittle fragmentation. Therefore, under mild loads and smooth conditions, ceramics may exhibit minimal wear (e.g., polished oxides can slide for extended periods with negligible loss), but under high loads or impact conditions, catastrophic wear due to fracture may occur [3]. For example, high-purity ceramics such as silicon nitride are used for ball bearings: in pure rolling conditions, wear is nearly negligible, but impacts or vibrations can destroy the balls. It's also worth noting that ceramics often form tribochemical films – reacting with the environment (e.g., Si_3N_4 forming silicates in the presence of moisture) – which can influence wear either positively (protective film) or negatively (brittle fracture of the film).

In practical applications, ceramic materials are used where extreme hardness and high-temperature resistance are critical. Examples include: ceramic seals and bearings for chemically aggressive environments, ceramic-reinforced brake discs (carbon-carbon composites or silicon carbide ceramics) in high-performance vehicles for stable friction and minimal disc wear at elevated temperatures, and cutting tools (ceramic or cermet tools for high-speed metal cutting with minimal wear). In such situations, ceramics perform exceptionally well – with very low wear even when machining much softer metals. However, due to the brittleness of ceramics, designs often avoid tensile and impact stresses, or ceramics are combined with metallic components (as coatings or within composites) to harness their benefits without excessive risk of fracture.

In summary, metals offer toughness and easy processing with moderate tribological properties; polymers provide low friction and self-lubrication at the cost of higher wear; ceramics deliver exceptional hardness and wear resistance but with the risk of brittle failure. These differences are clearly illustrated when comparing their numerical values for hardness, friction coefficients, and typical wear mechanisms – the subject of the next chapter.

3. TRIBOLOGICAL CHARACTERISTICS OF MATERIALS

This chapter discusses three key properties that describe the tribological behavior of materials in greater detail: hardness, friction, and wear. These characteristics are interconnected and often collectively determine the suitability of a material for applications involving friction. For example, material hardness influences wear rate, while the coefficient of friction between two surfaces depends on the material combination and their surface characteristics. Particular attention is given to quantitative data that illustrate differences between metals, polymers, and ceramics, along with a review of empirical laws.

Table 1. The hardness of certain metallic, ceramic, and polymeric materials

Metals	**Vickers hardness number (HV) range from soft to hard**	**Ceramics**	**Vickers hardness number (HV)**	**Polymers**	**Vickers hardness number (HV)**
Tin	5	Limestone	250	Polypropylene	7
Aluminium alloys	25–140	Magnesium oxide	500	PMMA	20
Gold	35	Tungsten carbide	2500	Polycarbonate	14
Copper	40	Titanium nitride	2900	PVC	16
Iron	80	Alumina	2500	Polyacetal	18
Mild steel	140–280	Zirconia	1300	Polystyrene	21
Ferritic stainless steel	170–300	Quartz	1200	CR39	40
Martensitic stainless steel	450–800	Soda-lime silica glass	490	Urea Formaldehyde	41
Ausstenitic stainless steel	180–400	Granite	850	Epoxy	45
Tool steel	700–1000	Silicon nitride	750	Diamond	10,000

3.1 Hardness

Hardness is a measure of a material's resistance to localized plastic deformation (such as indentation or scratching). In tribology, hardness is significant because it often correlates with the material's ability to resist wear – harder materials tend to lose fewer particles via abrasive and adhesive wear mechanisms. Typical hardness values vary drastically among metals, polymers, and ceramics. For illustration, the Vickers hardness (HV) values of several materials are presented below [5].

The high hardness of ceramics explains their durability under abrasive conditions – abrasive particles that would easily scratch metal or plastic are often unable to damage ceramic surfaces. Besides, the low hardness of polymers means that they deform more readily under load and may wear out faster [4]. Empirically, the relationship between hardness and wear is often described by Archard's law:

$$V/L = (W/H) \cdot K, \tag{1}$$

where:

V = volume of material worn away,
L = sliding distance,
W = normal load,
H = hardness of the material
K = wear coefficient (dimensionless, dependent on material pairing and conditions).

This equation clearly shows that, all else being equal, a softer material (lower H) will have a higher V/L ratio, meaning it will wear out faster under a given load. Figure 1 (based on Ashby's data) shows a diagram comparing material hardness (x-axis) to their wear rate constants k_a (y-axis).

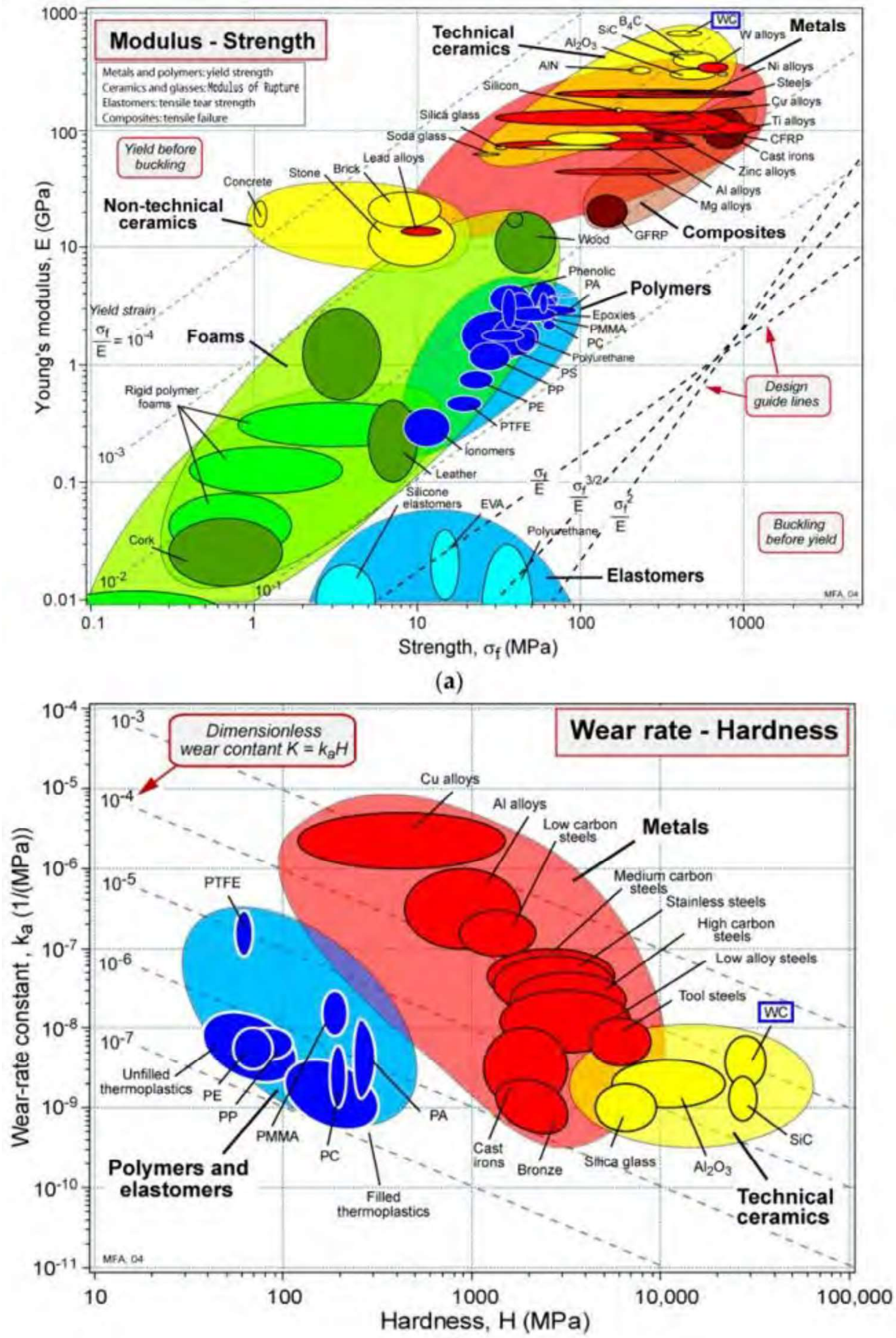

Figure 1. Ashby diagrams for different materials. (a) Young's modulus vs. strength, (b) wear-rate constant vs. Hardness (blue: polymers and elastomers, red: metals, yellow: technical ceramics) [1]

The diagram reveals a general trend: materials with higher hardness tend to have lower wear constants (i.e., better wear resistance). For instance, polymers (on the left, with hardness between 10–100 MPa) typically have k_a values from 10^{-7} to 10^{-4}, while harder ceramics (right, with hardness above 10,000 MPa) exhibit k_a values between 10^{-9} and 10^{-7} [8].

Thus, hardness significantly affects wear resistance: soft materials like polymers and soft metals may exhibit wear rates several orders of magnitude higher than ultra-hard ceramics.

Consequently, components exposed to intense abrasive wear (e.g., pump impellers for sandy fluids, milling cutters, grinding tools) are typically made of the hardest possible materials or have hardened surface layers.

However, extreme hardness alone is not sufficient – the material must also possess enough toughness to avoid brittle fracture under stress. Ashby emphasized the need to balance hardness with toughness when selecting materials for wear-prone components [8]. In his approach, performance indices often combine properties – e.g., for wear resistance under impact, a material with a high $H \cdot K_{Ic}$ product (hardness × fracture toughness) is desired. [1]

3.2 Coefficient of Friction

Friction between two materials is described by the dimensionless coefficient of friction (μ), which is the ratio between the frictional force and the normal load in contact zone. The value of μ depends on the material combination of the surfaces, their finish (roughness), sliding speed, load, environment (air, vacuum, lubricant), and other factors. For engineering purposes, the Coulomb model is often used, where μ is considered a constant for a given material pair under specific conditions.

From a tribological standpoint, the goal is often to achieve the lowest possible friction coefficient to reduce energy losses (frictional heating) and wear. However, in certain applications (e.g., brakes, pneumatic tires), a high and stable friction coefficient is desirable to ensure strong braking force or traction. In this paper, the focus is on cases where lower friction leads to better efficiency and reduced wear.

The typical range of friction coefficients for different materials (under dry conditions) can be roughly ranked as follows:

- **Polymers** have the lowest values (μ ≈ 0.1–0.6),
- Followed by **metals** (μ ≈ 0.4–0.8 for clean metal pairs),
- While **ceramics** can exhibit moderate values (μ ≈ 0.2–0.6), depending on surface roughness and chemistry.

These are general guidelines – actual values may vary. Here are some specific examples from the literature:

- **Metal–metal (dry):** Typically around μ ≈ 0.5 [6]. Steel-on-steel without lubrication usually yields μ ≈ 0.4–0.6. If the surfaces are very clean and smooth, "sticking" and even cold welding may occur, resulting in μ > 0.7. Mild steels tend to be more adhesive and have higher friction, while bronze-steel combinations yield lower values (≈0.4) due to lubricating additives like lead or graphite. **Metal–metal (lubricated):** Can drop to μ ≈ 0.01–0.1 depending on the oil and lubrication regime. In the hydrodynamic regime (where an oil film separates the surfaces), effective friction is very low.
- **Polymers:** As previously mentioned, PTFE (Teflon) has one of the lowest known friction coefficients – 0.05–0.1 when in contact with smooth metal [6, 7]. Other engineering plastics: polyethylene (PE) ≈ 0.2, nylon (PA) ≈ 0.2–0.4, polyoxymethylene (POM) ≈ 0.2. Polyurethane (PU) is somewhat higher due to its viscous nature. Polymer-on-polymer friction can be higher due to stickiness but is often reduced by pairing with dissimilar surfaces (e.g., metal–polymer is more common). Rubbers (elastomers) exhibit high friction on dry surfaces (e.g., rubber on dry asphalt μ ≈ 1 or more), which is desirable for tires but not typical in machine sliding surfaces.
- **Ceramics:** Ceramic pairs (e.g., aluminum oxide on aluminum oxide) may initially have relatively high friction due to surface roughness, but with wear and polishing, the coefficient may stabilize at moderate values ≈ 0.3. Ceramic–metal combinations often yield lower friction than metal–metal due to the absence of micro-welding – e.g., steel on Al_2O_3 may produce μ ≈ 0.3 instead of 0.5. Glass-on-glass is also relatively smooth

when clean (μ ≈ 0.4), but in the presence of moisture, chemical adhesion may increase. Generally, small contact areas typical for hard ceramics reduce adhesion and thus friction [3].

It is important to understand friction mechanisms:

- For **metals**, sliding surfaces form microscopic junctions, and friction includes the force to break these (adhesive component) and to deform surface asperities (deformation component).
- For **polymers**, friction involves viscous losses due to polymer deformation and possibly surface melting.
- For **ceramics**, friction may involve fracture and wear of surface asperities (which consumes energy and increases friction).

It should also be noted that the coefficient of friction is not an absolute constant – it depends on the operating conditions. For example, for many materials, μ decreases with increasing sliding speed up to a certain limit (since high speeds can induce shear dynamics with less time for adhesion), but then increases if overheating occurs. Additionally, μ may decrease with increasing load in polymers (as the surface becomes smoother) [7], or increase in metals if the lubricant film breaks down. Therefore, when selecting materials, the actual working conditions must be considered – for instance, steel sliding against steel under light load with oxidation may exhibit a lower effective μ (due to the formation of a protective oxide layer) than under moderate load, where the oxide is constantly worn off, exposing fresh metallic surfaces that tend to stick.

3.3 Wear

Wear is the progressive loss of material from a surface due to mechanical action (such as friction, particle erosion, cavitation, etc.). This paper focuses on tribological wear caused by sliding or rolling contact between surfaces. The result of wear can include dimensional change (e.g., thinning) and generation of wear debris (particles), which may further affect the system (e.g., by contaminating lubricants or forming dust).

Understanding wear is complex, as it depends on the properties of both contacting surfaces – including their microhardness, chemical reactivity, and operating conditions (load, speed, temperature and environment).

In engineering tribology, several wear mechanisms are identified [4]:

- **Adhesive wear** – occurs when two surfaces locally bond (weld) and during movement, material fragments are torn off. This is common between similar materials (e.g., metal-on-metal) and results in material transfer from one surface to another or the loss of particles. It arises from close contact between clean surfaces and high localized stresses.
- **Abrasive wear** – happens when harder asperities or particles scratch and gouge the softer material, removing particles. This is similar to grinding: the harder surface "cuts" grooves into the softer one. It often produces matte, scratched surfaces.
- **Surface fatigue (contact fatigue)** – occurs in rolling or oscillating contacts, where repeated subsurface stress induces microcracks that eventually reach the surface and break away as debris (e.g., pitting in gears or bearings) [4]. This mechanism is influenced more by material strength and toughness than by hardness alone.
- **Tribochemical (oxidative) wear** – is a special case where surface chemistry changes (e.g., oxidation) during friction, and the resulting layer is then worn away. An example is mild wear of steel, where a thin iron oxide layer constantly forms and is worn off and slowing overall material loss. This wear regime is considered mild, as the wear debris is usually fine oxide dust rather than large metal fragments.

The *wear rate* is defined in engineering as the amount of material lost per unit of distance (or time). As previously mentioned, according to Archard's law, the wear coefficient K characterizes the wear system. Typical values of K range from approximately 10^{-2} (very poor – severe wear) to 10^{-8} (excellent – minimal wear) [4]. For example, unlubricated mild steel against mild steel can have $K \approx 10^{-3}–10^{-4}$, while lubricated hardened steel against hardened steel can reach as low as $K \approx 10^{-7}$. A polymer against steel may exhibit K in the range of $10^{-5}–10^{-4}$ (the polymer wears out), whereas ceramic-on-ceramic under mild conditions can have $K \approx 10^{-7}$ or lower. In Ashby's diagram (Fig. 1b), a quantity similar to K is shown (normalized to pressure), but the trend is the same – polymers show higher wear rates than metals, and metals higher than ceramics under typical loading conditions.

Ashby diagrams significantly contribute to understanding wear through so-called wear mechanism maps. In a study with S. Lim (1987), a wear map for steel was constructed, with contact parameters such as pressure and sliding speed on the axes, while regions of the map indicate the dominant wear mechanisms under given conditions [2]. These maps show, for example, that under low pressures and temperatures, mild oxidative wear dominates (low wear rate), while higher pressures lead to adhesive wear (higher rate), and even higher pressures result in abrasive or deformation wear (highest wear rate). Such diagrams help engineers predict the wear regime and select materials or operating conditions that keep the system in the "mild" wear zone. For instance, steel will wear less if a thin oxide film is maintained (mild wear) than if the surfaces are cleaned to bare metal (severe adhesive wear).

In practical material selection, wear resistance is often quantified through tests (e.g., the pin-on-disk test measures volume loss over a defined distance and load). Engineers use this data, together with known mechanisms, to rank candidate materials. For example, for a bearing operating without lubrication in a dusty environment, a hard material (resistant to dust-induced abrasion) and self-lubricating (reducing adhesion) would be preferable – a graphite-filled polymer composite might perform better than bronze or even some steels.

In summary, the tribological properties of materials show the following trends: hard and chemically inert materials exhibit lower wear rates, softer materials provide lower friction but at the cost of higher wear, and the coefficient of friction can be optimized by pairing different materials (e.g., hard-soft pairings) and using lubricants.

4. CASE STUDY: MATERIAL SELECTION BASED ON TRIBOLOGICAL PROPERTIES

As a concrete example, we examine the selection of material for a sliding bearing (bushing) that must operate under dry friction conditions. Let's assume it is a slowly rotating pin bearing under medium load, and continuous lubrication is not possible (e.g., a hinge or joint exposed to outdoor dust). The goal is to find a bushing material that provides long service life without lubrication, with low friction and minimal wear. The shaft is made of steel (hardened or at least strong steel), so the bushing material must be tribologically compatible with steel.

Key requirements for this bearing include:

1. **Low coefficient of friction against steel**, without external lubrication (for smooth and efficient operation)
2. **High wear resistance** in dry, dusty conditions (to maintain dimensions and prolong lifespan)
3. **Adequate hardness and strength** to withstand loading without permanent deformation
4. **Dimensional stability and corrosion resistance** under outdoor conditions (shouldn't swell from moisture or rust)
5. **Cost and availability**, though considered secondary due to the application's critical nature

According to these criteria, we consider candidates from all three material groups.

4.1 Metallic candidates

The traditional choice for such sliding bearings includes copper alloys (bronze) or brass, as well as nodular cast iron. Bronze (a copper alloy with tin, often with lead or phosphorus) has been used for centuries in sliding bearings due to its relatively low coefficient of friction against steel—especially when impregnated with oil or containing lead, which acts as a solid lubricant. The hardness of bronze is moderate (around 50–100 HV), which is significantly softer than the steel shaft—ensuring that the bronze wears out before the steel does (which is desirable, as replacing a bushing is cheaper than replacing a shaft). Additionally, bronze can absorb fine abrasive particles into its microporous structure, effectively removing them from the contact surface and protecting the shaft. Steel bushings (e.g., hardened steel on hardened steel) would likely have higher friction and a risk of seizure without oil—thus, steel-on-steel is not a good option under dry running conditions. Cast iron with graphite offers the advantage that graphite flakes act as a lubricant—gray cast iron has traditionally been used for sliding tables in machine tools due to its low friction and wear resistance. However, cast iron is more brittle and may crack under impact compared to bronze. In our example with the shaft, **bronze would be the better metallic choice**, as it is tougher than cast iron and can be precisely machined into a bushing.

4.2 Polymeric candidates

Modern self-lubricating polymer bearings are available, for example, those made from polyamide (nylon) or acetal plastic (POM, Delrin), often filled with solid lubricant particles (PTFE, graphite) or reinforcing fibers. The main advantage of polymers is their very low friction without the need for external lubrication – for instance, oil-filled nylon or PTFE-filled nylon can slide against steel with a coefficient of friction around $\mu \approx 0.2$ or lower, which is already better than a bronze bearing under dry conditions [7].

Polymer bearings are also corrosion-resistant, maintenance-free, and operate quietly (they dampen vibrations). Their downside is lower load capacity: their elastic modulus and hardness are much lower, so under higher loads they may deform (the bearing may "sink in" and lose clearance) or wear more rapidly. Nevertheless, for moderate loads, a polymer bearing with thicker walls can support similar loads as a bronze one, thanks to the large contact area (the polymer spreads slightly under load, reducing contact pressure).

Suitable candidates include:

- **PA6 or PA66 (nylon)** with oil or MoS_2 additives,
- **POM (Delrin)**, commonly used for gears and bearings,
- High-performance **PTFE composites** (although PTFE alone is soft and is often combined with fiberglass or bronze powder for added strength).

Polymers are more prone to wear at elevated temperatures (they soften), or in the presence of abrasive dust (since dust is often mineral-based and very hard, it can scratch polymers). In our case, **dust is a potential issue** – sand can quickly wear down nylon. However, **polymer bearings often “absorb” dust into their matrix**, causing less damage than it would inflict on metal (where it would act like abrasive paper).

4.3 Ceramic Candidates:

Pure ceramics (e.g., a ceramic bushing and ceramic shaft) are generally not practical for this type of bearing due to their brittleness and assembly challenges (ceramics cannot tolerate misalignment – they would crack immediately). However, composite solutions are possible: for example, a steel shaft coated with a thin ceramic layer (such as chromium oxide or DLC – Diamond-Like Carbon), paired with a bushing made from another material. Ceramic bushings are used in water pumps (e.g., Al_2O_3 bushings with ceramic shafts) where the environment is clean and there is liquid cooling, but for dry outdoor friction, this is not ideal.

Ceramics offer excellent wear resistance and practically require no lubrication to achieve low friction (due to their chemically inert and smooth surfaces), but a single impact or shaft deflection could crack the bushing – which is a high risk. Moreover, ceramic-on-steel without lubrication can lead to faster wear of the steel compared to bronze or polymer (because ceramics are so hard they abrasively wear the steel as the mating surface). Thus, a bushing made from, say, silicon nitride might "survive" wear, but the shaft would suffer – not a good combination.

After considering all candidates, the selection is narrowed down to the two most promising options: bronze and a polymer composite (e.g., reinforced nylon). Now, according to Ashby's approach, we can rank these options based on the defined criteria:

- *Friction:* The polymer composite (nylon + PTFE) will have a lower coefficient of friction (≈0.2) than bronze on steel (≈0.4 dry). **Advantage: polymer.**
- *Wear resistance:* Bronze is quite resistant, especially if periodically lubricated or leaded; the polymer will initially perform well, but in the presence of heavy dust, it may wear faster. However, modern polymer bearings often last tens of thousands of cycles before wearing out. It's hard to declare a clear winner – it depends on details – but in dry and dusty environments, we give a slight edge to bronze (more resistant to abrasion). **Advantage: slight for bronze.**
- *Load capacity and stiffness:* Bronze handles higher loads without deformation (E modulus ≈ 100 GPa vs nylon ≈ 2–3 GPa). If loads approach the material's limit, the polymer may crack or deform over time through creep. **Advantage: bronze.**
- *Corrosion resistance:* Bronze develops a patina outdoors but retains properties, while the steel shaft needs protection; polymers do not corrode at all. Both are acceptable – **Advantage: slight for polymer.**
- *Maintenance:* Polymer requires no lubrication; bronze ideally should be greased occasionally to reduce friction/wear. Polymer also handles dry running better. **Advantage: polymer.**
- *Effect on shaft:* Very important – the polymer is softer than steel and won't wear the shaft, whereas bronze and steel have more similar hardness. While bronze is expected to wear first, some shaft wear is still possible over time (although minimal, especially if graphite is present). **Advantage: polymer (protects the shaft).**

After such an analysis, a decision can be made: For the given application, we propose a polymer composite bushing, e.g., made of cast nylon filled with oil microcapsules or PTFE particles. This choice provides minimal friction without maintenance and will not damage the steel shaft even in the presence of dust (particles will embed into the polymer rather than scratch the steel). Although the polymer bushing will wear out faster over time compared to a bronze one, it is inexpensive and easy to replace, and its lifespan can still be satisfactory (e.g., 5–10 years of operation depending on usage), with the added benefit of smoother movement.

An alternative solution could be bronze impregnated with solid lubricant (so-called "Oil-impregnated bronze" (*It typically contains Cu (88-90%), Sn (10-12%), and sometimes small amount of graphite to further reduce friction) or graphite-impregnated bronze*), which somewhat combines both approaches—bronze carries the load, while the lubricant in its pores reduces friction. This would be a robust solution if occasional higher impacts or temperatures are expected where a polymer would not survive.

It is important to emphasize that the choice here was made primarily based on tribological criteria. In other scenarios, the outcomes may differ—for example, for a high-speed bearing with low load in a vacuum, ceramic (silicon nitride) balls in steel rings are the best option (since no lubrication is possible, and ceramics have low wear in a vacuum). The complete set of conditions must always be considered.

Methodologically, this example follows Ashby's steps: the requirements were defined, the list narrowed based on key properties (excluding materials that do not meet hardness or stability criteria) and then performance indices were used (e.g., “high wear resistance with low μ”—which implies high hardness and self-lubrication) to rank the candidates. Finally, the decision also relies on empirical experience and the availability of specific materials (as the market offers ready-made polymer bearings, which facilitates implementation).

5. CONCLUSION

The selection of an optimal material for tribologically stressed components is a multi-criteria task that requires an in-depth understanding of material properties and the mechanisms of friction and wear. This paper compares metals, polymers, and ceramics in terms of hardness, friction, and wears resistance. Metals stand out due to their proven combination of strength and toughness, but in the absence of lubrication, they typically exhibit higher friction and are prone to adhesive wear. Polymers naturally exhibit low coefficients of friction due to their elasticity and self-lubricating behavior, but they suffer from higher wear rates and are limited in terms of load-bearing capacity and temperature resistance. Ceramics possess extreme hardness and wear resistance, making them ideal in abrasive environments, but they are brittle and require careful design due to the risk of fracture and specific wear regimes.

The analyzed case study illustrates that the material selection process depends on defining priorities (friction – wear – strength) and comparing candidates against those criteria. This comparison should be carried out systematically by using graphs and selection methods that allow filtering and ranking of materials based on property combinations. One effective method is to filter materials using Ashby diagrams, such as the hardness–wear diagram, which provides a broader view of how different material families perform and what can be expected of them. In addition, concepts like wear mechanism maps [2] help predict dominant wear regimes under specific conditions, thus guiding the material choice. For instance, knowing that a material will operate in a mild oxidative wear regime under certain conditions may favor its selection.

In conclusion, the optimal choice of a material for tribological applications is often a compromise: balancing hardness (for wear resistance) with toughness (to prevent fracture), achieving low friction while avoiding excessive wear, all while taking into account practical factors such as cost, availability, and manufacturability. By integrating scientific knowledge (such as Ashby’s materials data) with engineering experience, today’s designers can more confidently select materials that will ensure longer lifespan and greater efficiency for tribological components.

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