Appendix A: Material Properties

Contents

Appendix A: Material Properties Reference

A.1 Structural Metals

A.1.1 Ferrous Metals (Iron-Based)

Material	Density (kg/m^3)	Young's Modulus (GPa)	Yield Strength (MPa)	Tensile Strength (MPa)	Thermal Expansion (×10¯6/°C)	Thermal Conductivity (W/(m·K))
Mild Steel (A36)	7,850	200	250	400-550	11.7	50
Structural Steel (A572 Gr50)	7,850	200	345	450	11.7	50

Material	Density (kg/m^3)	Young's Modulus (GPa)	Yield Strength (MPa)	Tensile Strength (MPa)	Thermal Expansion (×10¯6/°C)	Thermal Conductivity (W/(m·K))
4140 Steel (Annealed)	7,850	200	415	655	11.5	42
4140 Steel (Q&T)	7,850	200	1,000-1,400	1,100-1,600	11.5	42
1018 Cold Rolled	7,870	205	370	440	11.7	52
Stainless 304	8,000	193	215	505	17.3	16
Stainless 316	8,000	193	205	515	16.0	16
Stainless 17-4 PH (H900)	7,800	197	1,170	1,310	10.8	17
Cast Iron (Gray, Class 30)	7,200	100-140	200-300	210-340	10.8	50
Cast Iron (Ductile, 60-40-18)	7,100	169	276	414	11.8	36
Tool Steel (D2, Hardened)	7,700	210	1,700-2,000	1,900-2,200	11.5	20

Notes: - **Mild Steel (A36):** Most economical structural material. Good weldability. Used for frames, gantry beams, base plates. - **A572 Grade 50:** Higher strength than A36 (50 ksi vs. 36 ksi). Better strength-to-weight ratio. Common in structural tubing. - **4140 Alloy Steel:** Medium-carbon chromium-molybdenum alloy. Excellent toughness when heat-treated. Used for shafts, spindles, high-stress components. - **Stainless 304/316:** Austenitic stainless. Corrosion-resistant. Non-magnetic. Work-hardens during machining (difficult to cut). Used in food/medical/marine applications. - **17-4 PH:** Precipitation-hardening stainless. Combines corrosion resistance with high strength. Used for shafts, fasteners in corrosive environments. - **Gray Cast Iron:** Excellent vibration damping (10× steel). Low cost. Used for machine beds, bases. Not weldable. - **Ductile Iron:** Better ductility than gray iron. Weldable. Used for gears, couplings, heavy-duty frames.

A.1.2 Non-Ferrous Metals (Aluminum, Copper, Titanium)

Material	Density (kg/m^3)	Young's Modulus (GPa)	Yield Strength (MPa)	Tensile Strength (MPa)	Thermal Expansion (×10⁻6/°C)	Thermal Conductivity (W/(m·K))
Aluminum 6061-T6	2,700	69	276	310	23.6	167
Aluminum 7075-T6	2,810	72	503	572	23.4	130
Aluminum 2024-T3	2,780	73	345	483	22.9	121
Aluminum 5083-H111	2,650	70	145	290	23.8	117
Aluminum Plate Tooling (MIC-6)	2,700	69	172	228	23.6	155
Copper C110 (Pure)	8,940	120	70	220	16.5	391
Brass C360 (Free-Machining)	8,500	97	125	340	20.5	115
Bronze C932 (Bearing Bronze)	8,800	103	172	379	18.0	59
Titanium Ti-6Al-4V (Annealed)	4,430	114	880	950	8.6	7.2

Notes: - **6061-T6:** General-purpose structural aluminum. Good corrosion resistance, weldable. Used for gantry beams, plates, brackets. 1/3 weight of steel. - **7075-T6:** Aircraft-grade aluminum. Highest strength aluminum alloy. Poor weldability. Used for high-stress components where weight matters. - **2024-T3:** High-strength aluminum with copper. Excellent fatigue resistance. Used in aircraft structures. Not very corrosion-resistant (requires coating). - **5083:** Marine-grade aluminum. Best corrosion resistance. Non-heat-treatable. Used for waterjet tanks, enclosures in corrosive environments. - **MIC-6 (Cast Aluminum Plate):** Stress-relieved casting. Excellent flatness and stability. Used for machine beds, fixture plates, optical tables. - **Titanium Ti-6Al-4V:** Aerospace grade. High strength-to-weight ratio. Excellent corrosion resistance. Difficult to machine (low thermal conductivity causes tool heating). Used in high-performance applications.

A.1.3 Comparison Chart: Strength-to-Weight Ratio

Specific Strength = Yield Strength / Density (higher is better for weight-critical applications)

Material	Yield Strength (MPa)	Density (kg/m^3)	Specific Strength (kN·m/kg)
Aluminum 7075-T6	503	2,810	179
Titanium Ti-6Al-4V	880	4,430	199
4140 Steel (Q&T)	1,200	7,850	153
Aluminum 6061-T6	276	2,700	102
Mild Steel (A36)	250	7,850	32

Conclusion: Titanium and 7075 aluminum offer best specific strength, but titanium is 10-20× more expensive and difficult to machine.

A.2 Engineering Plastics and Composites

A.2.1 Thermoplastics

Material	Density (kg/m^3)	Young's Modulus (GPa)	Tensile Strength (MPa)	Max Temp (°C)	Water Absorption (%)	Applications
UHMW Polyethylene	930	0.8	22	80	<0.01	Low-friction bearing surfaces, chip deflectors, wear strips
Acetal (Delrin)	1,420	3.1	70	90	0.25	Gears, bushings, low-load bearings, insulators
Nylon 6 (PA6)	1,140	2.8	80	120	1.5-2.5	Cable carriers, wear strips, gears (requires lubrication)
Nylon 6/6 (PA66)	1,150	2.9	83	130	1.5-2.5	Higher strength than Nylon 6, similar applications
Polycarbonate (Lexan)	1,200	2.4	65	130	0.15	Machine windows, guards, impact-resistant shields
Acrylic (PMMA)	1,180	3.2	72	90	0.3	Windows, guards (higher scratch resistance than polycarbonate)

Material	Density (kg/m^3)	Young's Modulus (GPa)	Tensile Strength (MPa)	Max Temp (°C)	Water Absorption (%)	Applications
PTFE (Teflon)	2,200	0.5	20-30	260	<0.01	Ultra-low friction bearings, gaskets, seals
PEEK	1,320	3.6	100	260	0.1	High-performance bearings, seals, electrical insulators
PVC (Rigid)	1,400	3.0	52	60	0.04	Ducting, chip guards, low-cost enclosures

Selection Guidelines:

For Bearing Surfaces: - **Light loads (<50 N), low speed:** UHMW (best wear resistance, self-lubricating) - **Moderate loads (50-500 N), moderate speed:** Acetal/Delrin (higher strength, better dimensional stability) - **High loads (>500 N):** Bronze bushings or linear ball bearings (plastics inadequate)

For Machine Windows/Guards: - **Impact resistance priority:** Polycarbonate (250× stronger than glass, but scratches easily) - **Scratch resistance priority:** Acrylic (harder surface, but 10× weaker than polycarbonate) - **Best compromise:** Polycarbonate with hard coat (MR-10 coating)

For Electrical Insulation: - **General purpose:** Acetal, Nylon (good dielectric strength, low cost) - **High temperature:** PEEK, G-10 fiberglass (withstand >200°C)

A.2.2 Thermoset Plastics

Material	Density (kg/m^3)	Young's Modulus (GPa)	Tensile Strength (MPa)	Max Temp (°C)	Applications
G-10 Fiberglass (FR4)	1,850	18	310	150	Electrical insulation, PCB substrates, mounting plates

Material	Density (kg/m^3)	Young's Modulus (GPa)	Tensile Strength (MPa)	Max Temp (°C)	Applications
Phenolic (Bakelite)	1,300	5-10	40-60	150	Electrical insulators, vintage machine components
Epoxy Resin (Unfilled)	1,150	3.0	55	120	Adhesives, coatings, composite matrix

A.2.3 Composite Materials

Material	Density (kg/m^3)	Young's Modulus (GPa)	Tensile Strength (MPa)	Cost ($/kg)	Notes
Epoxy Granite (Polymer Concrete)	2,300-2,500	25-45	50-80	$2-$5	Excellent vibration damping (5-10× cast iron), thermal stability. Used for machine beds. DIY-friendly.

Material	Density (kg/m^3)	Young’s Modulus (GPa)	Tensile Strength (MPa)	Cost ($/kg)	Notes
Carbon Fiber UD (Unidirectional)	1,550	135-150	1,500-2,000	$30-$80	Highest stiffness-to-weight ratio. Fiber direction critical. Used in aerospace, high-speed gantries.
Carbon Fiber Woven	1,550	70-80	600-800	$25-$60	Balanced properties in-plane. Easier to layup than UD. Used for panels, tubes.

Material	Density (kg/m^3)	Young's Modulus (GPa)	Tensile Strength (MPa)	Cost ($/kg)	Notes
Fiberglass (E-glass/Epoxy)	1,850	25-35	300-500	$5-$15	Lower cost than carbon. Good electrical insulation. Used for enclosures, insulators.
Granite (Natural Stone)	2,700	50-70	10-20 (compression)	$8-$20	Traditional metrology base material. Excellent thermal stability and damping. Heavy (2.7× denser than aluminum).

Epoxy Granite Formulation Example:

Typical mix ratio (by weight): - Granite aggregate (crushed): 70-80% - Epoxy resin: 15-20% - Hardener: 5-10% - Fillers/additives: 0-5%

Properties: - Young's modulus: 35 GPa (steel = 200 GPa, but epoxy granite has 1/3 density) - Damping ratio: 0.015-0.030 (cast iron: 0.003, steel: 0.0001) - Thermal conductivity: 1.5 W/(m·K) (low □ minimal thermal gradients) - Thermal expansion: 12-15 mum/(m·°C) (similar to steel)

DIY Machine Bed Construction: 1. Build mold from melamine-coated plywood 2. Install inserts for linear rails (threaded bushings in mold) 3. Mix epoxy resin and aggregate (mixer required, 5-10 min mixing) 4. Pour/vibrate to remove air bubbles 5. Cure 24-48 hours at room temperature (or 4-8 hours at 60°C) 6. Machine flat surfaces after cure (grind or scrape)

Advantages over cast iron: - DIY-friendly (no foundry required) - Customizable shape (complex molds possible) - Better damping (reduces chatter in machining) - Corrosion-resistant - Embeds metal inserts easily (rail mounting)

Disadvantages: - Lower stiffness than cast iron (larger cross-sections needed) - Creep over time under sustained load (1-2% over years) - Cannot be welded or brazed

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A.3 Material Selection Guidelines by Application

A.3.1 CNC Machine Frame/Base

Requirement: High stiffness, damping, thermal stability, low cost

Material	Stiffness	Damping	Thermal Stability	Cost	Weight	Verdict
Welded Steel Tubing	□ □ □ □ □	□ □ □ □ □	□ □ □ □ □	□ □ □ □ □	Heavy	**Best for budget builds.** Easy to fabricate, weldable.
Cast Iron	□ □ □ □ □	□ □ □ □ □	□ □ □ □ □	□ □ □ □ □	Heavy	**Best for precision machines.** Requires foundry or purchase castings.
Epoxy Granite	□ □ □ □ □	□ □ □ □ □	□ □ □ □ □	□ □ □ □ □	Heavy	**Best for DIY precision builds.** Damping + thermal stability.

Material	Stiffness	Damping	Thermal Stability	Cost	Weight	Verdict
Aluminum Extrusion	□□□□□	□□□□□	□□□□□	□□□□	Light	**Best for portable/modular machines.** 80/20 ecosystem.

A.3.2 Gantry Beam (Horizontal Spanning Member)

Requirement: High bending stiffness (I), low weight, torsional rigidity

Material / Shape	Stiffness-to-Weight	Deflection (1m span, 1kN center load)	Cost	Verdict
Steel Rectangular Tube (100×50×5mm)	Reference	0.85 mm	$	**Standard choice.** Good stiffness, weldable.
Aluminum Rectangular Tube (100×50×5mm)	73% of steel	1.17 mm	|Lighter but less stiff than s… section) || *Carbon Fiber Tube (100×50×3mm wall)* | 180 | *Best stiffness-to-weight* | *Expensive, requires speci… *80/20 Extrusion (15 Series 1.5")* | 40	**Easiest to assemble (modular).** Lower stiffness requires larger sections.

Design Rule: Hollow tubes provide best stiffness-to-weight ratio. Torsional rigidity of rectangular tube 3-5× better than I-beam of same weight.

A.3.3 Linear Motion Shafting

Requirement: Hardness for bearing wear, straightness, corrosion resistance

Material	Hardness (HRC)	Straightness	Corrosion Resistance	Cost	Applications
Hardened Chrome-Plated Steel	58-62	+/-0.01 mm/300mm	Good (chrome layer)	$	Standard linear bearing shafts. Inductive hardened, chrome-plated.
Stainless 440C (Hardened)	58-60	+/-0.01 mm/300mm	Excellent	$$	Corrosive environments (waterjet, marine). Full stainless (no plating).
Case-Hardened 1045	50-55 (case)	+/-0.02 mm/300mm	Fair (requires coating)	$	Budget shafts. Soft core (tough), hard surface (wear-resistant).

Diameter Selection: - 8mm: Light duty, <50 N load - 12mm: Medium duty, 50-200 N load - 16mm: Heavy duty, 200-500 N load - 20mm+: Very heavy duty, >500 N load

A.3.4 Fasteners (Bolts/Screws)

Requirement: Strength, corrosion resistance, cost

Material / Grade	Tensile Strength (MPa)	Corrosion Resistance	Cost	Applications
Grade 8.8 Steel (Black Oxide)	800	Poor (rust indoors)	$	Standard structural fasteners. Most common.
Grade 10.9 Steel (Black Oxide)	1,040	Poor	$	High-stress joints (motor mounts, spindle clamps).
Stainless 304 (A2-70)	700	Excellent	$\vert Corrosive environments. Slightl$ $*Stainless 316 (A4-80) *$ $*\vert 800 \vert Superior (marine grade) \vert$ $	Waterjet, marine, chemical exposure.

Torque Specifications: See Appendix B.1 for detailed torque tables.

A.4 Material Cost Comparison (USD per kg, Bulk)

Material	Cost ($/kg)	Relative Cost
Mild Steel (A36)	$0.50-$1.00	□ □ □ □ □
Structural Steel Tubing	$1.00-$2.00	□ □ □ □ □
Aluminum 6061	$3.00-$5.00	□ □ □ □ □
Aluminum 7075	$8.00-$15.00	□ □ □ □ □
Stainless 304	$4.00-$8.00	□ □ □ □ □
Cast Iron (Castings)	$2.00-$5.00	□ □ □ □ □
Epoxy Granite (DIY)	$2.00-$5.00	□ □ □ □ □
Carbon Fiber (Prepreg)	$30.00-$80.00	□ □ □ □ □
Titanium Ti-6Al-4V	$25.00-$50.00	□ □ □ □ □

Small Quantity Markup: Expect 2-5× prices for small quantities (<10 kg) vs. bulk (>100 kg).

A.5 Thermal Properties Summary

Critical for precision machines: Materials with low thermal expansion and high thermal conductivity minimize dimensional changes from temperature fluctuations.

Material	Thermal Expansion (mum/(m·°C))	Thermal Conductivity (W/(m·K))	Thermal Expansion × Length (mum/°C for 1m)
Aluminum 6061	23.6	167	23.6
Steel (Mild)	11.7	50	11.7
Stainless 304	17.3	16	17.3
Cast Iron	10.8	50	10.8
Titanium	8.6	7.2	8.6
Epoxy Granite	12-15	1.5	13.5
Carbon Fiber (axial)	-0.5 to +2	5-10	~0

Example: 1 meter aluminum beam expands 23.6 mum per °C temperature change. 10°C temperature swing = 236 mum (0.236 mm) dimensional change.

Thermal Compensation Strategies: 1. **Material Selection:** Use cast iron or epoxy granite (low expansion) for precision machine bases 2. **Temperature Control:** Enclose machine, use chillers to stabilize temperature (+/-1°C) 3. **Software Compensation:** Measure temperature, apply correction factors in CNC control 4. **Symmetric Design:** Pair materials with matched expansion coefficients

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End of Material Properties Appendix