Structural Materials
Metals and Metal Alloys

- Aluminum: Elemental Al is seldom used in mechanical parts; aluminum alloys have better properties for such applications.
  - Alloy 1100 (0.12% Cu): Low-strength alloy with excellent formability and high corrosion resistance. Not heat-treatable. Primary use is for spinning and deep-drawn parts. It can be strengthened by cold working: Machines well, has excellent weldability, and can be brazed with or (in vacuum) without flux.
  - Alloy 2024 (4.5% Cu, 0.6% Mn, 1.5% Mg): A high-strength, heat-treatable structural alloy commonly used in the T4 or T351 condition. Resistance to stress corrosion is poor. In bar or rod form tempered to T8 condition, it is more corrosion-resistant. Machinability is good, but it is difficult to weld.
  - Alloy 6061 (0.6% Si, 0.25% Cu, 1.0% Mg, 0.2% Cr) : Best general-purpose structural aluminum alloy. With moderate strength, good dimensional stability, good machinability, and excellent weldability. It can also be brazed.
  - Alloy 7075 (1.6% Cu, 2.5% Mg, 0.3% Cr, and 5.6% Zn): A high-strength alloy, especially T6. Stress corrosion resistance is maximized in the T73 condition. Machines well, but welding is not recommended .
  - Alloy 356 (7% Si and 0.3% Mg): This alloy has good castability by sand, permanent mold, and die casting methods and moderate to high strength. It is highly recommended for general-purpose optical instrument applications. Machinability is good. Castings can be repaired by welding.

Temper	Characteristics
F	As fabricated. Applies to products shaped by cold working, hot working, or casting processes in which no special control over thermal conditions or strain hardening is employed.
O	Annealed. Applies to wrought products that are annealed to obtain lowest strength temper, and to cast products that are annealed to improve ductility and dimensional stability.
H	Strain-hardened wrought products only). Applies to products that have been strengthened by strain hardening, with or without supplementary heat treatment to produce some reduction in strength.
W	Solution heat-treated. An unstable temper applicable only to alloys that naturally age (spontaneously at room temperature) after solution heat treatment.
T	Heat-treated to produce stable tempers other than F, 0, or H. Applies to products that are thermally treated, with or without supplementary strain hardening, to produce stable tempers. The T is always followed by one or more digits, e.g, 6061-T6

- Beryllium: This lightweight, high-stiffness, high-thermal-conductivity material offers many structural advantages in opto-mechanical applications. Dimensional stability is excellent. Thermal expansion characteristics differ significantly in the different directions of the hexagonal crystal structure of the elemental material. Corrosion resistance is generally excellent at room temperature because of the thin layer of beryllium oxide that forms on surfaces exposed to air. Machinability is at best poor. The material is quite brittle. Welding is not recommended, although electron beam methods have had some success. Some varieties can be brazed.

  The most common forms of supply for structural beryllium are vacuum hot-pressed block, hot extruded billet, and cross-rolled sheet. The highest uniformity of characteristics results from manufacture by hot isostatic pressing techniques. The latter process is usually used for optical components (scanners, mirrors, etc.) and some critical structural parts.

- Copper: Copper and its alloys are used in applications requiring excellent electrical and/or thermal properties, resistance to corrosion, ease of fabrication, good strength and fatigue resistance, and nonmagnetic properties. Easily soldered, brazed, and plated, copper is frequently used in heat exchangers, tubing, valves, and heat transfer straps as well as wire and electrical parts. Beryllium copper is frequently used for springs, whereas alloys containing up to 6% lead and brasses are widely used for screw-machine parts and mounting hardware (bolts, rivets, etc.).

- Invar and Super-Invar: Low-expansion alloys of Fe and Ni are used when control of thermally induced dimensional changes is required by the application. Invar, (36% Ni with small quantities of Mn, Si and C) and has a virtually invariable (hence the name) and low CTE over a limited temperature range (typically 4 to 38 °C). The CTE changes relatively rapidly outside this range. The actual value of CTE in a given Invar part depends somewhat on its temperature and machining history. For maximum stability, parts should be annealed at 95 to 150 °C and cooled slowly to room temperature.

  Super-Invar alloy (Fe/31% Ni/5% and Co) can have near-zero CTE with special heat treatment processing, but only over a very limited temperature range. The somewhat slower change of CTE with change of temperature of standard Invar may make it preferable to Super-Invar in some applications involving significant temperature changes. Further, Super-Invar undergoes a phase change when cooled to under -50 °C so it is not a good material of choice when exposure to such low temperatures is anticipated. On the other hand, standard Invar is much less stable over extended time (typical dimensional change 2 ppm/yr) than Super-Invar or several other low-expansion materials. The high stability of Super-Invar is attributed to the amount of mechanical work performed on the material during its manufacture.

- Magnesium: Good strength and lightness of weight make Mg a good candidate material for applications in which it can be protected from corrosion. Parts can be made by casting, by machining from wrought bars, plates, or sheets, and by forging. Because of its low wear resistance, inserts of harder materials are generally installed (by heat shrinking or threading) in magnesium parts such as rollers and wheels.

Corrosion resistance of magnesium depends on the surface protection provided, composition of the part and adjacent parts, and environment. Parts made of dissimilar materials should be chemically compatible (typically some aluminum alloys) or separated so that they cannot form a galvanic couple. Particularly active in contact with magnesium are stainless steels, Ti, Cu, and the Al alloys. Organic films such as epoxies and high-temperature-resistant fluorinated hydrocarbon resin coatings can be used as corrosion insulation between the dissimilar metals.

- Carbon Steel: Carbon steel alloys are used where ever high strength, high endurance, and good wear is required. The most commonly used types are low-carbon and high-carbon (spring) steels. Most types machine and weld well. Coating or plating is required for corrosion resistance.
- Corrosion-Resistant Steel: Corrosion-resistant (CRES) or stainless steels contain at least 10% Cr and owe their corrosion-resisting properties td a film of CrO^2 that forms on the surfaces. Their ductility and hardness values are higher than those of carbon steels. As a class, they are difficult to machine due to their high work-hardening nature. A few varieties (including type 416) are more easily machined because they contain additives such as Su or Se. The corrosion resistances of such free-machining varieties are somewhat reduced. Stainless steels may be subjected to heat treatment for annealing, hardening, or stress relieving depending on the application requirements. All types can readily be welded to the same or other types of CRES steels. Brazing in a vacuum or hydrogen atmosphere is preferred for attaching stainless to other metals.
- Titanium: Ti is a medium-density, nonmagnetic element that can be highly strengthened by alloying and deformation processing. It is resistant to corrosion and has a coefficient of thermal expansion (CTE) compatible with many common crown-type optical glasses. Hence, it is frequently used in cells and lens barrels for high-performance optical systems exposed to large temperature variations. Variety Ti-6Al-4V has especially favorable properties including reasonable workability and castability. Joining by brazing is routine; welding can be accomplished, but may cause change in material properties. Excellent welds can be made by electron beam and laser techniques. Titanium parts can also be made by powder metallurgy methods including hot isostatic pressing. There has been some success in polishing optical surfaces onto small (10 mm x 15 mm) faces of titanium prisms. Surface roughnesses of about 18 A rms and flatnesses to about $\lambda/2$ wave (with about 20% roll-off) were measured.

Key Characteristics of Aluminum

Aluminum in general (and extruded aluminum profiles in particular) offers a number of advantages over other materials (and other forming processes). Some other materials may offer some of the beneficial characteristics of aluminum profiles, but aluminum can offer a complete range of benefits at once. Aluminum extrusion is a versatile metal-forming process that enables designers, engineers, and manufacturers to take full advantage of a wide array of physical characteristics:

Aluminum is Lightweight. Aluminum weighs less by volume than most other metals. In fact, it is about one-third the weight of iron, steel, copper, or brass. Lightweight aluminum is easier to handle, less expensive to ship, and is an attractive material for applications in fields such as aerospace, high-rise construction, and automotive design.

Aluminum is Strong. Profiles can be made as strong as needed for most applications. Cold-weather applications are particularly well-served by aluminum because, as temperatures fall, aluminum actually becomes stronger!

Aluminum Exhibits High Strength-to-Weight Ratio. Aluminum offers a unique combination of light weight and high strength. Without aluminum, space travel might never have been realized. Engineers are discovering that bridge decks constructed from extruded aluminum can bear heavier live loads, in part because the aluminum bridge deck itself weighs so much less than a conventional steel deck.

Aluminum Resists Corrosion. Aluminum offers excellent corrosion resistance; it does not rust. Aluminum is protected by its own naturally occurring oxide film, a protection that can be further enhanced by anodizing or other finishing techniques.

Aluminum is an Excellent Thermal Conductor. Based on weight and overall cost, aluminum conducts heat (and cold) better than other common metals. These factors make aluminum ideal for applications requiring heat exchangers, especially because extrusion, as a metal-forming process, is well-suited to produce shapes that make optimal use of thermal conduction properties.

Aluminum Does Not Emit Sparks. Because aluminum is nonsparking, it is appropriate for applications involving explosive materials or taking place in highly flammable environments.

Aluminum Conducts Electricity. Bulk power transmissions generally take place via aluminum because, pound-for-pound, aluminum is twice as conductive as copper.

Aluminum is Nonmagnetic. Because aluminum does not acquire a magnetic charge, it is useful for high-voltage applications, as well as for electronics, especially where magnetic fields come into play or where sensitive magnetic devices are employed.

Aluminum is Resilient. Aluminum combines strength with flexibility and can flex under loads or spring back from the shock of impact.

Aluminum is Reflective. Highly reflective aluminum can be used to shield products or areas from light, radio waves, or infrared radiation.

Aluminum is Not Combustible. Aluminum does not burn and, even at extremely high temperatures, does not produce toxic fumes.

Aluminum is Suited to Extreme Cold. The strength of aluminum actually increases under very cold temperatures, making it especially useful for cryogenic applications and in the extreme cold of outer space, as well as for aircraft and for construction in high latitudes.

Aluminum Can be Recycled. Aluminum retains a high scrap value. It can be recycled indefinitely without losing any of its superior characteristics, making it especially appealing according to both environmental and economic criteria.

Aluminum Accepts a Variety of Common Finishes. Aluminum can be finished with liquid paint (including acrylics, alkyds, polyesters, and others), powder coatings, anodizing, or electroplating.

Aluminum Profiles are Seamless. Complex shapes can be realized in one-piece extruded aluminum sections without having to effect mechanical joining methods. The resultant profile typically is stronger than a comparable assemblage, less likely to leak or loosen over time.

Aluminum Profiles Can be Joined in Many Ways. Extruded aluminum sections can be joined by all major methods in use today, including welding, soldering, or brazing, as well as though use of adhesives, clips, bolts, rivets, or other fasteners. Integral joining methods may be especially useful for certain designs.

Aluminum Profiles are Economical. Extrusion tooling is relatively inexpensive and may not require long lead times. Even short-run prototypes often can be produced at moderate cost.

Aluminum Alloys

Non-Heat-Treatable Alloys

The initial strength of alloys in this group depends upon the hardening effect of elements such as manganese, silicon, iron and magnesium, singly or in various combinations. The non-heat-treatable alloys are usually designated, therefore, in the 1xxx, 3xxx, 4xxx, or 5xxx series.

Since these alloys are work-hard-enable, further strengthening is made possible by various degrees of cold working. Alloys containing appreciable amounts of magnesium when supplied in strain-hardened tempers are usually given a final elevated temperature treatment called stabilizing to ensure stability of properties.

Heat-Treatable Alloys

The initial strength of alloys in this group is enhanced by the addition of alloying elements such as copper, magnesium, zinc, and silicon. Since these elements in various combinations show increasing solid solubility in aluminum with increasing temperature, it is possible to subject them to thermal treatments that will impart pronounced strengthening.

These treatments include solution heat treatment, quenching and precipitation or age, hardening. By the proper combination of solution heat treatment, quenching, cold working and artificial aging, the highest strengths are obtained.

Annealing characteristics

All wrought aluminum alloys are available in annealed form. In addition, it may be desirable to anneal an alloy from any other initial temper, after working, or between successive stages of working such as in deep drawing.

Effect of Alloying Elements

1xxx series - Aluminum of 99 percent or higher purity has many applications, especially in the electrical and chemical fields. Excellent corrosion resistance, high thermal and electrical conductivity, low mechanical properties and excellent workability characterize these compositions. Moderate increases in strength may be obtained by strain-hardening. Iron and silicon are the major impurities.

2xxx series - Copper is the principal alloying element in this group often with magnesium as secondary addition. These alloys require solution heat-treatment to obtain optimum properties. In some instances artificial aging is employed to further increase the mechanical properties. This treatment materially increases yield strength, with attendant loss in elongation. Its effect on tensile strength is not so significant. The alloys in this series do not have as good corrosion resistance as most other aluminum alloys, and under certain conditions they may be subject to intergranular corrosion.

3xxx series - Manganese is the major alloying element of alloys in this group, which are generally non-heat-treatable. Because only a limited percentage of manganese, up to about 1.5 percent, can be effectively added to aluminum, it is used as a major element in only a few instances.

4xxx series - The major alloying element of this group is silicon, which can be added in sufficient quantities (up to 12%) to cause substantial lowering of the melting point without producing brittleness in the resulting alloys. For these reasons aluminum-silicon alloys are used in welding wire and as brazing alloys where a lower melting point than that of the parent metal is required.

5xxx series - Magnesium is one of the most effective and widely used alloying elements for aluminum. When it is used as the major alloying element or with manganese, the result is a moderate to high strength non-heat-treatable alloy. Alloys in this series possess good welding characteristics and good resistance to corrosion in marine atmosphere.

6xxx series - Alloys in this group contain silicon and magnesium in approximate proportions to form magnesium silicone, thus making them heat-treatable. Though less strong than most of the 2xxx or 7xxx alloys, the magnesium-silicon alloys possess good formability and corrosion resistance, with medium strength.

7xxx series – Zinc in amounts of 1 to 8% is the major alloying element in this group, and when coupled with magnesium and copper (or without copper) results in heat-treatable alloys of very high strength. Usually other elements such as manganese and chromium are also added in small quantities. The out-standing member of this group is 7075, 7050 and 7049, which is among the highest strength alloys available and is used in air-frame structures and for highly stressed parts.

Mechanical Properties of Aluminum

UNS Alloy No	Temper	Yield Strength, kpsi	Tensile Strength, kpsi	Shear modulus of rupture, kpsi	Fatigue Strength, kpsi	Elongation In 2 in, %	Brinell Hardness H, b
A91100	-O	5	13	9.5	5	45	23
A91100	-H12	14	15.5	10	6	25	28
A91100	-H14	20	22	14	9	16	40
A91100	-H16	24	26	15	9.5	14	47
A91100	-H18	27	29	16	10	10	55
A93003	-O	6	16	11	7	40	28
A93003	-H12	17	19	12	8	20	35
A93003	-H14	20	22	14	9	16	40
A93003	-H16	24	26	15	9.5	14	47
A93003	-H18	27	29	16	10	10	55
A93004	-O	10	26	16	14	25	45
A93004	-H32	22	31	17	14.5	17	52
A93004	-H34	27	34	18	15	12	63
A93004	-H36	31	37	20	15.5	9	70
A93004	-H38	34	40	21	16	6	77
A92011	-T3	48	55	32	18	15	95
A92011	-T8	45	59	35	18	12	100
A92014	-O	14	27	18	13	18	45
A92014	-T4	40	62	38	20	20	105
A92014	-T6	60	70	42	18	13	135
A92017	-O	10	26	18	13	22	45
A92017	-T4	40	62	38	18	22	105
A92018	-T61	46	61	39	17	12	120
A92024	-O	11	27	18	13	22	47
A92024	-T3	50	70	41	20	16	120
A92024	-T4	48	68	41	20	19	120
A92024	-T36	57	73	42	18	13	130
A95052	-O	13	28	18	17	30	45
A95052	-H32	27	34	20	17.5	18	62
A95052	-H34	31	37	21	18	14	67
A95052	-H36	34	39	23	18.5	10	74
A95052	-H38	36	41	24	19	8	85
A95056	-O	22	42	26	20	35	
A95056	-H18	59	63	34	22	10	
A95056	-H38	50	60	32	22	15	
A96061	-O	8	18	12.5	9	30	30
A96061	-T4	21	35	24	13.5	25	65
A96061	-T6	40	45	30	13.5	17	95
A97075	-T6	72	82	49	24	11	150

Aluminum in Optics

Al mirrors (with aspheric surfaces) can be produced directly from an aluminum blank using single point diamond turning machines.

- The main advantages of aluminum are low cost and high thermal conductivity
    - Aluminum's high CTE requires either temperature control in the case of space applications, or post correction with active or adaptive optics for ground telescopes
- Bare Al is too soft to polish well and is generally over coated with electroless Ni
    - This makes Al difficult to use for cryogenic applications because the differences in coefficient of expansion between Ni and Al lead to large deformations during cool down
    - Depending on annealing and the type of alloy used, blanks may exhibit dimensional instability in the long term, but this should be easily correctable if the mirror is used in an active optics system
- Although Ni-coated Al has thus far been shunned for ground-based optical telescope applications, it could become an outstanding choice for active optics systems.
    - The high CTE is no longer an issue, since thermally induced deformations are automatically corrected by the active optics system
    - By using an aluminum structure and aluminum optics, a passively athermalised system will result
    - The remaining characteristics are all favorable: aluminum is relatively inexpensive, easy to machine, and has a high thermal diffusivity conducive to low mirror seeing.

AlumiPlate

Improved Diamond Turnability

The AlumiPlate electrodeposited aluminum layer is high purity (99.9+%) aluminum which can be **diamond machined** to a surface finish of 2x - 4x better than that achievable with uncoated Al6061 or with electroless nickel-plated mirrors. Because AlumiPlate aluminum has virtually no alloying elements or impurities included in the layer, there is a greatly reduced chance of comet-tails, pull-outs, surface pitting, plowing or breakage of diamond cutting tools. **On-axis parts have been turned to 18 Å rms and off-axis mirrors have been turned to 36 Å rms. In many cases, this can eliminate the need to polish** after diamond turning, saving money, time and uncertainty

Better Finish Means Less Scatter

The smoother (20 - 40 Å rms) surface of diamond machined AlumiPlate aluminum (vs diamond machined electroless nickel, 6061, or beryllium-based substrates) provides a surface with less roughness and less scatter. This allows the application of diamond turned AlumiPlate aluminum plated metal mirrors in shorter wavelength applications - **even into visible - enabling the use of net-diamond turned mirrors in multispectral applications**.

Reduced Bi-metallic Figure Distortion

The linear CTE (Coeff. Of Thermal Expansion) of AlumiPlate aluminum is close to that of 6061 aluminum substrates, minimizing the figure loss that can occur due to bi-metallic bending with other diamond machinable metallic coatings over 6061. This "same material athermalization" and the low modulus and low stresses of the alumin-um plating also can eliminate the need to attempt expensive complex plating balancing schemes.

Coefficient of Thermal Expansion µm/m/°C		
AlumiPlate™ aluminum	Al6061 aluminum	Electroless nickel
24.4	23.6	13 - 14.5

Reduced Diamond Tool Wear

The relatively soft, low stress AlumiPlate aluminum layer means lower cutting forces which saves on tool wear, breakage, and changeout time while yielding a deterministically-produced, repeatable net diamond turned figure.

Other Properties

- AlumiPlate electrodeposited aluminum can be used over mirror substrates of aluminum, steel, copper, NdFeB, beryllium as well as aluminum beryllium and aluminum silicon carbide MMC materials.
- **The purity** of the deposited aluminum is very high - over 99.9+%.
- **Reflectivity of high purity aluminum** is good in the visible region and very good in the near infrared.
- **Corrosion Resistance** is excellent - better than just about any other plated metal surface and better than virtually any bare metal mirror substrate.
- **Density** is 2.67 g/cm^3, similar to familiar aluminum alloys, indicating a very dense layer.
- The aluminum can be deposited to **any thickness -** typical thickness for diamond turning is 3 - 5mil (76 - 130m).
- Withstands **temperatures from cryogenic up to 550°C (1,000°F).**
- **Excellent Adhesion**.