Prototyping and Low Volume Production - Part2

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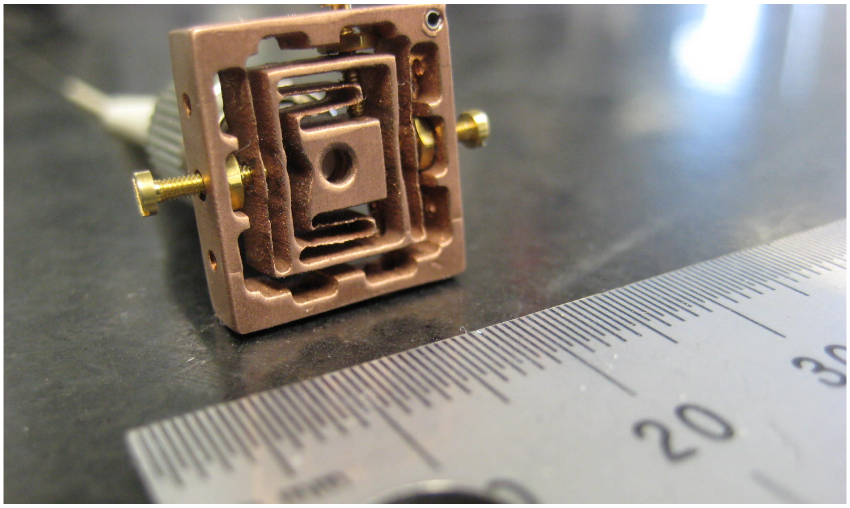
1. Flexures

There are two types of flexures: those cut from solid and those assembled from flexible strips. Both are easily fabricated by waterjet cutting. As a guideline, flexure cut from solid have a travel range of 1%-5% of size (i.e. a 100mm x100mm flexure will have a travel range below 5mm). Flexures assembled from flexible strips can have a travel range of 10%-20% of size. Clearly the travel range is a function of the elastic range of the material used. With thin Nitinol strips a travel range up to 50% of size can be achieved. Nitinol is a Ni-Ti alloy with an elastic range about 10X of steel.

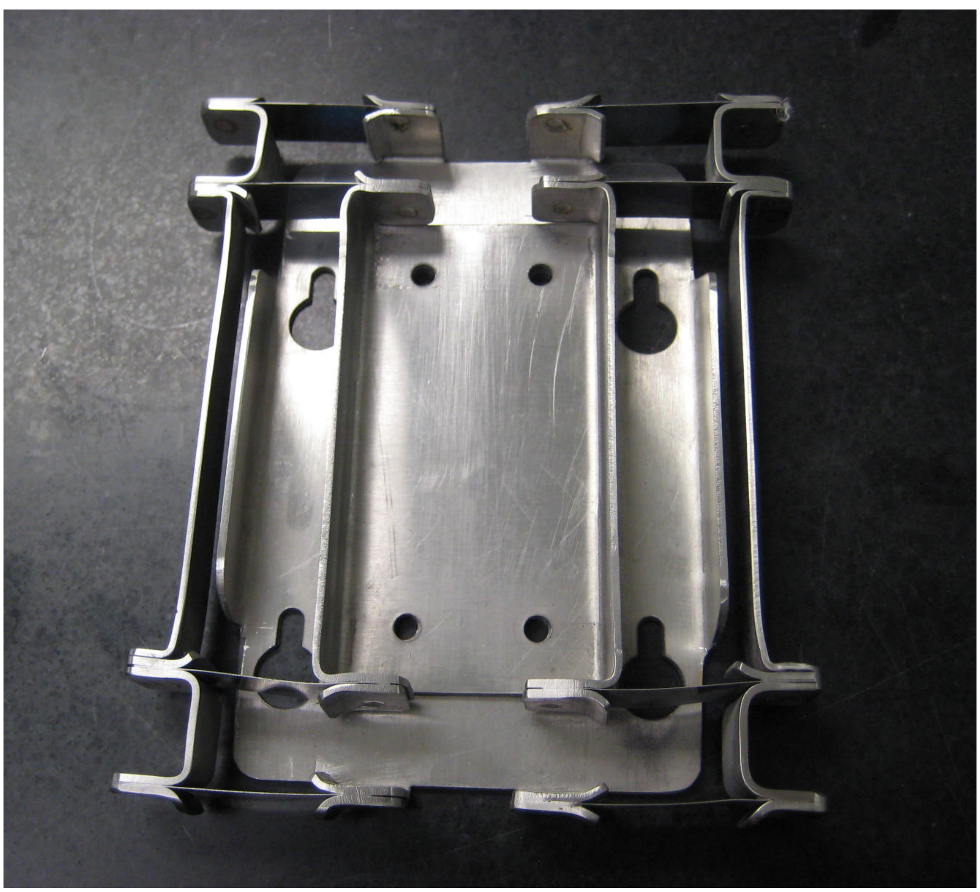
The key to accuracy of motion in a flexure is matching the flexible members both in dimensions and elastic properties. Good background on flexure design is the classic book "Instruments and Experiences" by R.V. Jones (1988). Because of the tolerances in waterjet cutting it is difficult to cut accurate vertical strips with a width below 1mm. One way around this is to drill and ream pairs of accurate holes before cutting. These pairs define flexure points and the rest of the members of the linkage are made stiff (i.e. wide). Such a flexure is shown in the introduction to Part 1. A close-up is shown here:

The quality of a flexure is measured by two figures of merits: the ratio of travel length to the deviation from straight line travel, and the stiffness in the undesired motion directions divided by the stiffness in the motion direction. Casually designed and built flexures have deviations from straight line travel of about 1% of travel and a ratio of cross-stiffness to stiffness in the motion direction of about 100:1. Very carefully designed and made flexures can reach linearity of travel of better than 1000:1 and stiffness ratios of better than 1000:1.

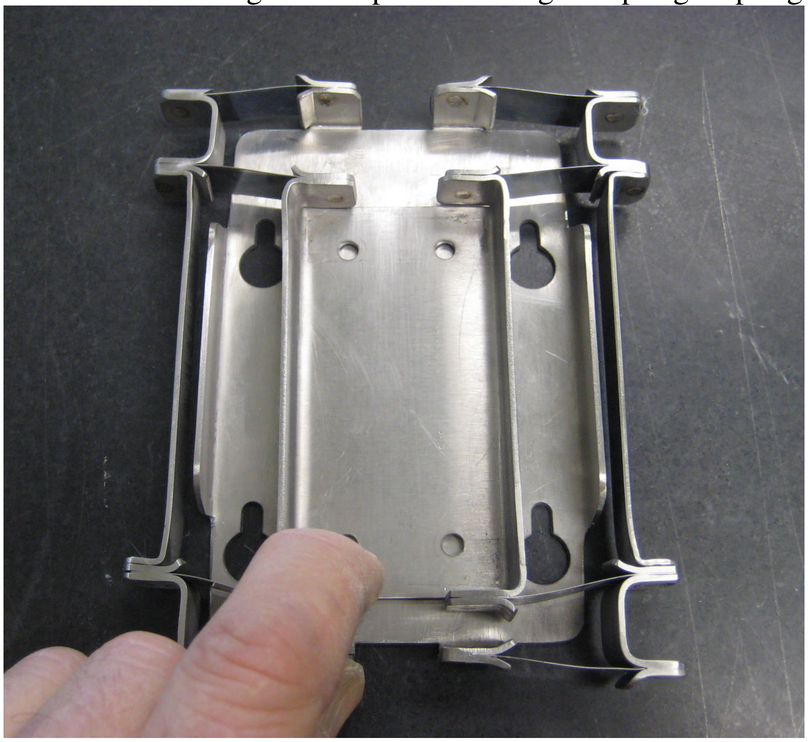
Small flexures cut by water-jet from solid are so inexpensive (a few minutes of cutting) that they can be considered "disposable". The following photo shows such a fiber-optics X-Y adjustment for a single-mode fiber (needs adjustment to better than 1um). Note that nuts are inserted into slots, to avoid tapping, and locking is done by tightening an opposing screw. This flexure actually also contains an angular adjustment (behind the X-Y adjustment, not visible in photo). The flexure is about 20x20mm and is about the smallest practical with a standard cutting nozzle. The material is heat-treated Type 25 Be-Cu.



A long range flexure made of sheet metal with inserted springs made of 0.2mm heat treated type 17-7PH stainless steel is shown here:



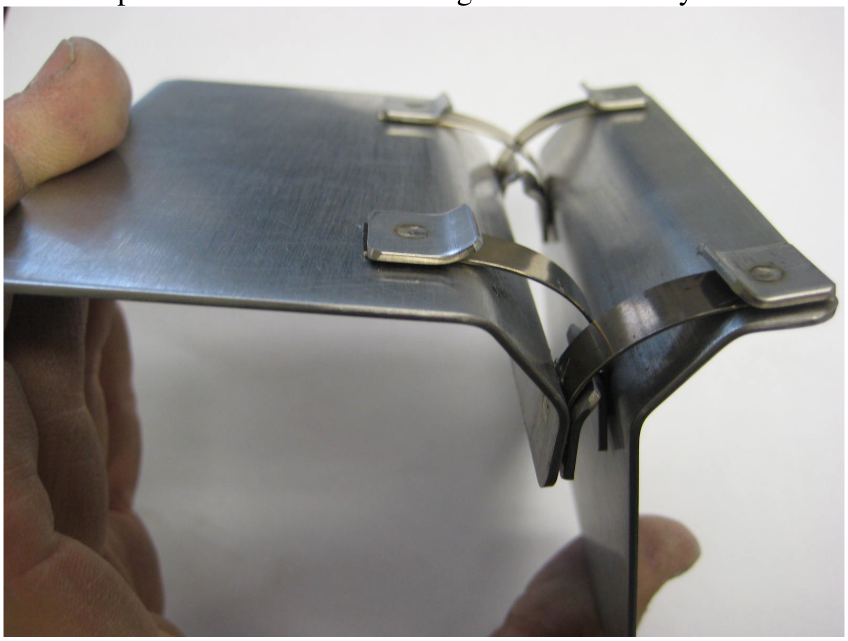
Note the curved edges of all parts touching the springs. Springs are spot welded.



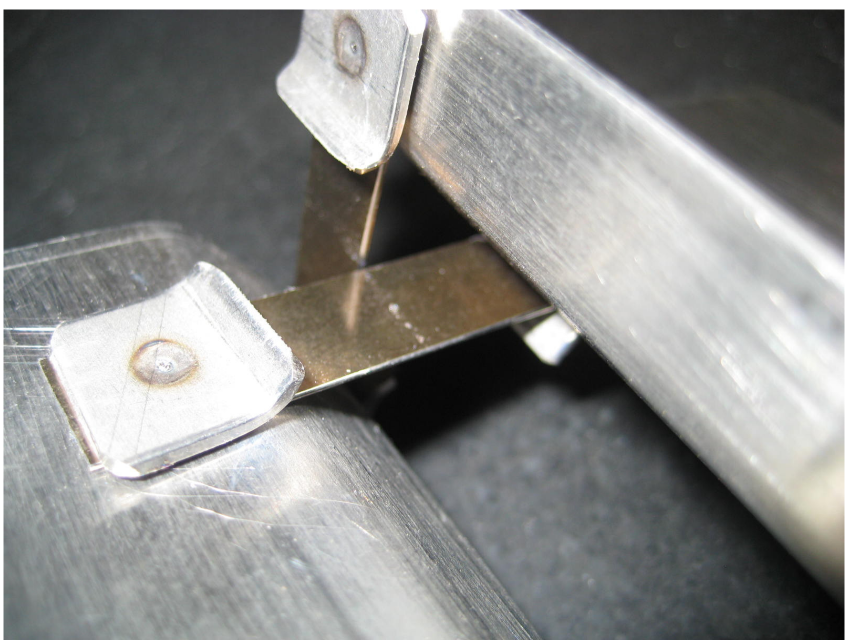
A very useful material for making springs and high strength stainless steel structures is type 17-7 PH condition A stainless steel. This is available as wire and sheets. In this condition the material is soft and is similar to mild steel. After heat treating it becomes hard and flexible with similar properties to the best spring steels. The heat treatment consists of heating to 760^0C, cooling to room temperature and heating to 565^0C for one hour. All temperatures can vary +/-10^0. Best source for this material in small quantities is www.sidecuts.com.

A related device is a flexural hinge, also known as a "cross strip hinge". For small angles it is made from spring steel (carbon steel or stainless steel). For large angle such as 90^0 Nitinol has to be used.

With strips made of Nitinol a 90 degree bend is easily achievable:



Nitinol is not weldable, but it can be spot welded between two layers of stainless steel:



As before, all edges are slightly curved to avoid stress point.

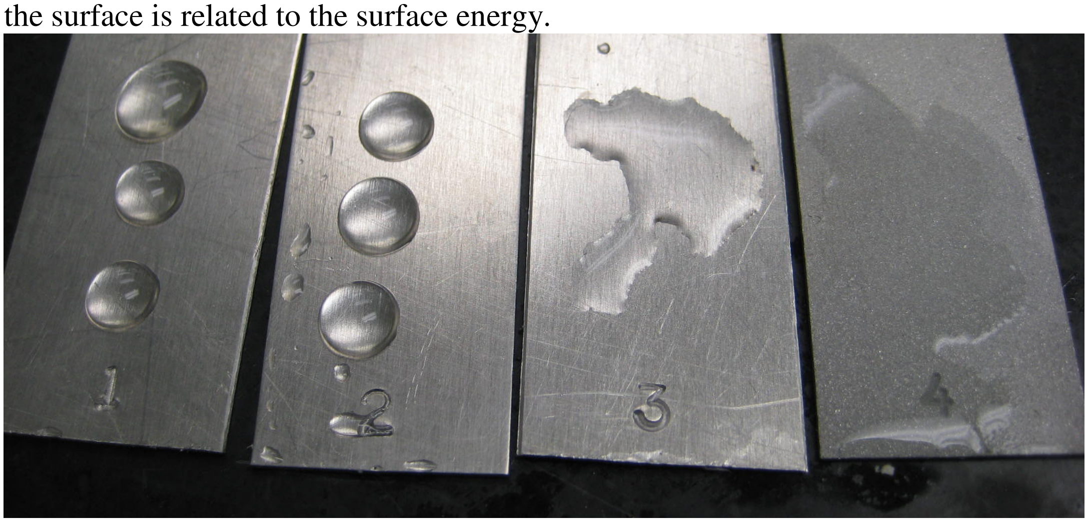
2. Making large structures

Complex large structures, typically requiring castings or weldments, can be easily built up from parts cut by water-jet cutting. The parts are held together by bolts, built-in clamp or by adhesive bonding. All adhesive joints are designed to operate in shear mode, as the adhesive is the strongest in this mode. The general philosophy follows wood joint design. Strength comparable to welding can be achieved in frames made of aluminum. This method offers two extra advantages over welded frames:

1. There is no distortion and the assembly can be done on a reference surface such as a granite surface plate.
2. After use, the structure can be disassembles by heating it up to 150^0-200^0 C and knocking it apart while hot.

The key to strong adhesive bonding is the same as to a lasting paint coat: surface preparation. Sandblasting is by far the best method, creating joints about 5X-10X stronger than other methods. Bonding is a combination of mechanical anchoring, by surface roughness, and chemical bonding. For chemical bonding the surface must have a very high surface energy. This is tested by wetting it with water, which has high surface tension. If the water spreads, the surface energy was sufficient to overcome the surface tension of the water. Bonding (as well as painting) has to be done within hours of surface preparation (otherwise a molecular layer of hydrocarbons will cover the surface). The following is a test showing the wetting of an aluminum sample with four different surface preparations: #1- as is, #2-cleaned with acetone by wiping several times, #3-cleaned with an abrasive cleaner such as Comet or Ajax and #4-sandblasted.

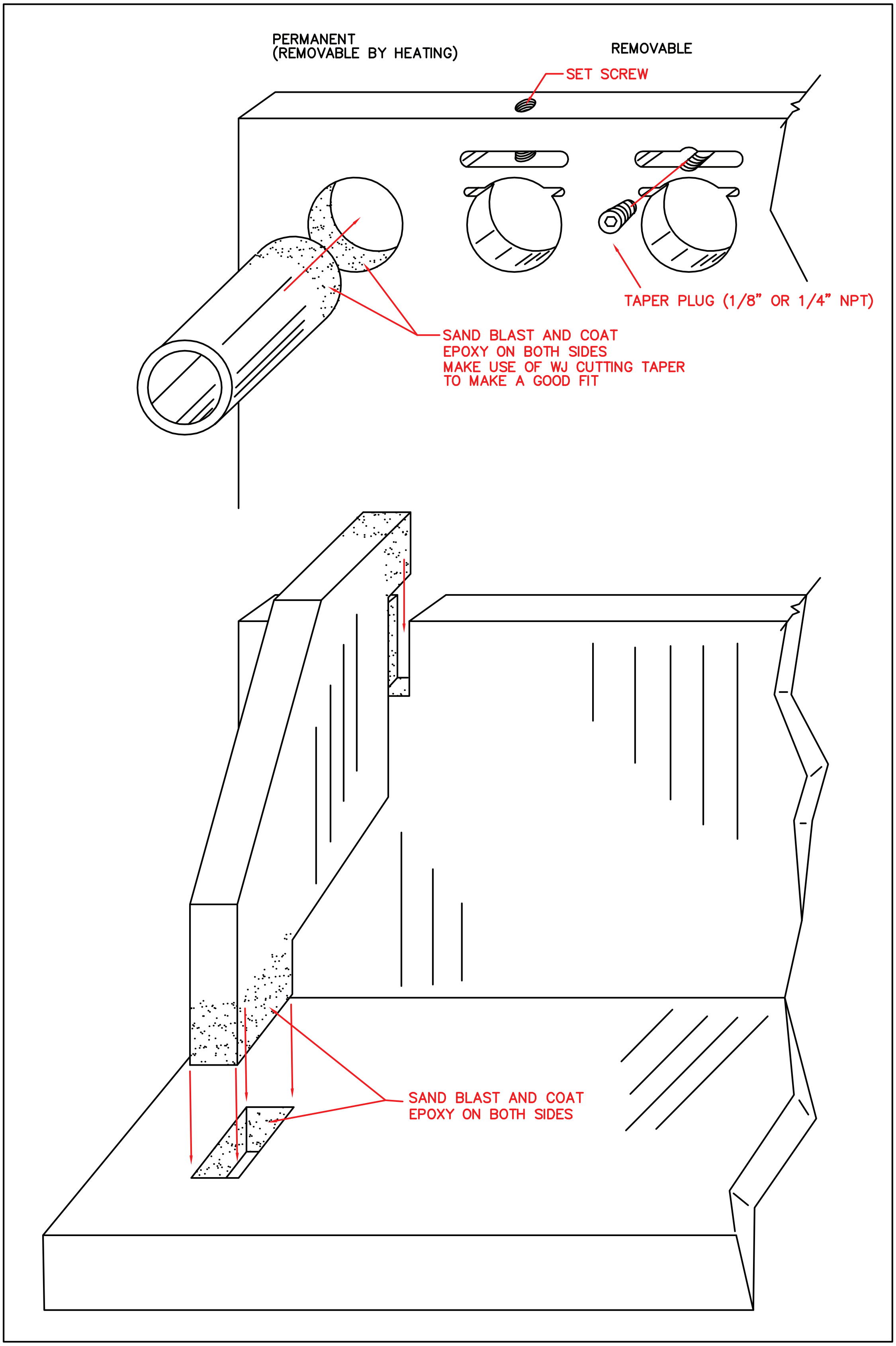
As you can see the often recommended cleaning with acetone is useless. Unless the sample looks like sample #4, or at least #3, it can not be painted or bonded. This test is known as “contact angle test”. The contact angle between the edge of the water drop and the surface is related to the surface energy.



The following drawing shows different types of joints for large structures. The advantage of the flexible clamps over a simple set screw is:

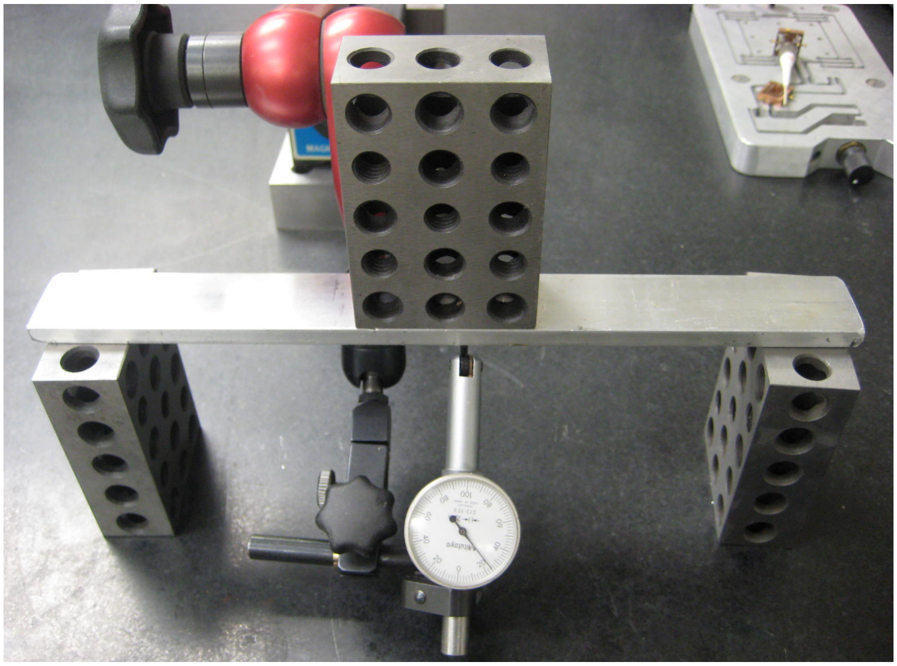
1. No marring of surfaces.
2. Force is distributed over a large area, therefore joints do not loosen with use.

Note that the slight natural taper of a waterjet cut plate can be used to great advantage in making the joints a slight press fit. After spreading adhesive, typically epoxy, on both surfaces, the parts are tapped into place. This prevents any misalignment while adhesive is curing. Epoxy adhesives take a long time to reach full strength. The standard “5 Minute” epoxy should be cured overnight (or shorter times at elevated temperatures).

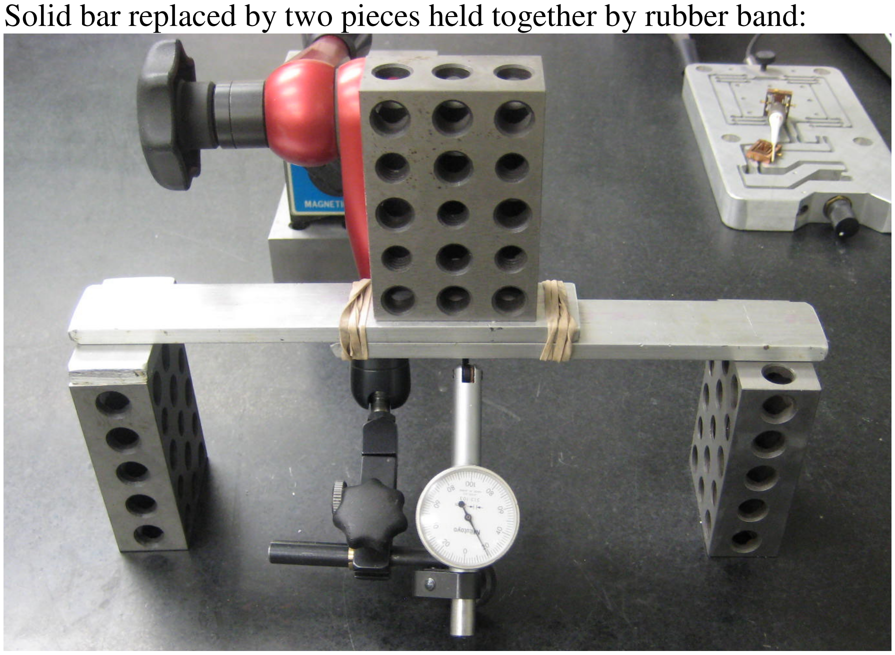

PERMANENT
(REMOVABLE BY HEATING)
REMOVABLE
SET SCREW
TAPER PLUG (1/8" OR 1/4" NPT)
SAND BLAST AND COAT
EPOXY ON BOTH SIDES
MAKE USE OF WJ CUTTING TAPER
TO MAKE A GOOD FIT
SAND BLAST AND COAT
EPOXY ON BOTH SIDES

Strength vs. Stiffness

When dealing with large structures it is important to understand the difference between strength and stiffness. Two metal bars held together by a rubber band have the same stiffness as a solid metal bar until the point that the force overcomes the tension of the rubber bands and the bars separate. This is not intuitive to most designers. Try the following experiment, in which the defection under the load is read by the dial gage below the bar:



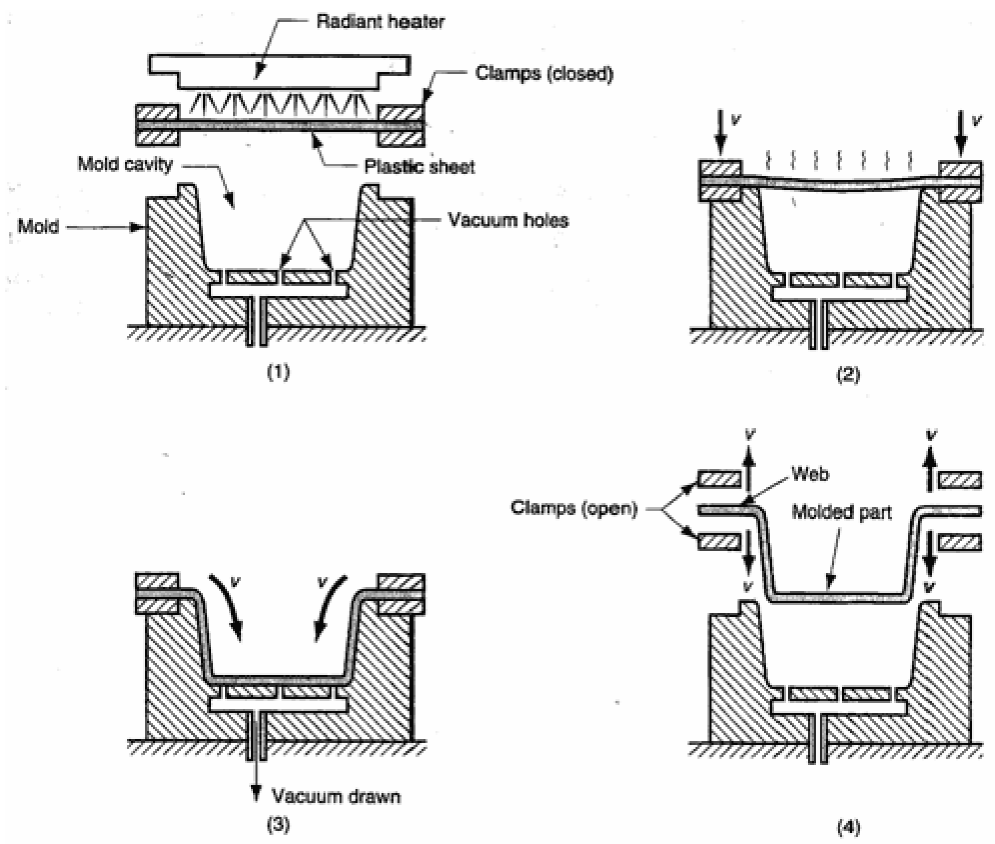
Solid bar replaced by two pieces held together by rubber band:



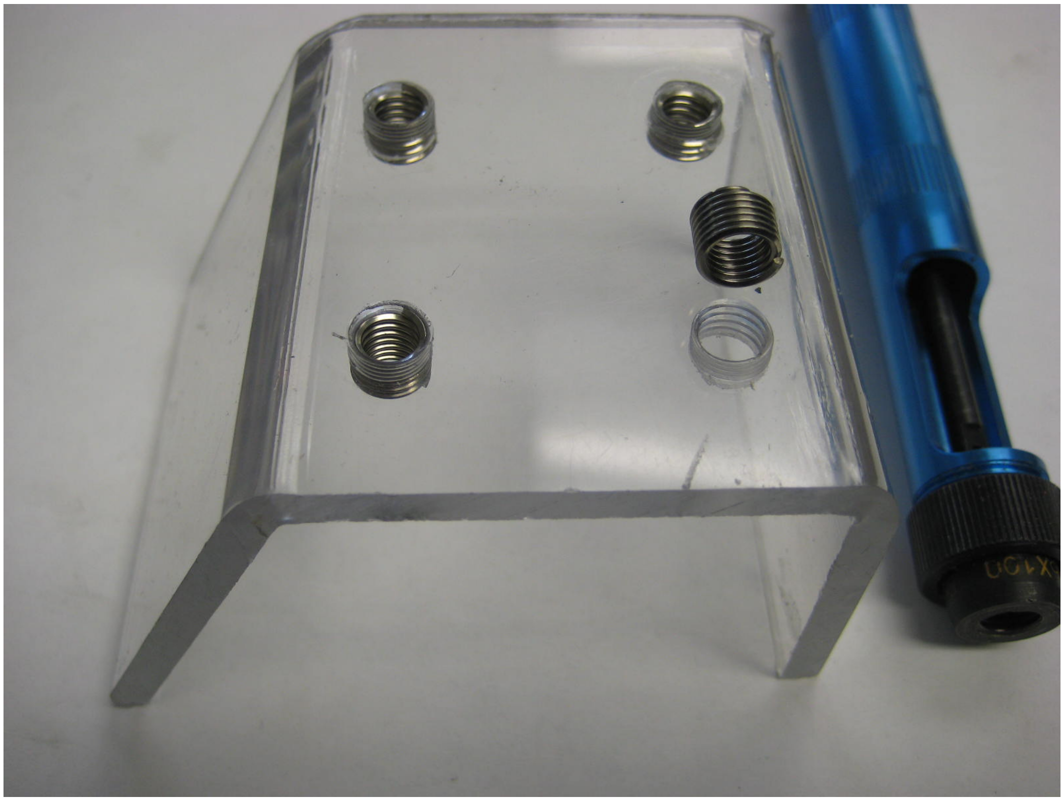
If you look at the gage carefully, the stiffness in the latter image actually went up (deflection went from 22um to 20um). Can you explain why?

3. Working with Plastics

In general there are two types of polymeric materials, or "plastics": thermoplastic (can be re-melted and easily recycled) and thermosetting (also known as "cross linked"), which can not be melted. They will soften and decompose when heated. In general cross-linked materials are harder and stronger. Thermoplastic materials, such as acrylics, can be easily formed when heated by simple molding tools (can be made of particle board or plywood) by using a two part mold, or by vacuum forming (using a single mode and suction). Parts can be made from thermosetting materials by mixing the resins and casting into simple mold. A wealth of data and videos is available on the internet on these methods.
A diagram explaining vacuum forming is shown below. A regular vacuum cleaner can be used as a vacuum source, the plastic sheet can be heated by hot air or radiant heat.



A very useful plastic material is Polycarbonate (known by trade name Lexan^R). Sheets of this plastic can be formed cold, similar to sheet metal. Unlike other transparent plastics (acrylics, polystyrene etc) it is not brittle and does not shatter. It is more expensive than acrylic but vastly superior. In general thread do not hold in plastics and require metal inserts, the most compact being the spring-like type known as Helicoils^R. The photo below shoes a 5mm thick part bent in a brake and tapped for Helicoils. The tool to the right is the Helicoil insertion tool.

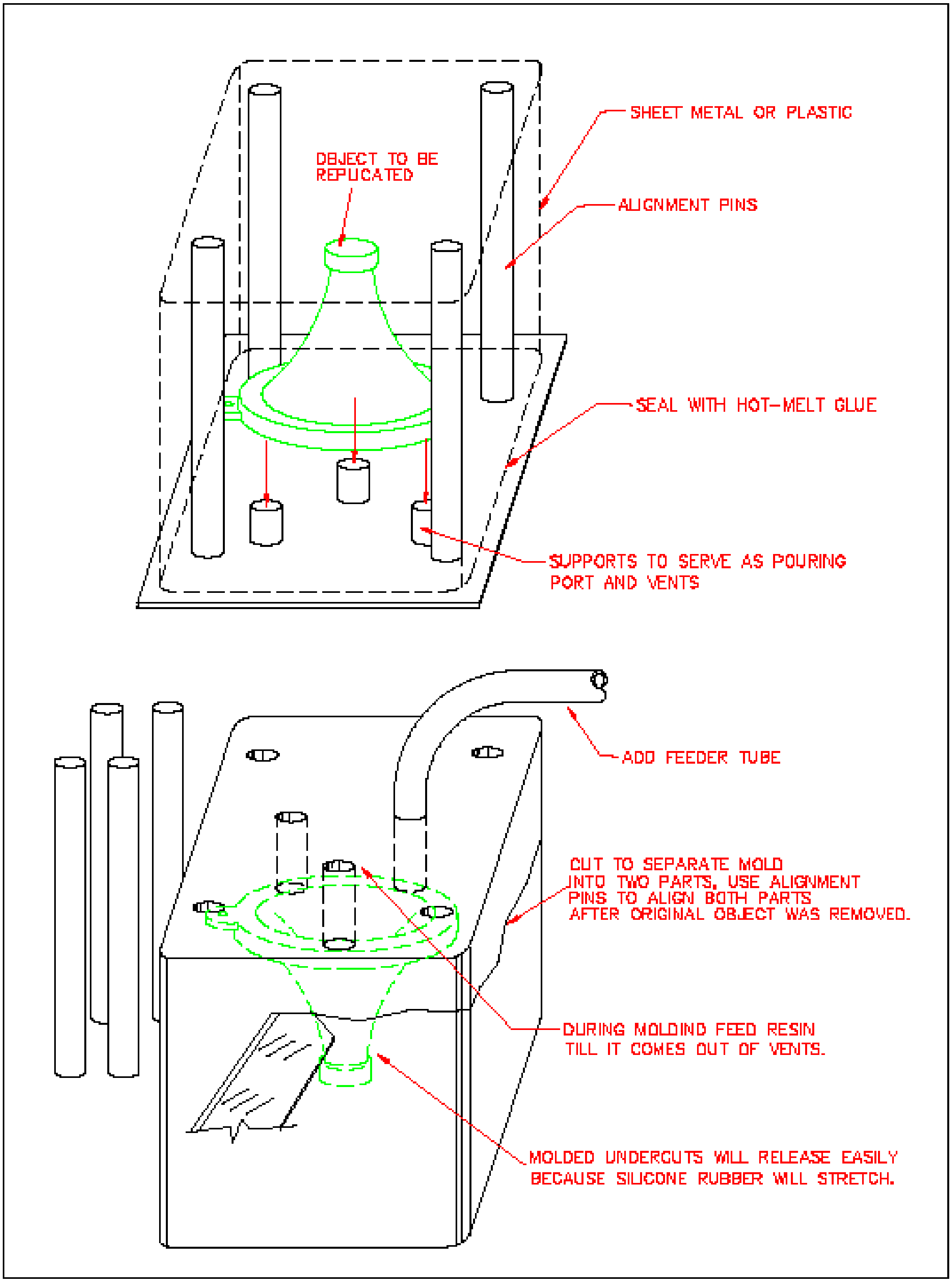


Complex 3D objects can be made out of plastic, mainly thermosetting resins such as Epoxy, Polyester and Polyurethane by making a RTV (**R**oom **T**emperature **V**ulcanizing) silicone mold. Suitable fillers like chopped glass fibers, carbon fibers, metal powders and even clean beach sand can be added to improve properties and reduce cost. As a general rule, fillers improve properties but make the material harder to pour, so highly filled polymers can only be used for molding simple shapes. Suitable pigments can be added, regular laser printer toner being an excellent black pigment for all polymers. Best is to use dry pigments to avoid any interference with curing that can be caused by an improper liquid pigment. The main advantage of silicone RTV over other mold-making materials are:

1. It is does not stick to the original object or the molding resins, so no mold releasing agent are needed.
2. Silicone RTV can withstand high temperatures (300^0 C continuously, and up to 400^0 - 500^0 for a short time). This allows casting of zinc alloy metal parts directly in these molds. It also allows accelerating the curing process of any resin by heating the mold, as well as pouring molten thermoplastic polymers into the mold.
3. Because of its flexibility complex parts having slots and undercuts can be cast in a one piece mold. The mold will stretch and release the object.

Do not confuse “Silicone Mold-Making RTV” with “Silicone Adhesive” you buy at the hardware store (which is formulated to stick to everything). You can even cast silicone rubber elastomeric parts in a silicone rubber mold by using mold release.

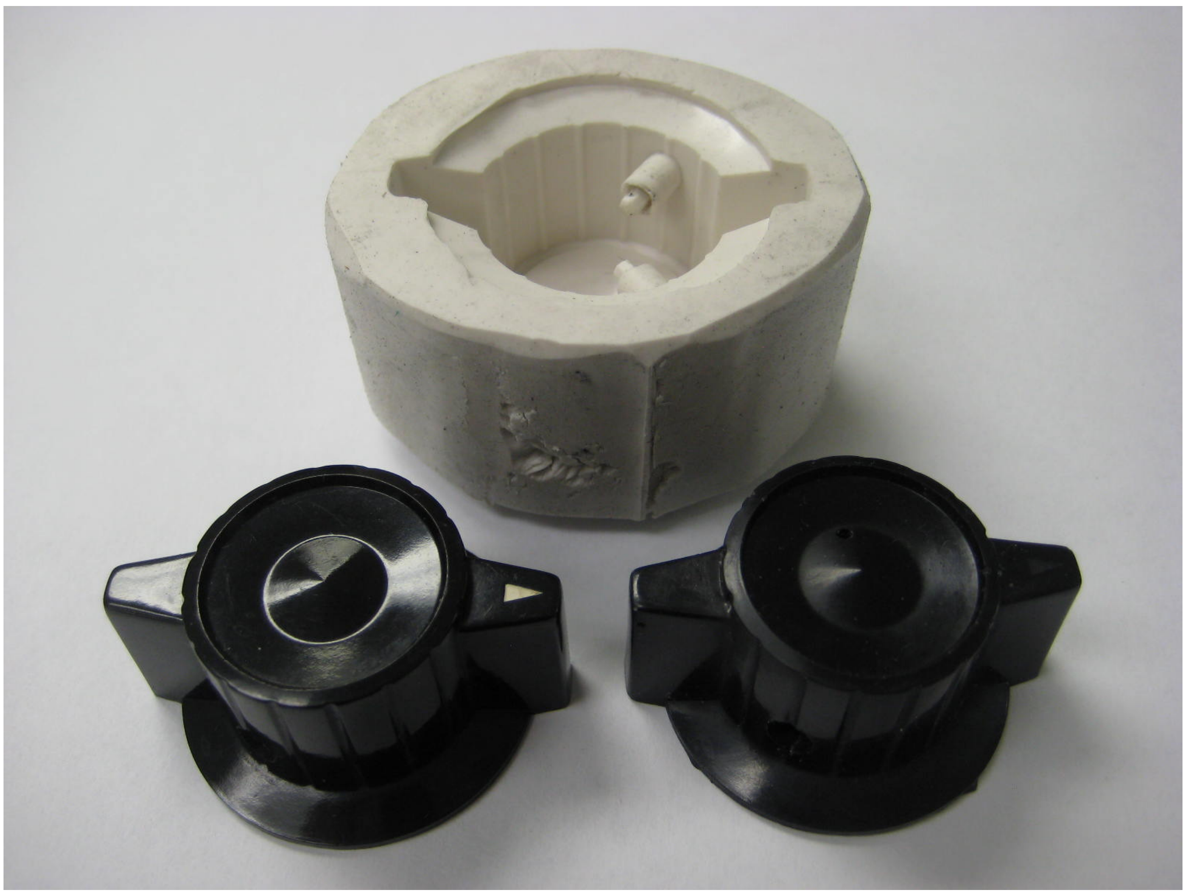
There is plenty of info on the internet, however the process described in all sites for making a two part mold is too complicated, and a better process is shown here:


SHEET METAL OR PLASTIC
OBJECT TO BE REPLICATED
ALIGNMENT PINS
SEAL WITH HOT-MELT GLUE
SUPPORTS TO SERVE AS POURING PORT AND VENTS
ADD FEEDER TUBE
CUT TO SEPARATE MOLD INTO TWO PARTS, USE ALIGNMENT PINS TO ALIGN BOTH PARTS AFTER ORIGINAL OBJECT WAS REMOVED.
DURING MOLDIND FEED RESIN TILL IT COMES OUT OF VENTS.
MOLDED UNDERCUTS WILL RELEASE EASILY BECAUSE SILICONE RUBBER WILL STRETCH.

The cutting of the old into two parts need not be done accurately (a jagged cuts actually helps alignment). The last few mm to the object can be torn rather than cut to avoid scratching the original.
The finished molds come in different shapes and sizes:

Both the catalyzed silicone rubber and the resin to be poured must be degassed by placing in a vacuum chamber for at least 30 minutes. Make sure the volume of the container is at least 5 times the volume of the liquid, as the liquid will foam up during degassing. Only the lowest viscosity resins (flowing like light oil) can be poured without degassing after mixing the ingredients together. After pouring the silicone mold around the original object it should be degassed again. To get the best results the pouring of the resin should be done in a vacuum oven (or at least vacuum chamber). The mold is connected by a tube to the resin container, which is located outside the chamber. Atmospheric pressure drives the resin into the mold. The advantage of this method is that any trapped air in the mold will disappear as soon as the vacuum is released at end of the pouring, since the bubble contains air at a very low pressure, about 0.1% of atmospheric, causing the volume to decrease 1000 fold at atmospheric pressure. Another advantage of this process is that any filler can be placed directly in the mold, so a very high percentage of filler or very coarse fillers, such as Kevlar or carbon fiber cloth, can be used. Silicone is normally too thick to be sucked into the mold by a tube, therefore it is poured outside the vacuum. For degassing and pouring an oil filled vacuum pump (known as a "roughing pump" in vacuum systems) is needed. A vacuum cleaner will not work. A photo of the set-up is shown below. The advantage of a vacuum oven is that the curing cycle can be accelerated by pouring at 60^0 C or heating mold after pouring. For silicone molds and parts the oven can be heated to 150^0 after the silicone rubber jelled, assuming the original item, still in the mold, can take the heat. As a rule of thumb any 10^0 temperature increase doubles the speed of the reaction (actual speed-up depends on the activation energy and given by the Arrhenius formula). To prevent leakage from the mold parting line brush liquid soap on the faces before putting the mold together.

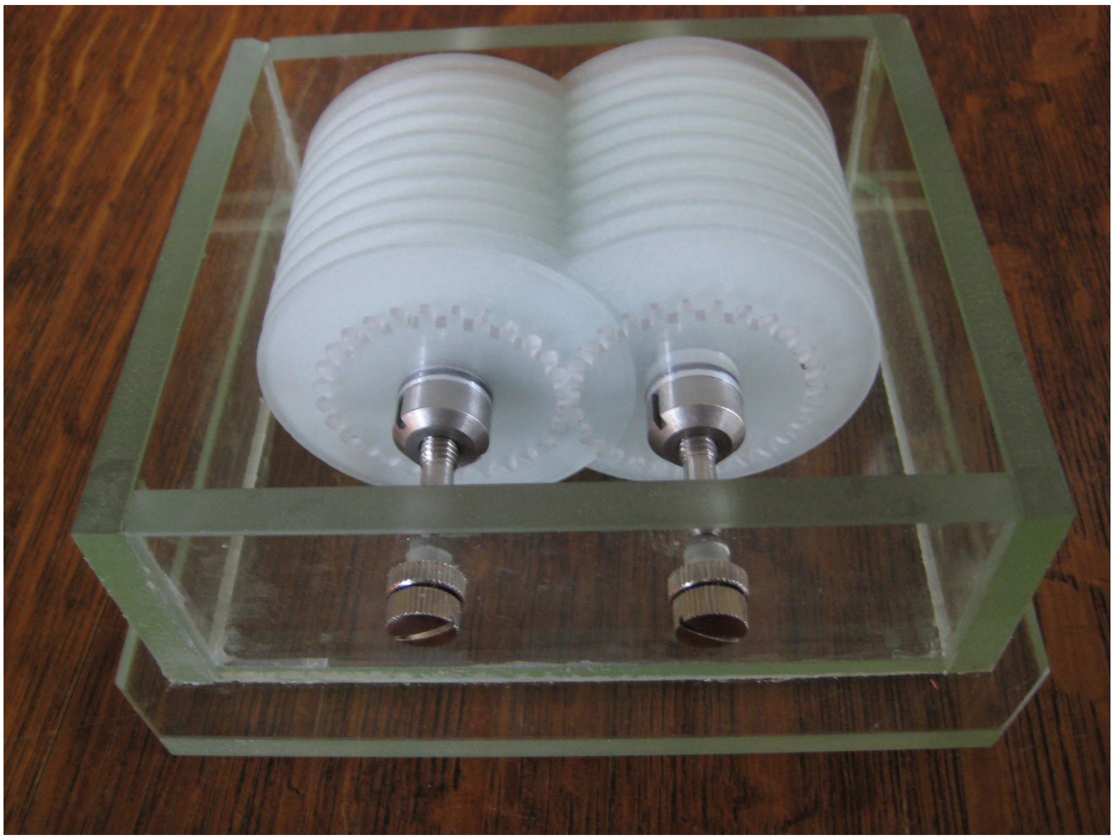
The RTV/Resin replication process can maintain dimensional tolerance of about 1% (higher when fillers used and mold is reinforced with internal metal screens). The total dimensional change from original object to replicated object is about 2.5% for epoxy, some in the mold shrinkage and some in the cast resin shrinkage. The process can maintain resolution down to the molecular level. Keep in mind that diffraction gratings and DVD are replicated using similar methods. A blue-ray DVD needs to maintain local accuracy (pit depth tolerance) in the order of nanometers and sub-micron features. In an old fashioned LP record the amplitude of the groove wall modulation was about 50um and the dynamic range of a good recording was about 80dB-90dB (10,000:1 to 30,000:1 in amplitude), which corresponds to replication accuracy of about 2-5nm.
An example of a very simple replication is shown below. Note that the side holes (for set screws) were cast without a problem, the mold pulled out from the holes. The LH knob is the original, RH knob is replicated in Epoxy+ black toner.



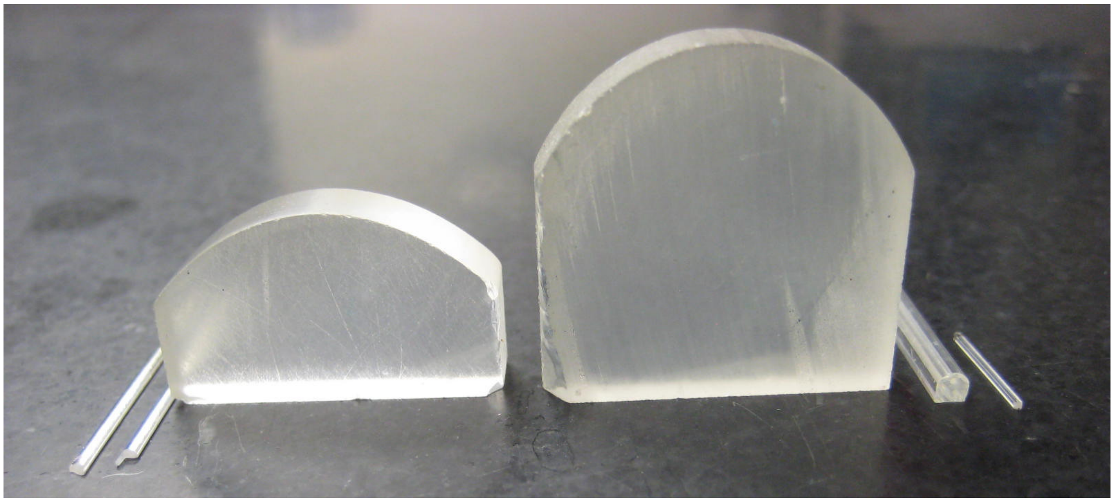
The most interesting applications of polymer replications are actually at the microscopic scale, where parts are too small to machine. The master can be done by micromachining techniques (photo-lithography etc) and many low cost copies can be made by replication. Life of a silicone mold is a few hundred parts. Mold should be baked at 200^0-250^0 every 10-20 parts to drive off impurities.

4. Working with glass

Glass can be cut very well (and at very high speeds) by waterjet cutting and can be bonded very well will silicone adhesives/sealant (the same ones you can buy at any hardware store) with minimal surface preparation- cleaning with abrasive cleaner, or even just water and soap. The silicone adhesive forms a tenacious chemical bond with the glass (just look at how large aquariums are held together). Other machining operation on glass parts have to be done with diamond grit tooling, which is not expensive. Here is an example of an all glass item made on a waterjet (the discs are sand-blasted):



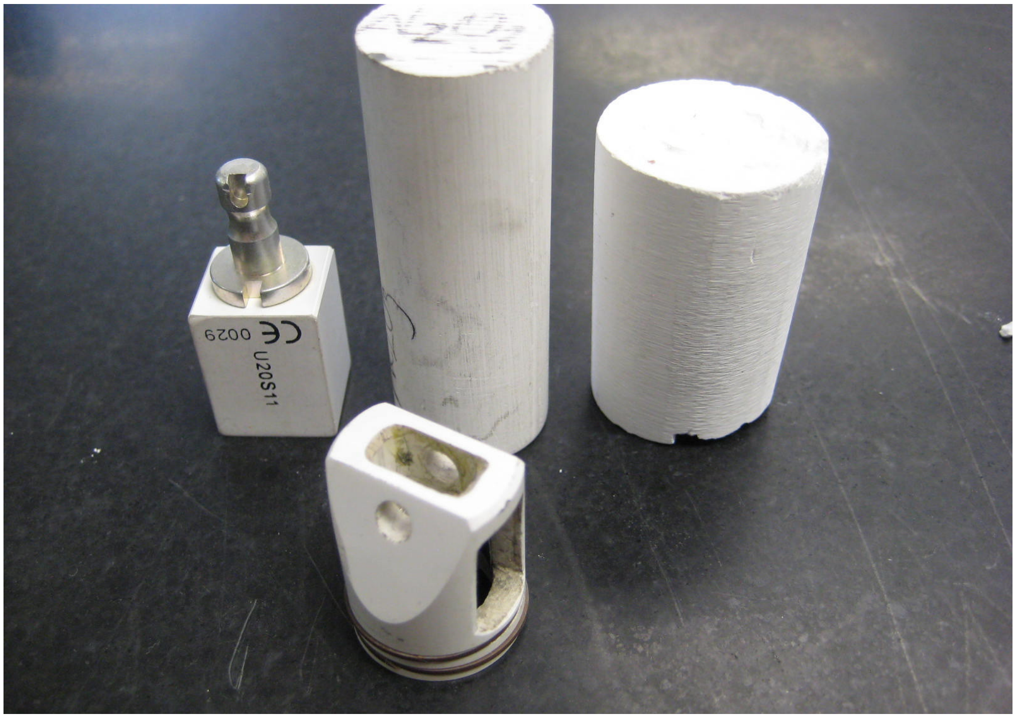
Glass has a few other unusual properties, the most amazing one is the ability to form miniature shapes by heating a glass rod and drawing (pulling) it. Most people know that a round rod, when drawn, will keep its round cross section. Few appreciate that this is true, only in glass, for any cross section. For example, a prism made of glass, when heated and drawn, will produce a long glass strand with a prismatic cross section which copies faithfully, including sharp corners, the cross section of the original prism. When the diameter is reduced by **N** the length will go up by $\mathbf{N}^2$ (for a constant volume) thus a lifetime supply of prisms can be easily made. Another advantage of this process is that the surface roughness scales as well, so a prism with a dull ground finish will become a very long prism with a small diameter having a perfect optical finish. The accuracy of the drawn object is about 1um, but part of the error is repeatable and can be compensated in the blank. This process is very valuable for manufacturing miniature prisms and cylindrical lenses, as the surfaces can be made non-cylindrical in order to reduce spherical optical aberrations. The photo shows a section of a blank and the “aspheric” optical lenses made from it.



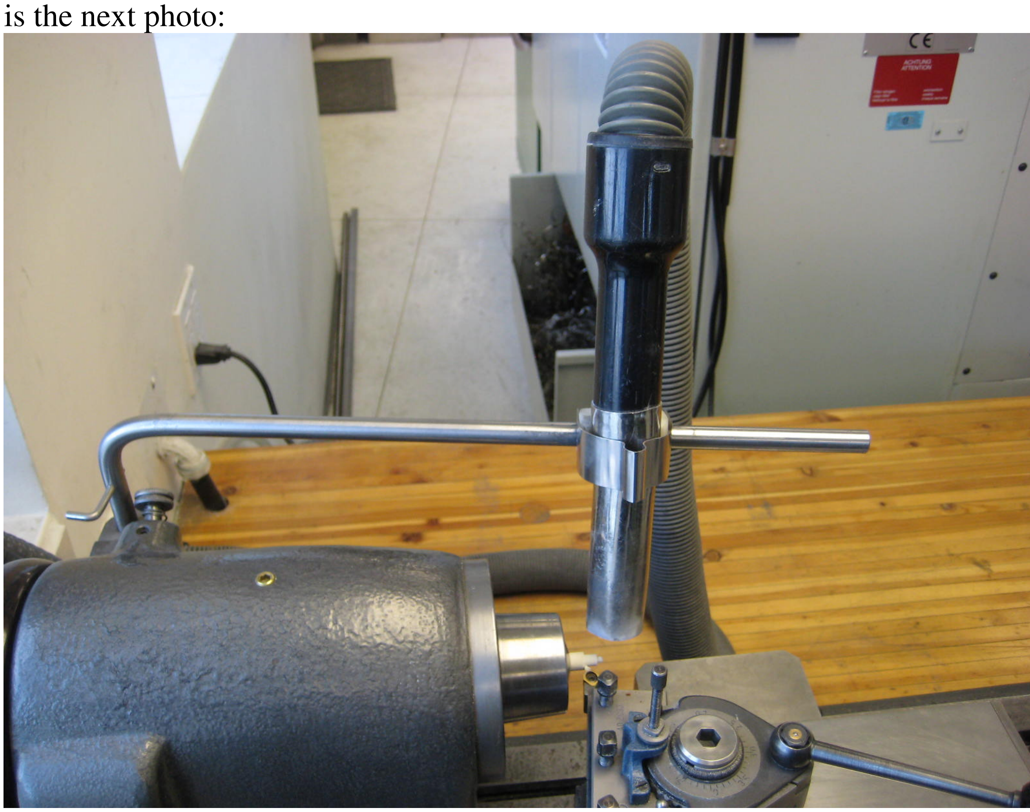
5. Working with Ceramics

Ceramic materials have an advantage over glass: parts don’t have to be machined in the final hard state; they can be made in two other ways:

1. Parts can be molded from the ceramic clay (same as pottery making). A good ceramic for that is porcelain, which is readily and cheaply available at pottery supply houses. After lengthy drying, parts are fired at about 1300^0C. They can be used without glazing (dull finish) or glazed.
2. Parts can be machined from a semi-fired (“green fired” or “bisque fired”) state and then fired to achieve full hardness. Two particularly useful ceramics commercially available in a machinable state are Alumina (aluminum oxide) and Zirconia (zirconium oxide). Do not confuse those with other machinable ceramics such as Micalex or Macor[R] that can not be fired to improve properties. The machinable alumina and zirconia have reasonable mechanical properties even before firing, and superb properties after firing. Fired zirconia has mechanical properties similar to tungsten carbide. Alumina is fired at about 1650^0C and zirconia at about 1550^0C. Machinable alumina as well as Micalex and Macor are available from suppliers such as McMaster-Carr (www.mcmaster.com). Machinable zirconia is available from dental supply houses (used to make crowns and other dental parts). Zirconia is a very inert material approved for use inside the human body. It has a melting point of over 2500^0 C and is a good thermal insulator. The following photo shows some alumina and zirconia blanks and a finished part made from zirconia (was machined before firing and finish machined after firing with diamond grit tooling). The blank on the left is a dental blank.



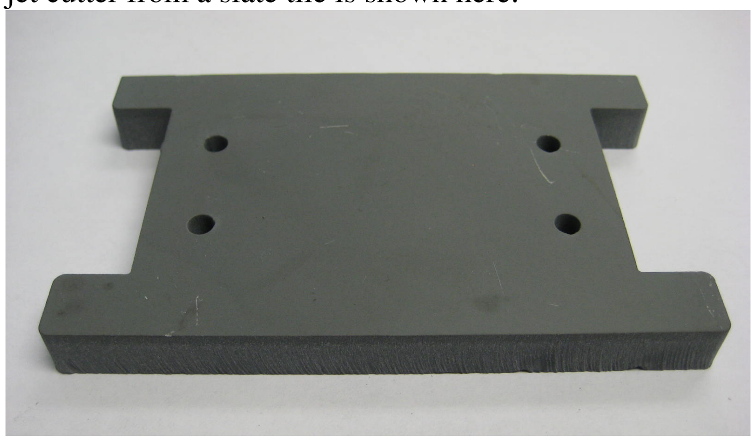
Machinable ceramics can be machined (before firing) with standard metalworking tools. Carbide tipped tools are preferred. Because of the abrasive dust they create during machining, a suction hose hooked up to a vacuum cleaner needs to be provided, as shown is the next photo:



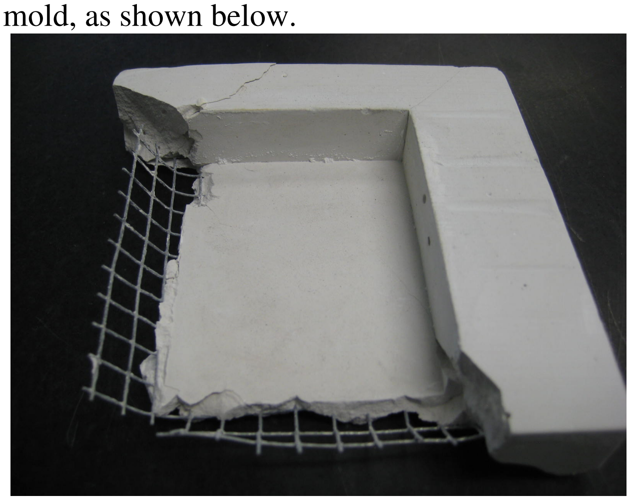
Low cost alternatives

While the basic ingredients of machinable ceramics are very inexpensive, but the materials sell for high prices. Before buying a slab of Micalex or machinable alumina (about $1000 for a 30x30x1cm piece) consider the following alternatives:

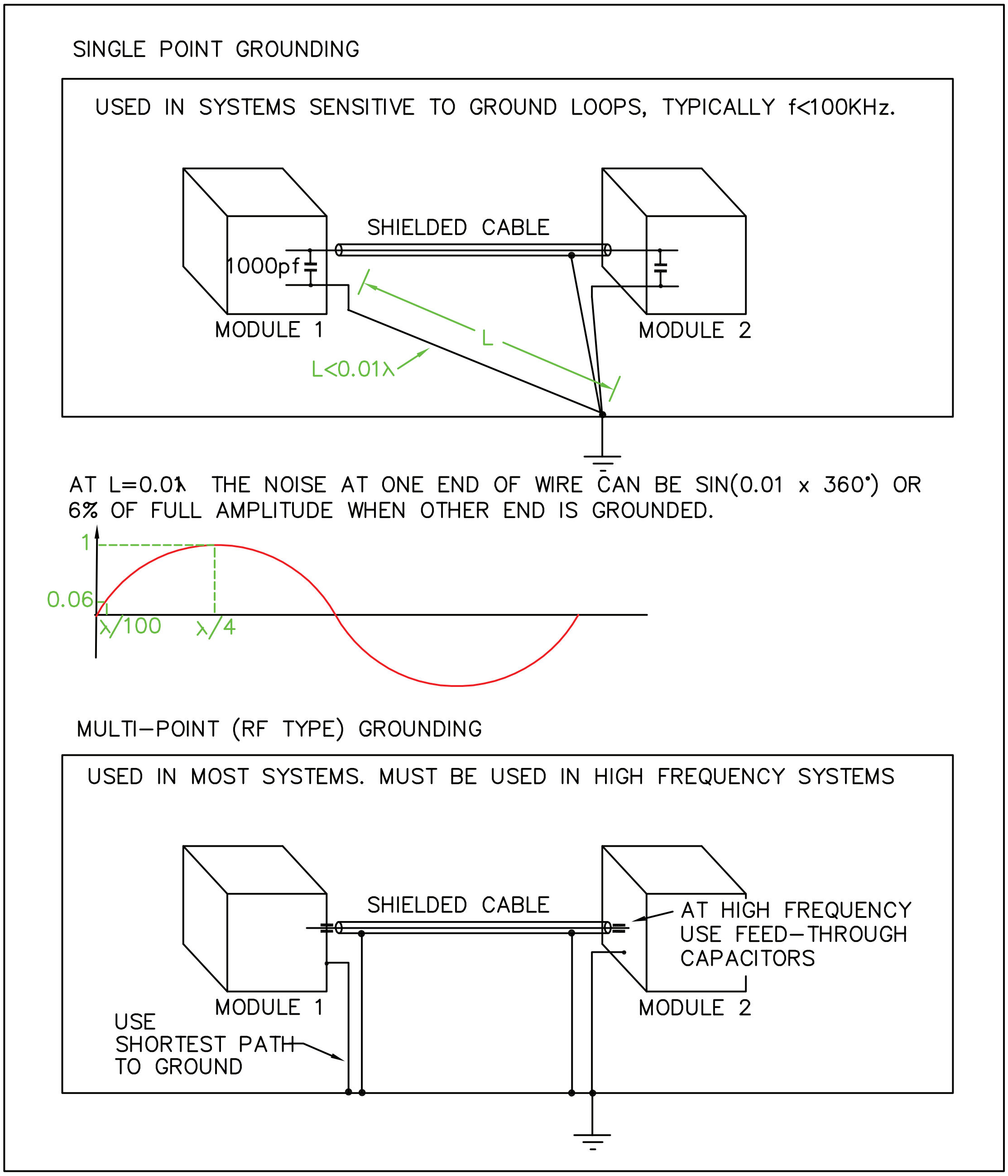
1. Slate. A common building material, used for roofs and floors. Sold in many shapes, including nicely ground 30x30x1cm tiles selling for about 1% of the price of machinable ceramics and available from stock in any city. Slate machines very well with all metalworking tools. It has a layered structure, with limited strength across the layers but very good strength parallel to them. (300-400 Kg/cm2, comparable to machinable ceramics). Slate can withstand substantial temperatures (about 1000^0C) but tends to delaminate into layers. This can be taken into account in the design. A part cut on a water jet cutter from a slate tile is shown here:



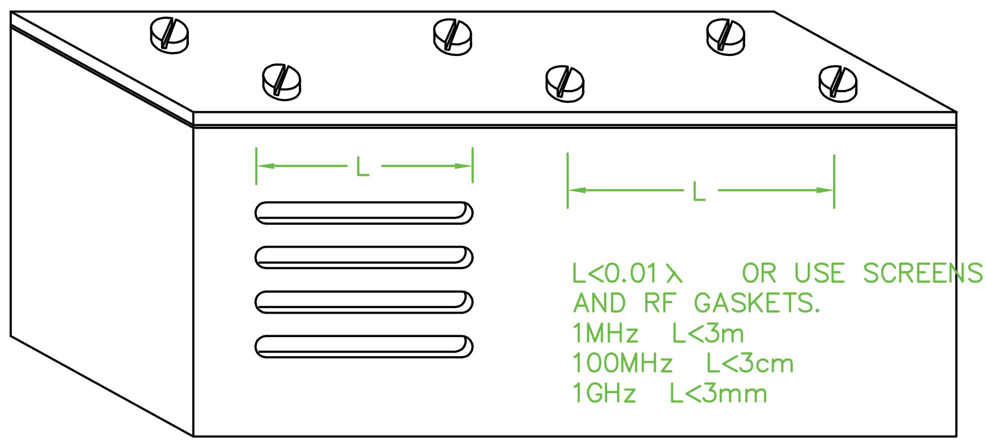
2. Plaster of Paris (Gypsum). This is the same material Drywall walls are made off. It is fairly soft but withstands temperature well (at least up to 1000^0C). It is available at art supply stores. The biggest advantage of the material is that it can be cast, and will copy the finest details, in very simple molds. Molds can be made of wood, cardboard, plastic, metal etc. It cures very rapidly (minutes to solidify+ a few hours of drying). It is easily machined after hardening. Its main disadvantage, beside softness, is being brittle and susceptible to fractures. This can be greatly improved by mixing it with fibers (ceramic fibers such as mineral wool are a good choice), or by embedding metal screens in the mold, as shown below.



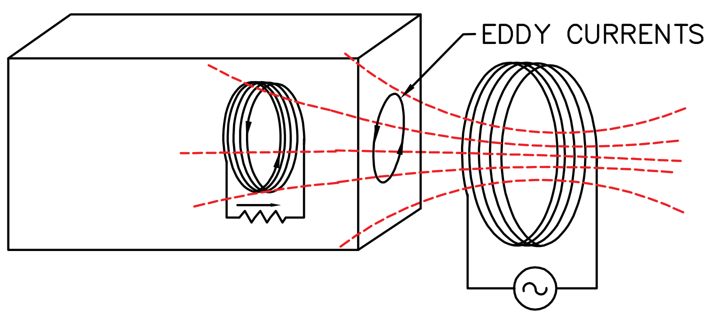
6. Electrical considerations



SHIELDING

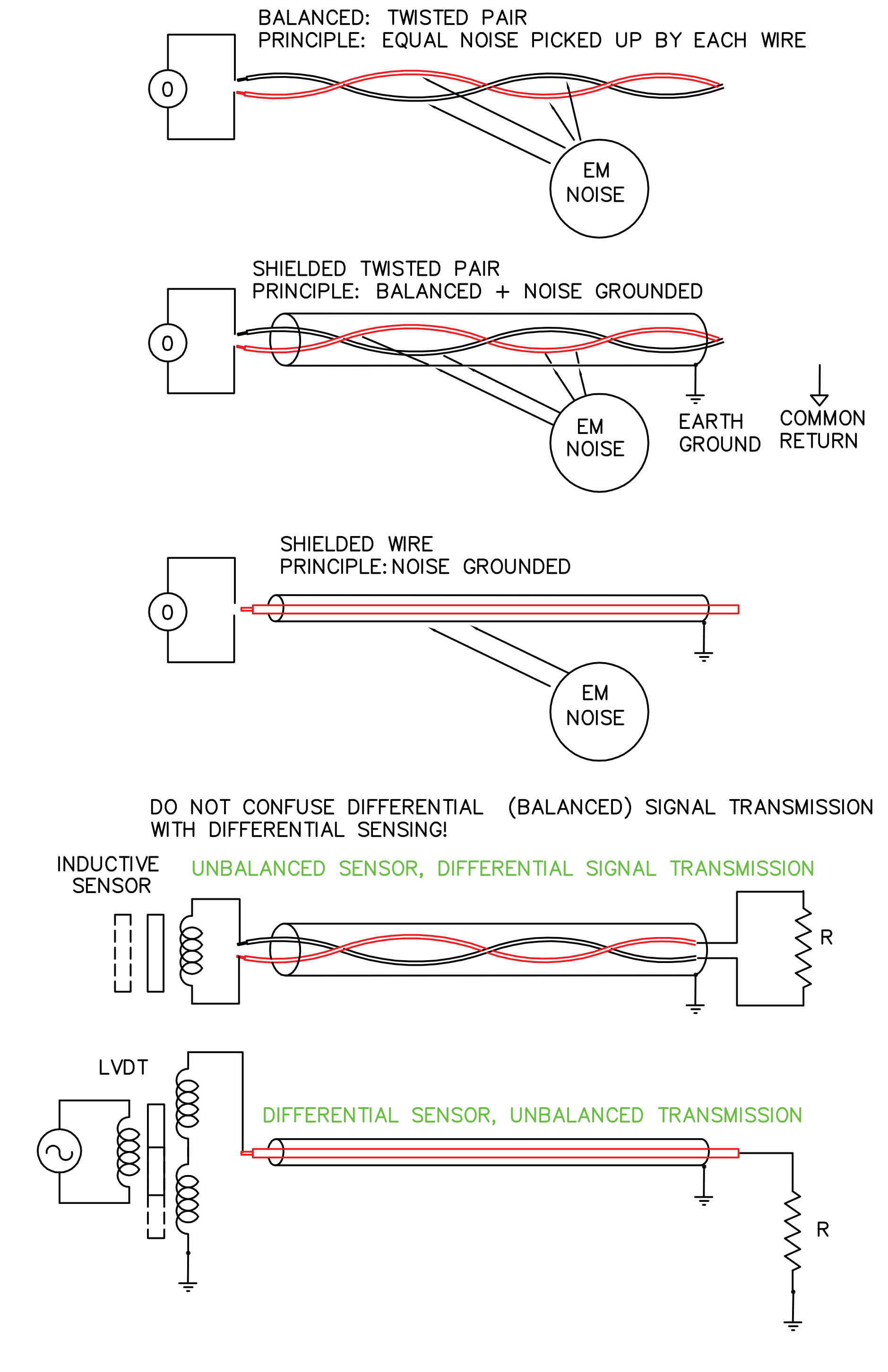


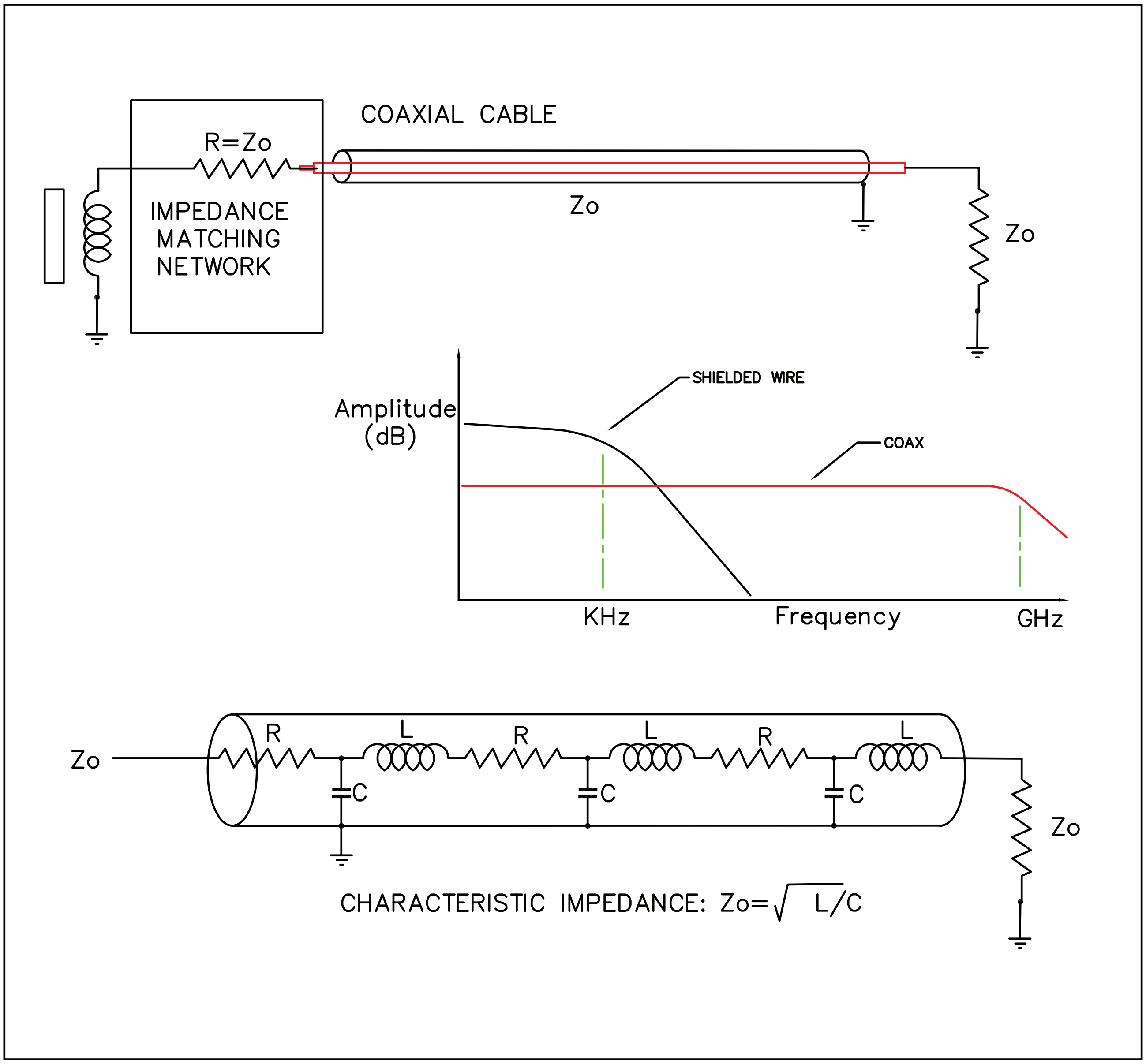
SURPRISING FACT:
VERY THIN METAL ENCLOSURES ONLY PROVIDE ELECTROSTATIC SHIELDING, DO NOT BLOCK ELECTROMAGNETIC FIELDS.



INDUCED EDDY CURRENTS ARE TOO LOW TO GENERATE AN OPPOSITE FIELD.

SIGNAL TRASMISSION





COAXIAL CABLE
R=Zo
IMPEDANCE
MATCHING
NETWORK
Zo
Zo
Amplitude
(dB)
SHIELDED WIRE
COAX
KHz
Frequency
GHz
Zo
R
L
R
L
R
L
C
C
C
Zo
CHARACTERISTIC IMPEDANCE: Zo=√ L/C