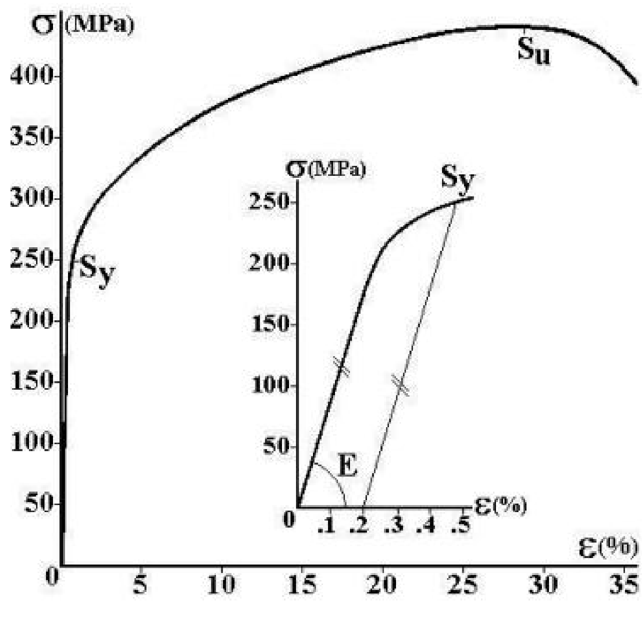
# Materials

The choice of structural materials is an important step to guarantee the robot's resistance without going over its weight limit. It is not a simple task to choose among the almost 100 thousand materials available, and for that it is necessary to know their mechanical properties.

## Mechanical Properties

Mechanical properties quantify the several responses of a material to the loads it bears. These loads generate stresses, denominated σ, usually measured in MPa (units similar to pressure, 1MPa = $10^6$Pa = 1N/mm$^2$). In English units, 1MPa is equivalent to 0.145ksi, where ksi stands for kilo pound-force per square inch (1 ksi = 1,000psi). For a uniform tensile stress distribution, stresses can be defined as the applied force divided by the material cross section area. These stresses also generate strains, denominated ε, which are a measure of deformation, of how much the material is elongated or contracted. The main mechanical properties can be obtained from the stress-strain curve.

The small graph to the center of the figure to the right shows the stress-strain curve of a material under small ε – in the example, smaller than 0.5% (it is the same graph as the large one, but zoomed in the region close to the origin). Note that, initially, the material has linear elastic behavior, in other words, the dependence between σ and ε can be represented using a straight line. The material stiffness is quantified by the modulus of elasticity E, or **Young modulus**, which is equal to the slope of this straight line (see figure). The larger the slope, the more rigid the material is.

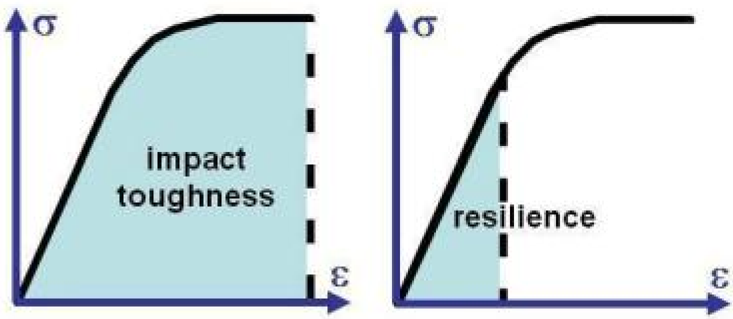


When applying increasingly larger loads, the plotted curve becomes no longer straight, becoming curved. This happens when the material begins to yield, which means it suffers permanent plastic deformations. When the stress reaches the **yield strength** Sy, the material already has 0.2% of permanent (plastic) deformation. In the previous graph, Sy is equal to 250MPa.

Looking now at the larger graph in the figure, note that the material continues yielding until the stress reaches a maximum value Su, known as the **ultimate strength**, after which the material breaks (in the above example, Su is about 450MPa). The **fracture strain**, εf, is the maximum strain that the material can tolerate before breaking. Beware that, although related, there are subtle differences between fracture strain and **ductility**. Ductility is the material capacity to plastically deform without breaking, while the fracture strain includes both elastic and plastic deformation components. So, if a material is ductile, then it has a high εf, but the opposite is not necessarily true: brittle tool steels can achieve a high purely elastic εf with almost no ductility.

The stress-strain curve is measured in slow traction tests. Therefore, Su measures the material resistance to static loads. The resistance to dynamic loads is measured by two other properties of interest: **impact toughness** and **resilience**. Both measure the resistance of the material to impacts. But the impact toughness measures how much impact energy the material absorbs before *breaking*, while the resilience measures such energy before it *starts to yield* (plastically deform).

The impact toughness depends not only on the material strength, but also on its fracture strain. The more it can deform while resisting to high stresses, the more impact energy it can absorb. This is why it is possible to estimate the impact toughness from the area below the entire stress-strain curve (as pictured to the right). Higher values of Su end εf result in a larger area under the entire curve, resulting in a higher impact toughness. The resilience can also be estimated from the area below the curve, but only in the linear elastic region,




where the stresses are below Sy (see figure above). That area is approximated by $Sy^2/2E$. But a tough material is not necessarily resilient, and vice-versa. For instance, the stainless steel (AS) type 304, the most used SS, tolerates large deformations but it is easily yielded. Therefore, it is very tough (because of the large εf), being good for armor plates that can be deformed. However, it has low resilience (because its Sy is low), and thus it should not be used in shafts (which should not get bent or distort) or in wedges (because if their edges are bent or nicked they lose functionality).

On the other hand, the steel from a drill bit, for instance, is very hard, it has a very high yield strength Sy, and thus it has high resilience.However, its εf is small and therefore its impact toughness is low.This is why drill bits do not make good weapons for combat robots,because they easily break due to impacts. Titanium is an excellent choice for use in combat robots because it is very tough(good for armor) and resilient(good for wedges) at the same time, as it will be discussed.

**Fracture toughness**, KIc (pronounced "kay-one-see"), is the resistance of the material to the propagation of cracks. It is measured in cracked specimens, under static loads that are slowly increased until the material fractures (breaks). KIc is measured using the unusual units $MPa\sqrt{m}$ or $ksi\sqrt{in}$. The higher the KIc of the material of an already cracked component, the higher the stresses it can withstand before fracturing. In most metals, it is observed that the impact toughness is very much related to the fracture toughness, even though the first is measured in dynamic and the other in static tests. More specifically, several experiments suggest that the impact toughness is directly proportional to $KIc^2 / E$, where E is the Young modulus. However, this is not always true for non-metals. Lexan, for instance, has a relatively high impact toughness for a polymer if cracks are not present. However, its fracture toughness is low, easily propagating cracks once they are initiated, usually around holes, which concentrate stresses.

Note that fracture toughness must be measured for very thick specimens to be called KIc. This is because fracture toughness has some thickness dependence, thinner plates can deform more easily and absorb more energy per volume than thick plates. It is found that the apparent fracture toughness of a very thin plate can reach up to twice the value of KIc. So, when searching for fracture toughness data, make sure you're getting KIc from thick specimen tests, and not a higher apparent value that cannot be compared to the KIc of other materials.

Finally, the **hardness** of a material is the resistance to penetration by other harder materials. If we press a very hard material (for instance the tip of a diamond) onto the surface of a softer one, the softer one will become dented. The larger and deeper the dent, the softer the material is. A very common hardness unit for hard metals is Rockwell C (HRc). The larger the value, the harder the material is. Another common hardness unit is Brinell (HB), measured in $kg/mm^2$. A conversion table between HRc and HB hardnesses can be found in Appendix A.

In general, among metals from the same family (such as among steels), the ones with higher hardness tend to have proportionally higher Su. For instance, you can estimate within a few percent Su ≅ 3.4 · HB for steels, where HB is in $kg/mm^2$ and Su is in MPa. This estimate is very useful in practice, because hardness tests are non-destructive and very fast to perform. For steels, this estimate is so good, with a low dispersion, that its coefficient of variation CV is less than 4%. Aerospace aluminum alloys have a relatively good correlation, Su ≅ 3.75 · HB, with CV = 6%. There are also estimates for other alloys, but the results have higher scatter (as seen from their higher CV). For instance, aluminum alloys from the 6000 series (such as 6061) have Su ≅ 3.75 · HB (CV = 12%), titanium alloys have Su ≅ 3 · HB (CV = 16%), and magnesium alloys have Su ≅ 4.2 · HB (CV = 20%). These estimates are very good for quick calculations, but use them at your own risk.

Among all the properties presented above, the most important ones in combat robots, as well as in most engineering applications, are without a doubt the impact and fracture toughnesses. Robots need to tolerate impacts and cracks without breaking.

Once having presented the main mechanical properties, we can analyze the main materials used in combat robot construction, as follows.

## Steels and Cast Irons

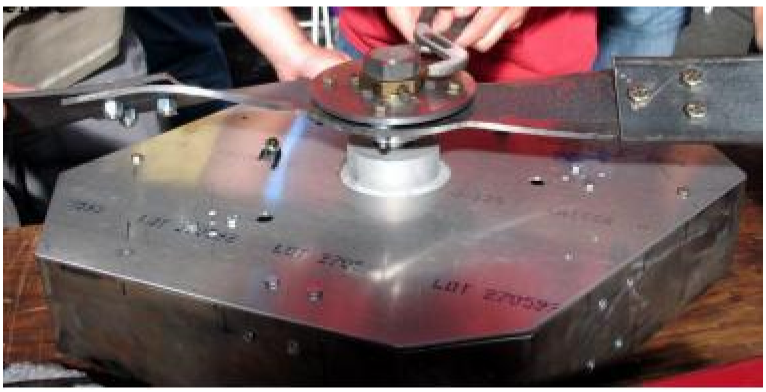
Steels are metals composed basically of iron and of some other (in general few) alloy elements. Depending on the type, they can be extremely resistant, however their high density would make an all-steel robot very heavy. The density of steels does not vary much, between 7.7 and 8.0, with average 7.8 (which means 7.8 times the density of water, or 7.8kg per liter of the material).

Their stiffness also varies very little, around E ≅ 200GPa (notice that 1GPa = 1000MPa). This means, for instance, that to deform a piece of any steel in 0.1% it would be necessary to apply a stress of 200GPa × 0.001 = 0.2GPa = 200MPa (29ksi), the equivalent to a force of 200N for each $mm^2$ of cross section of the material. On the other hand, the strengths of steels can vary a lot: the best steels get to be 10 times more resistant than low strength ones, therefore it is important to know them very well.

Low strength steels are ready to be used soon after being machined. However, many steels need to go through heat treatment (HT) after machining to reach high strengths. For instance, in steels, the HT consists of heating up the material to a high temperature (typically 800 to 900$^{O}$C, or 1472 to 1652$^{O}$F, but it varies a lot with the steel type) and cooling it in water, oil, powder or even air (the quenching process), and later heating it up for a few hours in a not so high temperature (typically 200 to 600$^{O}$C, or 392 to 1112$^{O}$F, the temper process). HT can be performed in your shop with just a torch and water or oil, however specialized companies are recommended for a better result with larger reliability in the resulting mechanical properties. It may cost around US$50 to heat treat a small batch of the same material.

The following are a few of the main types of steel used in combat robots.

- **1018 steel, 1020 steel**: they are mild steels, they have low carbon content, about 0.18% to 0.20% in weight respectively. They have low strength, but they are easily conformed, machined, and welded. They're usually used in shafts and in a variety of components. They are used in the robot structure due to their low cost, however their low yield strength Sy makes them easily bendable (therefore avoid using them in spinning weapon components that need to be well balanced, as pictured to the right). HT only gets to increase the strength and hardness of the surface of those low carbon materials, their interior continues with low strength.




- **1045 steel**: steel with medium carbon content (0.45%), it is used when larger strength and hardness are desired. It is used in high-speed applications, gears, shafts and machine parts. It is a cheap solution for the robot shafts, however it needs HT after machining.

- **1095 steel**: steel alloy with high carbon content (0.95%), with hardness and strength elevated after HT. It tends to be brittle, with low impact toughness. It is typically used in springs or cutting tools that require sharp cutting edges.

- **4130 steel**: steel with 0.30% carbon, with addition of chrome and molybdenum (also called chromoly) to increase strength. The low carbon content makes them a good choice for welding, allowing robots to have their structure formed by 4130 bars and tubes, which are welded together and then heat treated to reach great strengths.

- **4340 steel**: steel with 0.40% of carbon, with nickel in addition to chrome and molybdenum (chromoly), with even higher strength and impact toughness after HT than 4130 or 4140 (4140 is equivalent to 4130 but with 0.40% carbon). The typical applications are for structural use, such as components of the landing gear of airplanes, gears for power transmission, shafts and other structural parts. It is an excellent material for shafts, the weapon shaft of our middleweight spinner *Ciclone* is all made out of tempered 4340 steel. To reach high impact toughness, HT the 4340 in a way to leave it with final hardness between 40 and 43 Rockwell C – much more than that and the shaft becomes brittle, breaking under a severe impact, and much less than that will allow the shaft to easily yield. Our recipe for 4340 steel is to heat it up and keep it at 850°C (1562°F) for 30 minutes, quench in oil until reaching 65$^{O}$C (149°F) (important: in the case of shafts, dip it in vertically to avoid distortions), and soon afterwards temper at 480°C (896°F) for 2 hours.

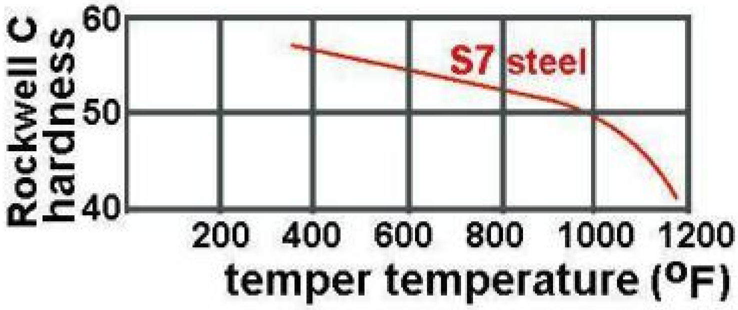
- **AR400 steel**: high hardness steel once used in the wedge of the famous middleweight Devil's Plunger, until it was replaced with titanium. AR stands for abrasion resistant, and 400 is its Brinell hardness. AR400 has almost the same mechanical properties as 4340 steel hardened to 43 Rockwell C, which is equivalent to 400 Brinell. It is also known as Hardox AR400 steel.

- **5160 steel**: steel with 0.60% of carbon, it contains chrome and manganese. Called spring steel, it has excellent impact toughness. It is usually used in heavy applications for springs, especially in the automotive area, such as leaf springs for truck suspension systems. The spinning bars of our middleweights *Ciclone* and Titan are made out of heat treated 5160 leaf springs. Be careful with the HT, the harder it gets, the lower the impact toughness – during the RoboCore Winter Challenge 2005 competition, *Ciclone*'s spinning bar was severely HT to reach a 53 Rockwell C hardness, so hard that it broke against the rammer *Panela* due to the reduced impact toughness. After that, we changed the HT without having any problems. The ideal hardness for 5160 steel in combat applications is between 44 and 46 Rockwell C, this is what we use now for *Ciclone* and Titan. Our recipe is to heat it up and keep it at 860°C (1580°F) for 30 minutes, quench in oil until reaching 65$^{O}$C (149°F) (important: in the case of spinner bars, dip it in horizontally to keep any spring-back effects symmetrical, preventing unbalancing effects), and soon afterwards temper at 480°C (896°F) for 2 hours.

- **stainless steels**: they are steels with more than 12% in weight of chrome, which forms a protective film that prevents corrosion. There are 60 types of stainless steel (SS), the most used one is the SS type 304, also called 18-8 for having 18% of chrome and 8% of nickel. It has an excellent combination of impact toughness and resistance to corrosion, and it doesn't need to be HT. SS 304 is a good material for the robot armor (despite being heavy) because, besides being very tough, it increasingly hardens after suffering impacts and deformations. However, SS 304 is easily deformed, making its resilience low, therefore avoid using it in parts that significantly lose functionality if bent or distorted such as shafts. There are other SS with higher resilience, they are the martensitic SS, the most famous of them are the types 410, 420 and 440: they need to be HT, after which they reach high Sy and Su, however their impact toughness is usually much lower than the one from 304. High end stainless steels are the precipitation hardened (PH) types, such as 17-7PH and 15-5PH, which are necessary mostly in high temperature applications.

- **tool steels**: tool steels can reach very high hardness values after HT. They are used to make tools and metal dies, however most of them have low impact toughness. The exceptions are the tool steels from the S series (S meaning Shock), which have a high impact toughness in addition to hardness, to be used in chisels, hammers, stamping dies, and applications with repetitive impacts. The S1 and S7 steels are the most used tool steels in combat robots, respectively in Brazil and in the US. They are mainly used in the weapon parts that get in contact with the opponent. The teeth from *Touro*'s drum are made out of S7 steel, as well as the spinning blade of the middleweight Hazard, pictured to the right. They are not too expensive, S1 steel can be found in Brazil for about US$13/kg (almost US$6/lb), while S7 steel can be found in the US at, for instance, www.mcmaster.com. Our recipe for S7 steel is to pre-heat up to 760°C (1400°F), equalize the temperature throughout the entire piece, continue heating up and keep it at 950°C (1742°F) for 30 minutes, then quench in oil (S7 can also be quenched in air, which is good to avoid warping due to the thermal shock with the oil) until $65^{O}$C (149°F), and immediately temper at a certain temperature for 2 hours. After cooling, it may be tempered again for 2 hours at the same temperature, what is

called a double temper, instead of a single one. The temper temperature depends on the desired hardness, see the graph to the right for single-tempered S7 steel: for a hardness value close to 60 HRc, use 392$^{O}$F (200$^{O}$C), while for values close to 52 HRc use 752$^{O}$F (400$^{O}$C). We've

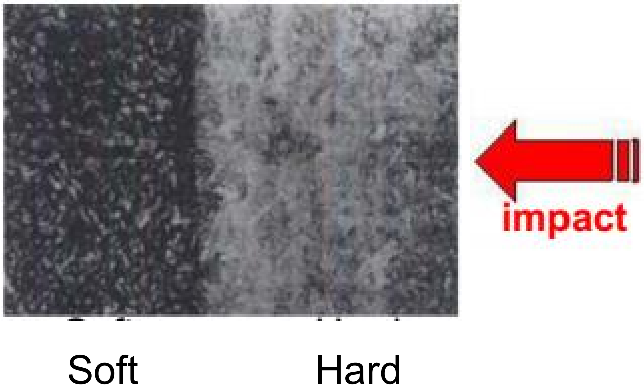



realized that there is a peak in impact toughness of the S7 steel at exactly 54 HRc, which can be achieved with a single temper with temperature around 600$^{O}$F (315 $^{O}$C). Impact tests performed on standard unnotched Charpy specimens made out of S7 at different tempers showed that they would absorb 309 J (Joules) of impact energy before breaking when at 54 HRc. "Nothing more, nothing less than 54 Rockwell C," as experienced builder Ray Billings once told us. This is because at either 56 or 52 HRc the absorbed energy drops to less than 245 J. This energy would rise back again beyond 300 J only for lower hardnesses, below 51 HRc (324 J for 50HRc and 358 J for 40HRc). Therefore, the best cost-benefit to have both impact toughness and hardness at high levels, to prevent the component from breaking while retaining its sharpness, is to use S7 steel at exactly 54 HRc. Not 55 HRc. Not 53 HRc.

- **AerMet steels**: it is a class of special high strength steels with high nickel and cobalt content, patented by the Carpenter company (www.cartech.com). There are 3 types with increasing hardness but decreasing toughness: AerMet 100, AerMet 310 and AerMet 340. The most famous of them, AerMet 100, is replacing older special nickel-cobalt steels such as AF1410 and HP-9-4-30. After HT it reaches hardnesses from 53 to 55 Rockwell C, with 2.15 times higher impact toughness than S7 steel. It is probably the metal with best ultimate strength and fracture toughness combination in the world at the present time, with Su = 1964MPa and KIc = 130MPa$\sqrt{m}$ (after HT). AirMet 100 is used in the lifting mechanism of the heavyweight BioHazard, enabling it to save weight using a compact 3/4" diameter shaft. It was also used in the output shaft of the 24V DeWalt Hammerdrill gearbox, as pictured to the right. As one would expect, it is very expensive, more than US$55/kg (US$25/lb) in the US. To obtain its best properties, heat it up to 885$^{O}$C (1625$^{O}$F) for 1 hour, cool to 66$^{O}$C (150 $^{O}$F) in 1 to 2 hours using either oil quenching or air cooling, then refrigerate to −73$^{O}$C (−100$^{O}$F) and hold for 1h. Then heat at 482$^{O}$C (900$^{O}$F) for 5 hours, never below 468$^{O}$C (875$^{O}$F), and finally air cool.

- **maraging steels**: it is a class of special high strength nickel-cobalt-molybdenum steels with very low carbon content. There are four commercial types, all of them with 18% nickel: 18Ni(200), 18Ni(250), 18Ni(300) and 18Ni(350), with Sy equal to 1400, 1700, 2000 and 2450MPa, respectively, after HT. To obtain these Sy properties, heat to $900^{O}$C ($1650^{O}$F) and hold for at least 1 hour, air cool to room temperature, then heat for 3 hours at $482^{O}$C ($900^{O}$F), and finally air cool. The 18Ni(350) needs 12 hours (instead of 3) at $482^{O}$C. Together with the AerMet alloys, these are the best steels for high strength and high toughness applications, however they are also expensive, between US$42/kg (US$19/lb) and US$64/kg (US$29/lb) in the US, at www.onlinemetals.com. The 18Ni(200) can reach higher KIc than AerMet 100, but 24% lower Su. The 18Ni(250) is a reasonable replacement for AerMet 100, but with 10% lower Su and KIc. The 18Ni(350) is recommended for low impact applications because it has one third of the KIc of AerMet 100, but its Su can almost reach the incredible mark of 2500MPa.

- **K12 Dual Hardness steel**: it is an armor plate with dual hardness sold by Allegheny Ludlum, with a high hardness front side to break up or flatten incoming projectiles, and a lower hardness back side that captures the projectile. The front side has a higher carbon content, reaching 58 to 64 Rockwell C hardness after heat treatment, metallurgically bonded to a lower carbon back side that reaches 48 to 54 Rockwell C, as pictured in the cross section to the right. With the hard front side facing out of your robot, you'll be able to break up or chip any sharp edges from your opponent's weapon, while the inner "softer" side will provide high toughness and prevent fractures. A careful and precise heat treatment is required to achieve optimum performance.




- **cast irons**: they are basically steels with more than 2.5% of carbon content. The carbon excess ends up generating graphite inside the microstructure, which is very brittle (anyone who's used a pencil knows that). In combat robots they are used in bearing housings and in a few gears. Be careful with this material, it has a low impact toughness – the 2004 version of our spinner *Ciclone* used cast iron flanged housings (pictured to the right) to hold the bearings of its weapon shaft, however one of them cracked from its own impact against other robots. Luckily, it still resisted until the end of the competition, despite the cracks. Since 2005 we've stopped using cast iron housings, and started to embed the weapon shaft bearings into the aluminum plates of the robot structure. We haven't had cracking problems with bearing housings ever since.

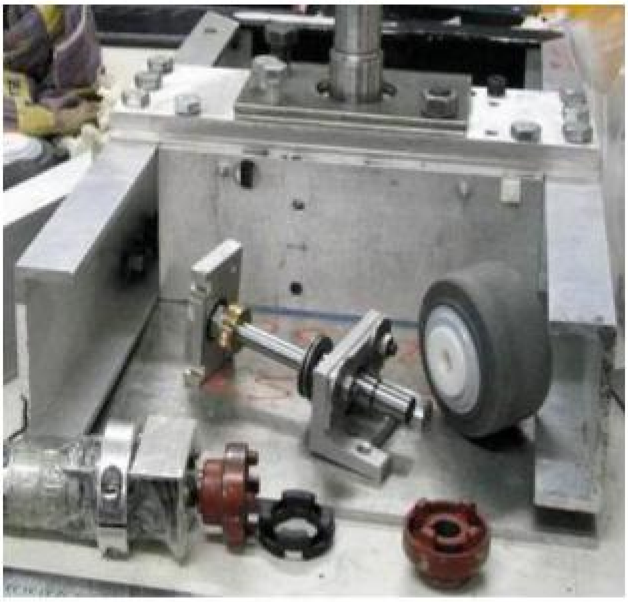
## Aluminum Alloys

Aluminum is a very light metal, it has about 1/3 of the density of steels, about 2.8, which makes it very attractive for the robot structure. Its stiffness is also around 1/3 of the one of steels, with a Young modulus E ≅ 70GPa. Many types of aluminum exist, usually denominated by a 4 digit number. The aluminum alloys from the 1000, 3000 and 5000 series (for instance the aluminum 1050, used in electric equipment, the 3003, used in kitchen utensils, and the 5052, resistant to sea corrosion) are low strength and should not be used in combat. Cast aluminum is even less resistant, and it should be avoided – the wheels of the 2004 version of our middleweight *Ciclone* were made out of cast aluminum and rubber, luckily they didn't break but they most likely would if hit by another spinner.

A few aluminum alloys from the 6000 series (such as the 6061-T6 and 6351-T6) have medium strength, becoming a reasonable choice for the robot structure. The alloys from the 2000 and 7000 series (such as the 2024-T3 and the 7075-T6) are called aerospace or aircraft aluminum due to their extensive use in aircrafts. With high Sy and Su, they are naturally the most expensive. The 7000 series alloys usually have higher Sy and Su than the 2000 series, but sometimes this comes along with a lower fracture toughness.

Aluminum alloys already come heat treated from factory, which saves us time and money when building a combot. Be careful with the denominations with the letter T, the number after it indicates which heat treatment was used: for instance, the aluminum 6061-T6 has much higher strength than 6061-T4, which suffered a different HT. The main types of aluminum alloys are discussed next.

· **6063-T5 aluminum**: it is the aluminum alloy used in almost all the architectural extrusions in the market, because it has high corrosion resistance, and it is relatively cheap. However, it has low strength, therefore avoid using it in the robot external structure. It can be used in the internal structural parts, to stiffen the robot or to support batteries. Because all aluminum alloys have roughly the same stiffness (due to their Young modulus always close to 70GPa), the 6063-T5 is as effective as any other more expensive aluminum alloy to stiffen the structure, its problem is just its low strength. Note that stiffness and strength are two different things: for instance, glass is much more rigid than Lexan (polycarbonate), however Lexan has a much higher ultimate tensile strength than glass. Several internal parts

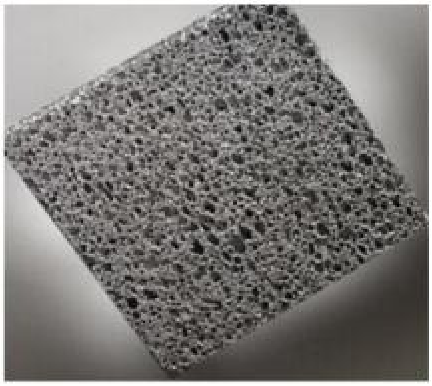


from our middleweight *Touro* are made out of 6063-T5 extrusions. Because it is difficult to find in Brazil C-channels or I-beams made out of structural aluminum such as 6061-T6, the side walls of our middleweight *Ciclone* ended up using 6063-T5 extrusions, as pictured to the right – but, to make up for that, they were reinforced with an outer layer of grade 5 titanium sheet. Depending on the quantity, 6063-T5 (or 6063-T52) costs between US$6 and US$13 per kg (between US$2.7 and US$5.9 per lb).

• **6061-T6 aluminum**: it is the most common structural aluminum alloy, used in several applications such as bicycle frames, structures, naval and truck components. It has medium strength, about twice the Su of 6063-T5, and it can also be welded. Compared to aerospace alloys, 6061-T6 has lower Sy and Su strengths, with a similar impact toughness. Its greatest advantage is its good weldability, much better than in most aerospace aluminum alloys. All the famous robots from Team Plumb Crazy are made out of 6061-T6 extrusions, as pictured to the right, as well as our hobbyweights *Tourinho* and *Puminha*. Extrusions can be found in the US, for instance, at Online Metals (www.onlinemetals.com).

• **5083-H131, 5086-H116, 5086-H32 aluminum**: despite their low yield strength, common to the marine alloys of the 5000 series, they have such a high impact and fracture toughness that they are used as armor plates in light weight military vehicles. They are good material candidates for very thick armor plates.

• **2024-T3, 7050-T7451, 7075-T6, 7075-T73, 7475-T7351 aluminum**: high strength aerospace alloys, with about 3 times the strength of 6063-T5. They are useful for structures that demand high strength-to-weight ratio, usually to manufacture truck wheels, fuselage of airplanes, screws, orthopedical belts, and rivets. They are the best commercially available aluminum alloys, in Brazil the 7050-T7451 and 7075-T6 cost around US$17/kg (almost US$8/lb). Considering that a middleweight with its entire structure made out of aluminum would need around 15kg (33lb) of this material, about US$250 would be enough to build it using the best aerospace alloys available, a good investment with a relatively low cost.



• 2324-T39 Type II, 2524-T3, 7039-T64, 7055-T74, 7055-T7751, 7085-T7651, 7150-T77, 7175-T736, 7178-T6 aluminum: high end aluminum alloys with improved mechanical properties over the traditional aerospace alloys. They are not readily available commercially.

• **Alusion** – very light aluminum foam (pictured to the right), available in several densities. Despite its low strength, it can be used as thick ablative armor plates mounted on top of the robot structure.

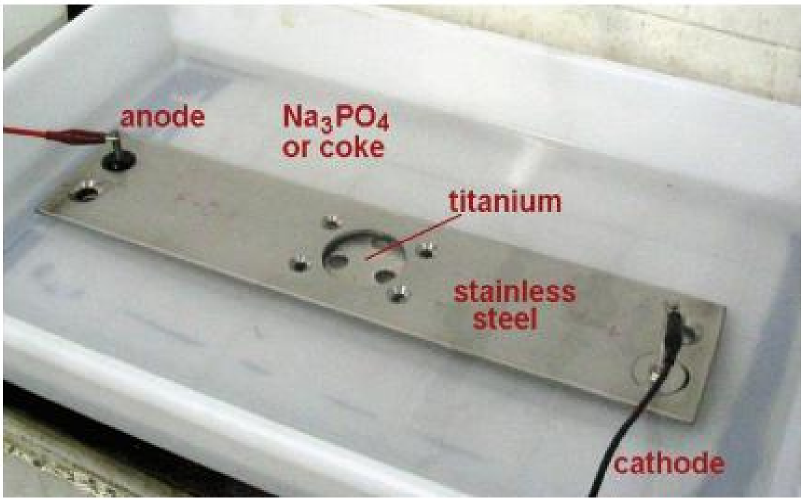
## Titanium Alloys

Titanium is one of the best materials for combat robots. With little more than half the density of steels (between 4.4 and 4.6), it reaches strengths 2.5 higher than 1020 steel. Or up to four times higher in a few military grade titanium alloys, making their strength-to-weight ratio so attractive that they're used in 42% of the F-22 fighter aircraft. Its Young modulus is E ≅ 110GPa, about half the one of steels. They are non-magnetic, non-toxic, and extremely resistant to corrosion, even in the presence of biological fluids, which explains their use in prosthetics and medical implants. Titanium generates beautiful white sparks when it is ground. Care should be taken with titanium chips from machining, they are flammable.

Titanium alloys are difficult to cut and drill. The secret to drill them is to use low spindle speeds in the drill and a lot of pressure on the part (always use a bench drill with them, never a manual one). And, most importantly, do not let the piece get hot, therefore use plenty of fluid. If there is heat build-up, titanium forms a thin oxide layer that is harder than the drill bit, and then several bits will be worn-out in the process. Use special cobalt drill bits to drill titanium, they will last longer. Practice is also important.

A curiosity about titanium (as well as niobium) is that its surface can be colored without paints or pigments, just using Coke (or Pepsi) in a technique called electrolysis or anodizing. The figure to the right shows an artistic painting made on a titanium plate. Note the range of colors that it is possible to obtain.

To color it, you need a piece of stainless steel (SS) with equal or larger area than the one of the titanium to be colored, a SS screw, a titanium screw, Coke, and a DC power source (of at least about 30V). The scheme is pictured to the right. Polish well the titanium surface and clean it with alcohol or acetone – do not leave any fingerprints. Place the titanium part (which will be the anode) and the SS one (the cathode) submerged in Coke (the electrolyte, which can also be replaced with Trisodium Phosphate Na3PO4), very close together but without making contact. Make sure the titanium screw is in contact with the titanium part to be colored but not with the SS plate (we used a rubber grommet to guarantee this, as shown in the picture), and the



AS screw only touches the SS piece. Connect the positive of the DC power source to the titanium screw and the negative to the SS one, without letting the wire contacts touch the electrolyte. Apply a certain DC voltage between 15 and 75V for a few seconds and it is done, the titanium part is colored!

A few of the colors that can be obtained are pictured to the right. The titanium color obtained by the electrolysis process depends on the applied voltage. The higher the voltage, the thicker will be the titanium oxide layer that is formed on the plate (anode), changing its color. This color change happens because the oxide layer causes diffraction of the light waves. The colors are gold (applying 15V), bronze (20V), purple (25V), blue-purple (30V), light blue (35V), white bluish (40 to 45V), white greenish (50V), light green (55V), yellow-greenish (60 to 65V), greenish gold (70V) and copper (75V). There are other colors up to 125V, but they are opaque, not very brilliant.

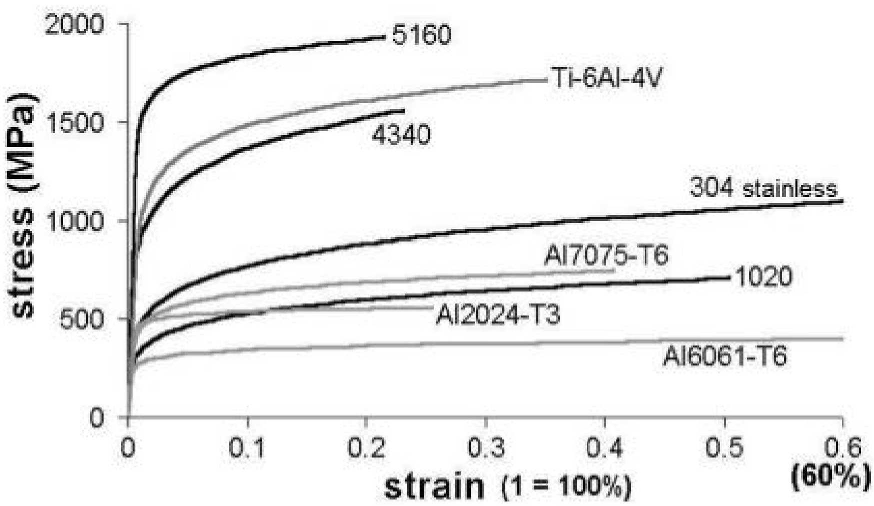
But the best option would be to use Trisodium Phosphate (Na3PO4, known as TSP), diluted at about 100 grams for each liter of distilled water (about 13oz/gallon). Besides being transparent (which allows you to see the colors as you increase the voltage), TSP is a detergent that helps to keep the titanium surface clean during the electrolysis, resulting


in a more uniform color. In the picture to the right you can see Titan's side walls, the top two plates before the process and the bottom one after being colored using TSP and 30V. Note the masking that we've used on the top plate, written TiTAN, made out of waterproof adhesive contact paper. The mask protects the region during electrolysis, leaving afterwards letters with the original color of the titanium (as it can be seen in "RioBotz" written on the bottom plate).

Commercially pure titanium, the most common of which is grade 2 titanium, has lower strength and higher density than aerospace aluminum, therefore it should not be used in combat robots. Use only high strength alloys such as grade 5 titanium, known as Ti-6Al-4V. Ti-6Al-4V has twice the strength of the best aerospace aluminum alloys and much higher impact toughness, with only 60% higher density. However, when welding grade 5 titanium, it is a good idea to use grade 2 as a filler material. This is because welds are prone to cracking due to thermally induced residual stresses, and grade 2 titanium filler, despite its lower strength, has a higher ductility that prevents such cracks and improves the overall impact and fracture toughness.

Ti-6Al-4V is also known as Ti-6-4, for having 6% aluminum and 4% vanadium in weight, mixed with 90% titanium. It is the most used high strength titanium alloy, combining excellent mechanical strengths and corrosion resistance with weldability. It is extensively used in the aerospace industry in a variety of applications in turbines and structural components up to 400$^{O}$C (752$^{O}$F). It can be heat treated (STA – Solution Treated and Aged), however the increase in ultimate strength is small, with the drawback of a 43% lower KIc. In practice, most combat robots use Ti-6-4 in the annealed condition, without further heat treating. It is usually available in the mill annealed condition. It can also be found in other two annealed conditions: recrystallization anneal (8% higher KIc) or beta anneal (33% higher KIc but much lower Su). Unfortunately, titanium grade 5 is expensive, about US$55/kg to US$80/kg (US$25/lb to US$36/lb). Notorious resellers are Titanium Joe ([www.titaniumjoe.com](www.titaniumjoe.com)), President Titanium ([www.presidenttitanium.com](www.presidenttitanium.com)), and Tico Titanium ([www.ticotitanium.com](www.ticotitanium.com)).

Ti-6-4 has an unbelievable impact and fracture toughness for its weight, we've used it in all side walls and bottom plate of our spinner Titan, as armor plates covering the aluminum walls of *Touro* and *Ciclone*, and in the wedges of Titan and *Puminha*. If you need an even higher fracture toughness, you could use the more expensive Ti-6Al-4V ELI (Extra Low Interstitial), which presents lower impurity limits than regular Ti-6Al-4V, especially oxygen and iron. The lower oxygen content increases the fracture toughness in 22% over mill annealed Ti-6Al-4V, however it lowers in about 10% the yield and ultimate strengths.




The graph to the right shows a comparison among steels, aluminum alloys and Ti-6Al-4V titanium used in combat robots, through their stress-strain curves. The curves stop at the strain where the material breaks. Remember that the higher the curve gets, the larger the Su strength to static loads until rupture. The farther the curve gets to the right, the higher the material can be plastically deformed before breaking, in other words, the higher their ductility and their εf. Note that the 7075 and 2024 aluminum alloys behave in a similar way to the 1020 steel (except for their lower impact toughness), however with only 1/3 of the weight. The stainless steel 304 has the largest area under the curve, resulting in a very high impact toughness, however it begins to yield under relatively low stresses.

## Magnesium Alloys

Magnesium is the third most used structural metal, after steels and aluminum alloys. The magnesium alloys ZK60A-T5 and AZ31B-H24 are excellent for the robot structure, because they have strength similar to 6061-T6 aluminum however with only 65% of its weight: the density of the magnesium alloys is only about 1.8, instead of 2.8 from aluminum. Their Young modulus is relatively low, E ≅ 45GPa, however their low density allows the use of very thick plates, resulting in very high stiffness-to-weight ratios. The impact toughness of the best magnesium alloys is similar to the one of high strength aluminum alloys.

The largest drawback of magnesium alloys is their extremely poor corrosion resistance: magnesium is in the highest anodic position on the galvanic series. Also, when tapping magnesium, choose coarse instead of fine threads to avoid stripping.

The ZK60A-T5 (US$62/kg or US$28/lb for small quantities) is the commercially available magnesium alloy with highest fracture toughness, however it is difficult to find large plates of that material. The alloy AZ31B-H24 (US$42/kg or US$19/lb for small quantities) is a little less resistant, but it is easier to find. The heavyweight lifter BioHazard has used these magnesium alloys to stay under the weight limit.

There are other magnesium alloys, such as Elektron WE43-T5 and Elektron 675-T5, however all of them have lower fracture toughness than ZK60A-T5 and AZ31B-H24. The new experimental alloy Elektron 675-T5, which was in its final stages of development in 2008, has the highest ultimate strength of all Mg alloys, Su = 410MPa.

Note that there are often misconceptions regarding the flammability of magnesium and its alloys. It may ignite when in a finely divided state such as powders, shavings from magnesium fire starters (pictured to the right), ribbon or machined chips, exposed to temperatures in excess of 445$^{o}$C (833$^{o}$F, the lowest Solidus temperature of all Mg alloys). However, in solid form, magnesium is very difficult to ignite. It has a high thermal conduction, quickly dissipating any localized heat. Also, most alloys self extinguish in the event of ignition, because of the oxide skin that forms over any molten alloy (in special in the presence of yttrium, such as in the two mentioned Elektron alloys). In practice, magnesium alloy ignition only happens due to sustained major fires (such as major fuel fires following an accident), similarly to aluminum ignition. The US Army is starting to use thick magnesium alloy plates as armor in its light weight vehicles, without any problems even during severe ballistic tests.

## Other Metals

A few other metals than can have structural application are:

- **copper alloys**: copper is an excellent electric conductor, and the bronze alloys (a copper alloy with, usually, tin) it generates are great for statues – but not for the structure of combat robots. Besides having lower strength than most steels, copper alloys are heavier, with density around 9.0. Bronze bushings (pictured to the right, showing the regular and flanged types), on the other hand, are a good option to be used as plain sleeve bearings in shafts for the wheels and weapons. The SAE 660 bronze,

  a.k.a. alloy 932, is hard, strong and nonporous, offering excellent resistance to shock loads and wear, it is the best option for sleeve bearings under high impact loads. Another option is the SAE 841 bronze, a.k.a. Oilite, a porous sintered material impregnated with roughly 18 percent SAE 30 oil – it is cheaper and it provides less friction than SAE 660, but it has lower strength and impact toughness. Brass (a copper alloy with zinc) also has low strength, but it is an excellent material for shim stock (pictured to the right), to be inserted in between parts to avoid slacks.

- **nickel superalloys**: they are a little heavier than steels, and they only present advantages if used at very high temperatures. The best superalloys can retain their high strength even at up to 80% of their melting temperatures. They can easily work at temperatures between 700 and $1000^{O}$C (1292 to $1832^{O}$F), which is great for components inside jet engines, but useless for combat, unless the competition is held in Venus or Mercury.

- **beryllium alloys**: theoretically, they are by far the best metals in the world to make a light and rigid structure. A few alloys such as the S-200 have Young modulus E = 303GPa (more than 4 times the stiffness of aluminum alloys) with density lower than 1.9. They find applications in nuclear reactors, inertial guidance instruments, computer parts, aircraft, and satellite structures. They would be a marvel in combat except for three problems: they are relatively brittle; beryllium must be processed using powder metallurgy technology, which is costly; and beryllium powder and dust, which can be released during the machining process, as well as in the wear and tear during combat, is highly toxic and cancerous. Because of that, competitions usually forbid their use. Do not use it, berylliosis disease can kill you. A curious fact is that beryllium and its salts taste sweet. Early researchers (who are not among us anymore) used to taste beryllium for sweetness to verify its presence. This is why it used to be called glucinium, the Greek word for sweet. Do not taste it, just take my word that it is sweet.

- **tungsten alloys**: very high density alloys, their application in combat robots is mainly for counterweights of spinning weapons. Tungsten, meaning "heavy stone" in Swedish, has in its pure form an amazing 19.35 density, with the highest melting point at atmospheric pressure among metals (3,422°C or 6,192°F), losing only to diamond's 3,547°C (or 6,416°F). It has also the lowest coefficient of thermal expansion of any pure metal. In its raw state, it is brittle and hard to work. However, when alloyed with 3% to 10% of nickel, copper and/or iron, it becomes relatively tough, extremely machinable, and it reaches

ultimate strengths Su between 758MPa and 848MPa. Their machining properties are similar to gray cast iron These tough high density alloys are known as ASTM-B-777-07 or Densalloy, with 4 different classes: class 1 (or HD17, with 90% tungsten, and a density of 17), class 2 (HD17.5, 92.5% tungsten, 17.5 density), class 3 (HD18, 95% tungsten, 18 density) and class 4 (HD18, 97% tungsten, 18.5 density). They can be found, for instance, at www.mi-techmetals.com, www.marketech-tungsten.com or www.hogenindustries.com, with a typical price between US$50 and US$100 per pound for special orders in small quantities. Small inexpensive tungsten weights can be found at www.maximum-velocity.com.

- **other high density alloys**: besides tungsten, there are several other high density alloys, however they're all extremely expensive. They usually have low strength, low toughness, or they are too dangerous to use in combat. The most famous high density materials are tantalum (with density 16.65 and reasonable mechanical properties with Su greater than 450MPa), depleted uranium (density 18.95, reasonable Su between 615MPa and 740MPa, toxic, used in tank armor and armor-piercing projectiles), gold (density 19.32, ductile but with low strength due to Su = 120MPa), rhenium (density 21.04, good mechanical properties, Su = 1070MPa), platinum (density 21.45, Su = 143MPa, low strength), iridium (density 22.4, Su = 1000MPa, brittle), and osmium (the material with highest density, 22.6, about twice the density of pure lead, with Su = 1000MPa, very brittle and toxic).

- **metallic glasses**: they are amorphous metals, which have a disordered atomic-scale structure similar to common glasses, in contrast to most metals, which are crystalline with a highly ordered arrangement of atoms. They can be produced from the liquid state by a cooling process so fast that the atoms don't have time to organize themselves as crystals. They usually contain several different elements, often a dozen or more, causing a "confusion effect" where the several different sized atoms cannot coordinate themselves into crystals. Also, they don't have a melting point. Instead, they become increasingly malleable as the temperature increases, just like most plastics, making them good candidates for injection molding. Liquidmetal is a company that sells glassy metals such as Vitreloy, an alloy with mostly zirconium and titanium that reaches Sy = 1,723MPa, nearly twice the strength of Ti-6Al-4V. But since the atoms are "locked in" in their amorphous arrangements, most currently available glassy metals cannot plastically deform at room temperature, resulting in low impact strength, which limits their use in combat. They also have a coefficient of restitution close to 1, meaning almost perfectly elastic impacts. In 2004 the first iron-based metallic glass was created, called "glassy steel," with very high strength.

## Non-Metals

Several non-metals need to be mentioned in combat robot design. The main ones are:

- **polycarbonate:** also known as Lexan, it is a polymeric thermoplastic (which softens and melts when heated, instead of burning), transparent to light waves and radio-control signals. It has high impact toughness, and it is very light, with density 1.2. It is used in combat robot armor, it absorbs a lot of energy as it is deformed during an impact. In spite of that, fewer and fewer robots have been using this material, because of its disadvantages: it has very low Young modulus (E = 2.2GPa, about 1% of the stiffness of steels, making the robot structure very flexible even for high thicknesses), it easily cracks (the cracks usually appear starting from the holes, and they propagate without absorbing much of the impact energy), and it is easily cut (becoming vulnerable to sawbots). To avoid cracking, chamfer all holes to remove sharp corners and edges, and provide the Lexan support with some damping, for instance using a thin layer of rubber or neoprene. Avoid tapping Lexan, if you must do it then guarantee that the hole is tapped very deeply with several threads, or else they might break. Never use threadlockers such as Loctite 242 in Lexan, because besides not locking, it causes a chemical reaction that makes it brittle. Acetone should also be avoided.

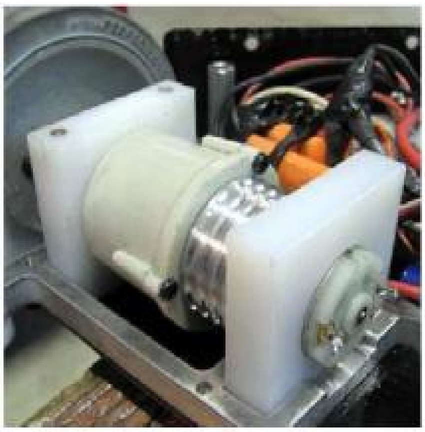
  Very thin sheets of Lexan make great drilling templates for top and bottom covers of the robot. This classic technique is very simple: once all the robot walls are finished and assembled, firmly attach the Lexan sheet on top of it, as if it were a robot cover. Since Lexan is transparent, it is easy to mark with a center punch the centers of the holes to be drilled, which must align with the already finished holes from the walls. If the Lexan sheet is very thin, it will bend as a cone into the holes from the walls as it is pressed by the center punch, improving the centering precision. After marking all hole centers, the Lexan sheet is ready to be fixed on top of the actual cover plates to be drilled.

- **acrylic**: good to build fish tanks, but do not use it in combat, because it has the same density as Lexan but with 20 to 35 times less impact toughness.

- **PETG**: it is a modified type of PET (polyethylene terephthalate) with an impact toughness in between the values for acrylic and Lexan. It is a cheap substitute for Lexan, but with worse properties. We've tried it in combat, and decided that it would be better used to make a nice transparent trophy shelf.

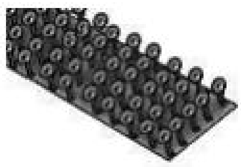
- **Teflon (PTFE, politetrafluorethilene)**: very low friction, it can be used as a sliding bearing for moderate loads, or as a skid under the robot to slide in the arena. Its main problem is its high cost.

- **UHMW**: Ultra High Molecular Weight polyethylene is a high density polyethylene that also has very low friction. Known as the "poor man's Teflon," it doesn't slide as well as Teflon, but it is cheap and it has higher strength. Shell spinners, such as Megabyte, use internal spacers made out of UHMW (circled in red in the picture to the right) between the shell and the inner robot structure, guaranteeing that the shell won't hit the internal metal parts of the robot even if it is bent, allowing it to slide with relatively low friction in case it makes contact. The high toughness of UHMW makes it a good choice even for structural parts, such as the motor mounts of the hobbyweight Fiasco, as pictured to the right.



- **nylon, delrin (acetal):** they are thermoplastic polymers with high strength, low density and relatively high toughness. They are good for internal spacers in the robots, and even as motor mounts, similarly to UHMW.

- **rubber, neoprene, hook-and-loop (velcro)**: excellent materials to dampen the robot's critical internal components, such as receiver, electronics and batteries. High-strength mushroom-head hook-and-loop (pictured to the right) is also excellent to hold light components.



- **epoxy**: excellent adhesive, good to glue fiberglass, Kevlar and carbon fiber onto metals. Clean the metal part with alcohol or acetone before applying it, to maximize holding strength. Always use professional epoxy, which cures in 24 hours, not the hobby grade.

- **phenolic laminate**: it is an industrial laminate, very hard and dense, made by applying heat and pressure in cellulose layers impregnated with phenolic synthetic resins, agglomerating them as a solid and compact mass. Also known as celeron, it is an excellent electric insulator. We mount all the electronics of our robots on such laminates, which are then shock-mounted to the robot structure using vibration-damping mounts (see chapter 4) or mushroom-head

hook-and-loop, resulting in electrical insulation as well. The regular phenolic laminates are relatively brittle, but a high strength version called garolite (available at www.mcmaster.com) has already been used even in the structure of antweights and beetleweights. The top cover of our beetleweight *Mini-Touro* was made out of garolite, however it was replaced with a titanium cover with same weight. Although thinner, the titanium top cover has a higher impact strength than the garolite version, which is important when facing offset horizontal spinners that know how to skillfully pop a wheelie to deliver an overhead attack with their weapon. The first prototype of our hobbyweight *Tourinho* was made out of garolite (a green variety for the side walls and a black one for the top and bottom covers, as pictured to the right), transparent to radio signals and very resistant. However, we ended up changing it to aluminum for two reasons the threads tapped in garolite, or in any other phenolic laminate, are brittle and easily break, and the better impact toughness of aluminum made up for its increased density (aluminum has density 2.8, and garolite 1.8).

- **wood**: it has low impact toughness if compared to metals. It should not be used in the structure, unless your robot is very skillfully driven, such as the wooden lightweight The Brown Note, which got the silver medal at Robogames 2008 after losing to the vertical spinner K2 (pictured to the right). A few builders have mounted wooden bumpers in front of their robot when facing spinners, to work as ablative armor: while a shell spinner chews up the wooden bumper of its opponent little by little, it loses kinetic energy and slows down, becoming vulnerable.

- **ceramics**: they are very brittle under traction, but under compression they are the most resistant materials in the world, so much that they are used underneath the armor plates of war tanks: the ceramic breaks up the projectiles, while their fragments are stopped by an inner steel layer. Ceramics are also extremely resistant to abrasion. The famous lifter BioHazard used 4" square 0.06" thick alumina tiles ($Al_2O_3$, which forms sapphires when in pure form) glued under its bottom to protect it against circular saws that emerged from the BattleBots floor.

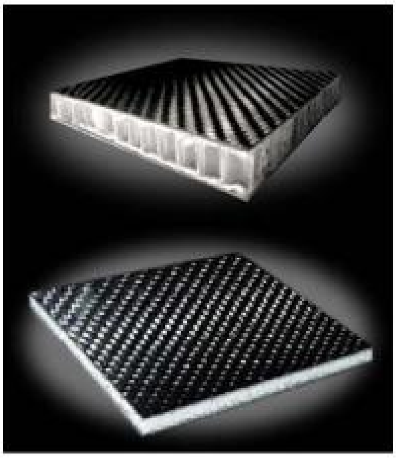
- **fiberglass**: known as GFRP (glass fiber reinforced polymer), it is made out of very thin glass fibers held together by a polymeric adhesive (known as the polymer matrix) such as an epoxy resin. It is very used in boats. It has potential use in the robot structure for being rigid and light, however its impact toughness is low if compared with the one of most metals.

- **Kevlar**: known as KFRP (Kevlar fiber reinforced polymer), it is a yellow fabric (pictured to the right) made out of aramid fibers, a type of nylon, 5 times more resistant than steel fibers of same weight. Used in bulletproof vests, it has extraordinary impact toughness. *Touro* uses a Kevlar layer covered with professional epoxy (the polymer matrix) sandwiched between the aerospace aluminum walls of the structure and the external Ti-6Al-4V plates of the armor, to


increase its impact toughness. The fabric is very difficult to cut, it is recommended to use special shears, found at www.mcmaster.com. Kevlar fabric is not expensive, we've used less than US$12 in *Touro* – more specifically, we've used the aramid fabric KK475, which costs about US$60/m$^2$ (less than US$6/ft$^2$) in Brazil.

- **carbon fiber**: known as CFRP (carbon fiber reinforcedpolymer), and available in several colors (as pictured to the right), it is very expensive but extremely rigid and light, and because of that it has been used in racing cars and in the fuselage of the new Boeing 787 and AirBus A350 (pictured in the next page But it is a myth that carbon fiber has high impact toughness. It surely has a high strength under static loads, but it does not take severe impacts. The undercutter Utterly Offensive is a good example of that, its carbon fiber baseplate (pictured to the right) self-destructed when it was scraped by its own spinning blade. The plate was later switched to titanium. Carbon fiber is not a good armor material, unless it is combined with Kevlar to achieve high impact toughness. Surely you could get away without Kevlar, using a very thick carbon fiber armor plate, but probably the added weight would have been better employed using, for instance, a titanium armor.


- **other polymer matrix composites**: there are several other composites that use a polymer matrix (such as epoxy or polyester) besides plain GFRP, KFRP and CFRP. For instance, you can tailor lay-ups of aramid and carbon fibers, cured (bonded) together with a polymer matrix, to achieve optimum impact toughness (due to Kevlar) and stiffness (due to carbon). It is possible to generate complex unibody structures by combining several parts into a single cured assembly, reducing or even eliminating the need for fasteners, saving weight and assembly time. This unibody can be joined together in three ways: cocuring, cobonding, or adhesive bonding. In cocuring, the uncured composite fabric



plies are cured and bonded together at the same time using the same polymer matrix. In cobonding, an already cured part, usually a stiffener, is bonded to an uncured one, usually a skin, at the same time the skin is cured. In adhesive bonding, cured composites or metals are bonded to other cured composites, honeycomb cores, foam cores or metallic pieces. The pictures to the right show two very rigid sandwich panels with respectively a polypropylene honeycomb core and a polymethacrylimide foam core, sandwiched by CFRP sheets (available at The Robot MarketPlace). Besides increasing the panel bending stiffness, the foam core also works as a shock mount, increasing the impact strength, becoming a

good option for the robot structure and even armor. An even higher stiffness-to-weight ratio can be obtained if the core is made out of balsa wood, as in the DragonPlate pictured to the right, however its impact toughness is relatively low.

- **metal matrix and ceramic matrix composites**: instead of having their fibers embedded and held together in a polymer matrix, these composites use either a metal or a ceramic matrix. The fibers (or even tiles in a few cases), which can also be made out of metal or ceramic, tend to increase the ultimate strength and stiffness of the matrix material. However, most ceramic matrix composites have low impact strength, which limits their use in combat, not to mention their very high cost. On the other hand, when part of a multi-layer composite armor plate, such as the Chobham armor, ceramic tiles embedded in a metal matrix can be very effective to shatter kinetic energy weapons.

## Material Selection Principles

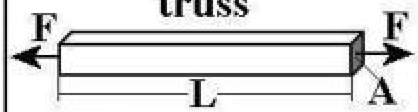
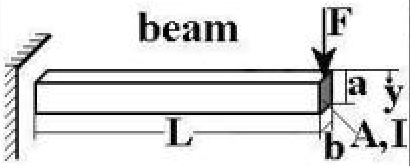
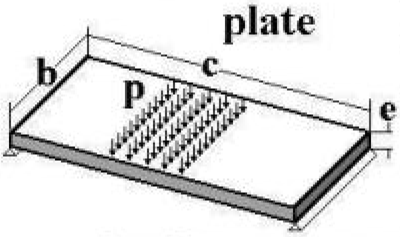
After presenting the main materials used (or not) in combat robots, the question is: which material should I use? “The most resistant” is not the correct answer. The most resistant materials per volume are steels, but a robot entirely made out of steel would be very heavy.

For instance, a 4mm (0.16”) thick steel plate weighs as much as an 11mm (0.43”) thick aluminum one. Which one is better, the 4mm steel or the 11mm aluminum?

The answer is not so simple. It depends on the function that the material will have, as it will be seen next.

## Stiffness Optimization

Classic solid mechanics calculations (summarized in the table to the right) show that a beam under traction, working as a trussed element (such as in the structure of trussed robots), has the largest possible stiffness with minimum mass if the material has the largest possible ratio between the Young modulus E and the density ρ. Steels have in average E = 200GPa and ρ = 7.8, therefore E/ρ ≅ 26. Aluminum (Al) alloys usually have E = 72GPa and ρ = 2.8, thus E/ρ ≅ 26. Titanium (Ti) alloys have E = 110GPa and ρ = 4.6, resulting in E/ρ ≅ 24. And, in magnesium (Mg) alloys, E = 45GPa and ρ = 1.8 resulting in E/ρ ≅ 25. In summary, there is almost no difference in choosing among steels, aluminum, titanium or magnesium alloys for a trussed element if the only requirement is to have a high stiffness-to-weight ratio, their E/ρ ratio is very similar, between 24 and 26.

| structural element type or function | min. mass for max. stiffness | min. mass for max. strength |
|---|---|---|
| truss   Young modulus E<br>specific mass ρ<br>elastic strength S | $\Delta L=\frac{FL}{EA}$<br>$m=\rho LA=$<br>$=\frac{FL^2}{\Delta L}\frac{\rho}{E}\therefore$<br>maximize $\frac{E}{\rho}$ | $\sigma=\frac{F}{A}$<br>$m=\rho LA=$<br>$=FL\frac{\rho}{\sigma}\therefore$<br>maximize $\frac{S}{\rho}$ |
| beam   $b=\alpha a$<br>$A=\alpha a^2$<br>$I=\alpha a^4/12$ | $y=\frac{4FL^3}{E\alpha a^4}$<br>$m=\rho L\alpha a^2=$<br>$=2\sqrt{\frac{\alpha FL^5}{y}}\frac{\rho}{\sqrt{E}}$<br>maximize $\frac{\sqrt{E}}{\rho}$ | $\sigma=\frac{6FL}{\alpha a^3}$<br>$m=\rho L\alpha a^2=$<br>$=L\alpha\left[\frac{6FL}{\alpha}\right]^{\frac{2}{3}}\frac{\rho}{\sigma^{2/3}}$<br>maximize $\frac{S^{\frac{2}{3}}}{\rho}$ |
| plate   load: pressure p<br>$b=\alpha c$ | $y=\frac{5pc^4}{32Ee^3}$<br>$m=\rho e\alpha c^2=$<br>$=\alpha c^3\left[\frac{5pc}{32y}\right]^{\frac{1}{3}}\frac{\rho}{\sqrt[3]{E}}$<br>maximize $\frac{\sqrt[3]{E}}{\rho}$ | $\sigma=\frac{3pc^2}{4e^2}$<br>$m=\rho e\alpha c^2=$<br>$=\frac{\alpha c^3}{2}\sqrt{3p}\frac{\rho}{\sqrt{\sigma}}$<br>maximize $\frac{\sqrt{S}}{\rho}$ |

$S=S_y$ if material is ductile or $S=S_u$ if fragile

However, for a plate under bending, which would be the case of most of the robot structural parts, such as side walls and top/bottom covers, stiffness is maximized with minimum weight if the material has the largest possible $E^{1/3}/\rho$ ratio. In this case, magnesium alloys are much better, with ratio 2.0, against 0.8 for steels, 1.0 for titanium alloys and 1.5 for aluminum alloys. The results are summarized in the table to the right.

| material | E/ρ | E1/2/ρ | E1/3/ρ |
|---|---|---|---|
| Steels | 26 | 1.8 | 0.8 |
| Al alloys | 26 | 3.0 | 1.5 |
| Ti alloys | 24 | 2.3 | 1.0 |
| Mg alloys | 25 | 3.7 | 2.0 |
| Lexan | 2 | 1.3 | 1.1 |
| Delrin | 2 | 1.3 | 1.0 |
| UHMW | 0.7 | 0.9 | 0.9 |
| wood | 3 - 19 | 2 - 5.1 | 1.8 - 3.4 |
| GFRP | 8.6 - 16 | 2.2 - 3 | 1.4 - 1.7 |
| CFRP | 44 - 96 | 5.3 - 7.9 | 2.6 - 3.4 |
| Be alloys | 164 | 9.4 | 3.6 |

As seen in the table, beryllium (Be) alloys would result in extremely light and rigid structures, however its use is usually prohibited in combat due to health issues.

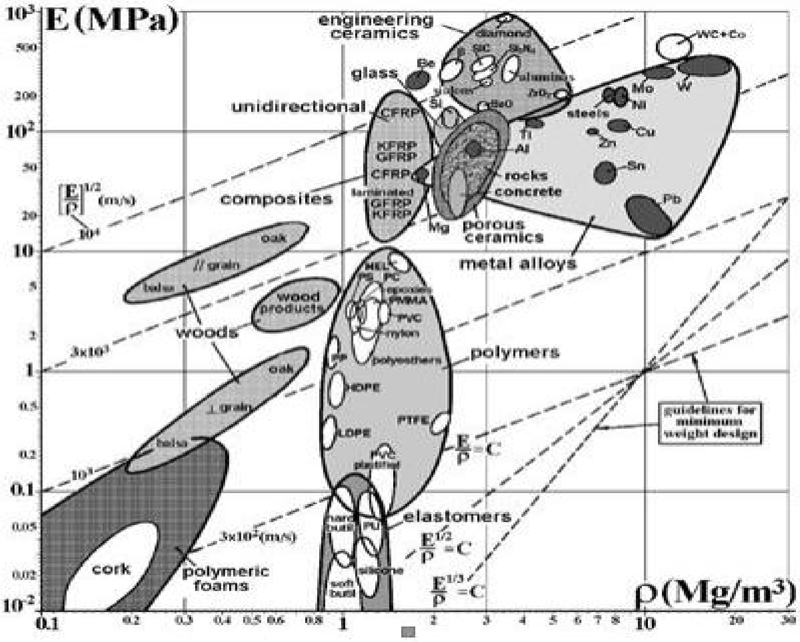
Among the allowed materials, carbon fiber (CFRP), Kevlar (KFRP) and fiberglass (GFRP) are the best choices for stiff and light beams and plates, however there are still the problems with the low impact toughness of carbon fiber and fiberglass, and the challenge in making an entire structure out of Kevlar fabric. In addition, their properties are not the same in all directions, they vary considerably. This is also true for woods, their stiffness and toughness perpendicular to their fibers are almost 10 times lower than parallel to them.

Lexan (polycarbonate) or delrin (acetal) would be awful as a trussed element under traction, their E/ρ is only 2. UHMW is even worse in that sense. Aluminum (Al) and magnesium (Mg) alloys have excellent stiffness with minimum weight, much better than Lexan, delrin, UHMW, steels, and even titanium alloys, for use in beams under bending, maximizing $E^{1/2}/\rho$, and for use in plates under bending, maximizing $E^{1/3}/\rho$.

Note from the weight optimization equations that the beam element in the previous figure assumes that both its width *b* and thickness *a* can be changed, only their aspect ratio $\alpha = b/a$ is assumed fixed. This could be true for internal structural components and for shafts, however all the robot's walls and covers cannot change their length *c* and width *b* without changing the robot design, only their thickness is a free design parameter.

Therefore, the plate element in the previous figure, which only allows its thickness *e* to change to optimize weight, without modifying *b* and *c*, is more appropriate for most structural parts. In summary, except for trussed elements, which are optimized by E/ρ, most of the robot's structural parts have their stiffness optimized by $E^{1/3}/\rho$ (as with plates), while shafts depend on $E^{1/2}/\rho$ (as with beams).

Since E and ρ do not vary much within the same type of material, it is possible to generate a large diagram comparing the applicability of each one. We've generated a graph in logarithmic (log-log) scale for several types of materials, whose ρ are represented in the horizontal axis and E in the vertical one. Using the log-log scale, we obtain guidelines that show materials with same E/ρ, $E^{1/2}/\rho$ and $E^{1/3}/\rho$ ratios, as explained below.



To choose materials to be used in light and stiff truss elements, consider the dashed guideline associated with constant E/ρ (labeled E/ρ = C). All the materials in the same straight line are equivalent, in other words, trusses of same weight made out of these materials would have the same stiffness. Now, draw parallel lines to this guideline. The higher the parallel line, the better will be the material. For instance, in the lowest guideline with constant E/ρ, we can see that plastified PVC is equivalent to cork. Going up to the next parallel E/ρ guideline, we reach the polyesters. The next parallel E/ρ guideline is a little below copper (Cu) alloys. A little above, note that, as expected, all steels, titanium (Ti), aluminum (Al) and magnesium (Mg) alloys are aligned, due to their E/ρ ≅ 25, as calculated before. The highest line with constant E/ρ in the figure goes through unidirectional carbon fibers (CFRP). A little further above we can see the infamous beryllium alloys (Be). This means that, to make a light and stiff truss, beryllium alloys would be better than CFRP, which is much better than copper alloys, which in turn is much better than polyesters, which are much better than corks (which have very low stiffness because they are foams).

To choose materials for light and stiff beams under bending, the procedure is similar, except that we'll use lines parallel to the guideline for constant $E^{1/2}/\rho$. And for plates under bending, use the guideline for constant $E^{1/3}/\rho$.

Note that steels, aluminum (Al), titanium (Ti) and magnesium (Mg) alloys are practically on the same straight line parallel to the guideline for trussed elements (constant E/ρ), so they are similar for such application, as we've already verified. However, when drawing parallel lines to the guideline for plates under bending (constant $E^{1/3}/\rho$), Mg is above Al, which is above Ti, and all of them are above steels. Therefore, it is not efficient to use steel to obtain light and rigid plates, as we had verified, it is much better to use Mg alloys.

An interesting result is that balsa wood can be the best material to make light and stiff plates (at least in a direction parallel to its grains). It is even better than titanium alloys or carbon fiber, you can easily check this from lines parallel to the constant $E^{1/3}/\rho$ guideline in the figure above. Anyone who's worked with model airplanes knows this very well. The internal structure of our fairyweight wedge Pocket is made out of balsa wood. Commercial airplanes would be much stiffer and lighter if they were made out of balsa wood, however aluminum alloys are used instead because of their higher impact toughness and weather resistance. Making a combat robot entirely out of balsa wood, including its external structure and armor, would be suicide. It would be extremely rigid, but it would break at the first impact. Thus, we must take into account other properties, not only stiffness.

## Strength and Toughness Optimization

The yield and ultimate strengths Sy and Su are also very important, and they need to be considered. High Sy is important for parts that should not have permanent deformations, such as shafts. And, naturally, high Su is also important to avoid rupture and to increase the fatigue life. As the strength (denominated by the letter S) varies a lot within the same alloy family, it isn't possible to generalize conclusions to all steels, aluminum alloys, etc, as we did for stiffness. It is necessary to study each particular material separately. The best materials for trusses, beams and plates are, respectively, the ones with highest $S/\rho$, $S^{2/3}/\rho$ and $S^{1/2}/\rho$, as shown before in the solid mechanics calculation table.

The results for yield strength ($S \equiv S_y$) are in the table to the right, for several representative.

| material | $S_y/\rho$ | $S_y^{2/3}/\rho$ | $S_y^{1/2}/\rho$ |
|---|---|---|---|
| UHMW | 24 | 8 | 5.0 |
| Delrin | 44 | 11 | 5.6 |
| Lexan | 50 | 13 | 6.4 |
| 1020 steel | 33 | 5 | 2.1 |
| 304 stainless | 34 | 5 | 2.1 |
| 4340 (43HRc) | 171 | 16 | 4.7 |
| S7 (54HRc) | 194 | 17 | 5.0 |
| AerMet 100 | 215 | 18 | 5.2 |
| 18Ni(350) | 303 | 22 | 6.1 |
| Al 6063-T5 | 54 | 10 | 4.5 |
| Al 6061-T6 | 102 | 16 | 6.2 |
| Al 2024-T3 | 124 | 18 | 6.7 |
| Al 7075-T6 | 169 | 22 | 7.8 |
| Ti-6Al-4V | 208 | 21 | 6.9 |
| AZ31B-H24 | 84 | 16 | 6.9 |
| ZK60A-T5 | 109 | 19 | 7.7 |
| Be S-200 | 228 | 30 | 11 |

materials. If we disregard CFRP, KFRP and GFRP, which would be the best options but they still have the problems mentioned before, it is noticeable that a trussed element under traction has the largest yield strength with lowest weight if made out of 18Ni(350) steel (ratio $Sy/\rho = 303$, see the table), followed by the S-200 beryllium alloy ($Sy/\rho = 228$), AerMet 100 steel ($Sy/\rho = 215$) and Ti-6Al-4V ($Sy/\rho = 208$). If beams under bending are considered, the best choice against yielding would be S-200 beryllium ($Sy^{2/3}/\rho = 30$), followed by 7075-T6 aluminum and 18Ni(350)

($K_{Ic}^{1/2}/\rho$ between 3.0 and 3.2), followed by 2024-T3 aluminum.

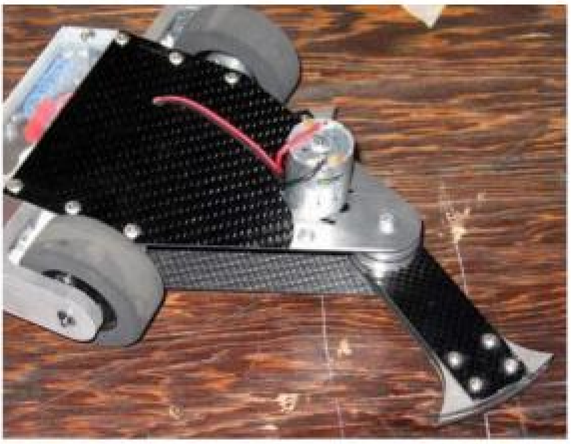
The material selection principles presented above allow us to choose a material to optimize a single mechanical property. For instance, the KIc calculations showed that 304 stainless steels and high strength magnesium alloys result in the toughest shafts with minimum weight, because shafts can be modeled as beams. But a 304 steel shaft would not be a good idea because of its low yield strength, allowing the shaft to easily get bent. And a magnesium shaft, despite being light, would need to have a very large diameter to achieve the desired toughness, which might not fit in the robot or require very heavy large diameter bearings and mounts. So, other considerations need to be introduced to decide which material is the best option for each part of the robot. This will be done next.

## Minimum Weight Design

Minimum weight design has the goal to find the best dimensions and materials to optimize the performance of a component while minimizing its weight. It assumes that the dimensions of the component can be changed without interfering significantly with the robot design. If a component is performing as expected, then the idea is to reduce its weight by changing its materials and dimensions without losing functionality. Alternatively, if a component is failing in combat, then the idea is to improve its mechanical properties through material and dimension changes, while adding as little weight as possible. In this last case, if the redesign is wisely performed, it may be even possible to achieve the improved functionality and lose weight at the same time.

The following analyses will focus on typical structural materials that have potential use in combat. Note that beryllium alloys and composites won't be included in the following sections. Even though they would be, in theory, the best choices for minimum weight design, they have limitations in their use as structural elements.

Beryllium alloys would be a great option to maximize stiffness and strength of trusses, beams or plates, however they would not be the best choice in the presence of impacts, due to their low KIc. In addition, they are usually not allowed in combat due to health issues, as discussed before.



And composites, such as CFRP, despite their outstanding mechanical properties, also have everal issues regarding their use. Composites aredifficult to fabricate (in special high precision parts), they have poor mechanical properties perpendicular to the direction of the fibers, they may delaminate, and they lose toughness if drilled. Not to mention their high cost, which usually limits their application to insect weight classes. If these issues are addressed, then CFRP is the best option for light structures with high stiffness and strength. This is true not only for trusses, but also for beams (such as the CFRP spinning bar pictured to the right) and plates (such as the CFRP structure of the same robot in the picture). If impact toughness is also necessary, then CFRP must be combined with, for instance, Kevlar. But unless you have experience with composites and a high budget, stick with the traditional structural materials: metal alloys.

The following analyses are also limited to general-purpose structural materials. Application-specific materials such as bronze, copper, PTFE (Teflon) and neoprene are not studied below. They are important in the robot to minimize friction (oil-impregnated bronze bearings, PTFE slide surfaces), to shock-mount parts (neoprene sandwich mounts), to lower electrical resistance (copper wires), and in several other tasks as described in the previous sections, but their applications are too specific for them to be compared with structural materials.

Finally, note that a few choices might seem subjective, but they are always backed up by measured properties. Note also that a few of the studied materials may be very difficult to find, such as the 2324-T39 Type II aluminum alloy used in the Boeing 777 plane, however they were included anyway for comparison purposes. Other alloys may also be unavailable in plates or bars, which might limit their applicability. For instance, the K12 Dual Hardness steel is only available in plates up to 1/2" thick, making it almost impossible to use it in shafts. And due to its dual hardness property, it will only be considered for plates that work as armor elements, its originally intended purpose.

## Minimum Weight Plates

As seen above, magnesium (Mg) and aluminum (Al) alloys are excellent materials to increase the stiffness of structural plates that must have their weight minimized. So, if you need to lose weight, it is in general a good idea to replace steel plates with high strength Mg or Al alloy versions. But if in this case you simply change the material without increasing the plate thickness, it is easy to see that you will lower the robot stiffness and strength. To calculate the increased thickness to avoid that, we'll need to use the equations shown in section 3.8 for bending stiffness of plates. It is easy to show that the scale factor for the thickness to keep constant the plate stiffness is $(Eold/Enew)^{1/3}$, where Eold and Enew are the Young modulii of the old and new materials.

So, to replace a steel plate without compromising its bending stiffness, you'll need, for instance, an aluminum one that is $(Esteel/EAl)^{1/3} \cong (205GPa/72GPa)^{1/3} \cong 1.42$ times thicker. This new thicker plate will still be lighter than the original one, because of the low density of Al alloys, which is 2.8 in average, instead of the steel average 7.8. The new plate will then have $1.42 \cdot 2.8 / 7.8 \cong 51\%$ of the weight of the original one, but with the same bending stiffness. This is a smart diet!

Similar calculations for constant bending stiffness can show that a steel plate can be switched to $(205/110)^{1/3} \cong 1.23$ times thicker titanium (Ti), weighing $1.23 \cdot 4.43 / 7.8 \cong 70\%$ of the original weight. So, if stiffness is your major concern, then switching to Al will save more weight than switching to Ti. Actually, the best choice would be Mg alloys: steel plates can be replaced with $(205/45)^{1/3} \cong 1.66$ times thicker Mg, weighing only $1.66 \cdot 1.8 / 7.8 \cong 38\%$ of the original weight, without changing their stiffness.]

But other material properties besides E are also relevant, depending on the functionality of the component. The table below shows important mechanical properties of several relevant structural materials, such as Su (measured in MPa), Sy (in MPa), KIc (in MPa√m), HB (hardness, using the Brinell scale), as well as E (in GPa) and the relative density ρ.

If we want to compare the performance of the listed materials as structural plates, then section 3.8 showed that we must calculate their $E^{1/3}/\rho$ ratio to evaluate stiffness, their $Sy^{1/2}/\rho$ for yield strength, $Su^{1/2}/\rho$ for ultimate strength, and $KIc^{1/2}/\rho$ for fracture toughness. Note that hardness is a local property, it only depends on the material, not on the dimensions of the component, therefore it can be directly compared without the need to consider any ratio with the density.

| | | physical and mechanical properties | | | | | | min. weight plate | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | material | ρ | E | Su | Sy | $K_{Ic}$ | HB | E* | Su* | Sy* | KIc* | HB' |
| ys | AZ31B-H24 | 1.78 | 44.8 | 255 | 150 | 28 | 77 | 100 | 86 | 76 | 93 | 11 |
| | ZK60A-T5 | 1.83 | 44.8 | 310 | 200 | 34 | 70 | 97 | 93 | 86 | 100 | 10 |
| M | Elektron WE43-T5 | 1.84 | 44 | 250 | 180 | 15.9 | 95 | 96 | 83 | 81 | 68 | 14 |
| g | Elektron 675-T5 | 1.95 | 44 | 410 | 310 | 16 | 114 | 91 | 100 | 100 | 64 | 17 |
| | Al 6063-T5 | 2.7 | 68.9 | 186 | 145 | 25 | 60 | 76 | 49 | 49 | 58 | 9 |
| | Al 6061-T6 | 2.7 | 68.9 | 310 | 276 | 27 | 95 | 76 | 63 | 68 | 60 | 14 |
| | Al 2024-T3 | 2.78 | 73.1 | 483 | 345 | 32 | 120 | 75 | 76 | 74 | 64 | 18 |
| | Al 2324-T39 Type II | 2.77 | 72.4 | 475 | 370 | 48 | 118 | 75 | 76 | 77 | 78 | 18 |
| s | Al 5086-H32, H116 | 2.66 | 71 | 290 | 207 | 49 | 78 | 78 | 62 | 60 | 83 | 12 |
| | Al 7050-T7451 | 2.83 | 71.7 | 524 | 469 | 31.5 | 140 | 74 | 78 | 85 | 62 | 21 |
| | Al 7055-T74 | 2.86 | 71.7 | 524 | 469 | 39.6 | 140 | 73 | 77 | 84 | 69 | 21 |
| m | Al 7055-T7751 | 2.86 | 71.7 | 638 | 614 | 27.5 | 171 | 73 | 85 | 96 | 58 | 26 |
| | Al 7075-T6 | 2.81 | 71.7 | 551 | 475 | 25 | 150 | 74 | 80 | 86 | 56 | 22 |
| | Al 7075-T73 | 2.81 | 72 | 505 | 435 | 29.7 | 135 | 74 | 77 | 82 | 61 | 20 |
| | Al 7175-T736 | 2.8 | 72 | 550 | 485 | 34 | 145 | 74 | 81 | 87 | 65 | 22 |
| | Al 7475-T7351 | 2.81 | 71.7 | 496 | 421 | 45 | 135 | 74 | 76 | 81 | 75 | 20 |
| Ti | Ti-6Al-4V (36HRc) | 4.43 | 110 | 992 | 923 | 72 | 336 | 54 | 68 | 76 | 60 | 50 |
| | Ti-6Al-4V ELI | 4.43 | 110 | 896 | 827 | 88 | 326 | 54 | 65 | 72 | 66 | 49 |
| | 1020 steel | 7.87 | 203 | 441 | 262 | 130 | 108 | 37 | 26 | 23 | 45 | 16 |
| | 304 stainless | 8.03 | 193 | 621 | 276 | 220 | 153 | 36 | 30 | 23 | 58 | 23 |
| | 4340 (43HRc) | 7.85 | 205 | 1448 | 1344 | 88 | 402 | 38 | 47 | 52 | 38 | 60 |
| | 4340 (39HRc) | 7.85 | 205 | 1310 | 1207 | 121 | 361 | 38 | 44 | 49 | 44 | 54 |
| | 4340 (34HRc) | 7.85 | 205 | 1172 | 1069 | 148 | 320 | 38 | 42 | 46 | 49 | 48 |
| | S7 (54HRc) | 7.83 | 207 | 1965 | 1520 | 55 | 544 | 38 | 55 | 55 | 30 | 81 |
| ls | AerMet 100 (53HRc) | 7.89 | 194 | 1965 | 1724 | 118 | 530 | 37 | 54 | 58 | 43 | 79 |
| | AerMet 310 (55HRc) | 7.89 | 194 | 2170 | 1900 | 71 | 560 | 37 | 57 | 61 | 34 | 84 |
| | AerMet 340 (57HRc) | 7.89 | 194 | 2380 | 2070 | 37 | 596 | 37 | 60 | 64 | 24 | 89 |
| | HP-9-4-30 (51HRc) | 7.75 | 200 | 1585 | 1280 | 126 | 495 | 38 | 49 | 51 | 45 | 74 |
| | 18Ni(200) (46HRc) | 8 | 183 | 1502 | 1399 | 142 | 426 | 36 | 47 | 52 | 47 | 64 |
| | 18Ni(250) (51HRc) | 8 | 190 | 1723 | 1702 | 121 | 491 | 36 | 50 | 57 | 43 | 73 |
| | 18Ni(300) (54HRc) | 8 | 190 | 2067 | 1998 | 80 | 544 | 36 | 55 | 62 | 35 | 81 |
| | 18Ni(350) (61HRc) | 8.08 | 200 | 2467 | 2446 | 42 | 670 | 36 | 59 | 68 | 25 | 100 |
| | K12 Dual Hardness | 7.86 | 205 | 1785 | 1626 | 72 | 670 | 38 | 52 | 57 | 34 | 100 |
| m. | Delrin | 1.41 | 3.1 | 76 | 62 | 3 | 86SD | 52 | 60 | 62 | 39 | 1 |
| | Lexan | 1.20 | 2.35 | 65 | 60 | 2.2 | 83SD | 56 | 65 | 71 | 39 | 1 |
| | UHMW-PE | 0.93 | 0.689 | 40 | 22 | 1.6 | 66SD | 48 | 65 | 56 | 43 | 1 |

To make things easier, we've normalized hardness and all the above ratios using the best materials from the table, resulting in a system of grade points between 0 and 100. The normalized hardness is called here HB', while the grades for minimum weight plates are represented by the property followed by the * symbol, namely E*, Sy*, Su* and KIc*, shown in the table. For instance, the best material from the table for a stiff plate is the Mg alloy AZ31B-H24, therefore its stiffness grade for plates is E* = 100. Aluminum alloys have E* between 73 and 76, Ti alloys between 52 and 54, and steels between 36 and 38. With these low grades for minimum weight plate design, steels would certainly flunk a "Stiffness 101" course!

These grades are also proportional to the weight savings you'll get. For instance, a 4340 steel plate can be replaced with a 1.42 times thicker 7075-T6 aluminum one that is E4340* / E7075-T6* = 38 / 74 = 51% lighter, as calculated before, without losing stiffness.

The best material for light weight plates with high ultimate and yield strengths is the experimental Mg alloy Elektron 675-T5, therefore its Su* = 100 and also S y* = 100. Unfortunately, there is no material that can optimize all properties at the same time. For instance, this very same Mg alloy has only HB' = 17, a very low score for hardness. Regarding hardness, the best materials in the table are the 18Ni(350) maraging and the K12 Dual Hardness steel alloys, hardened to 61 Rockwell C, equivalent to a 670 Brinell hardness, resulting in HB' = 100. Finally, the best material for light weight plates that must sustain impacts and avoid fracture in the presence of cracks is the Mg alloy ZK60A-T5, with KIc* = 100.

To decide which material to choose from the table for a light weight plate, we must know as well which of the above properties are more important. This depends a lot on the functionality of the plate in the robot. Except for shafts, bars and trusses, most of the robot's structural parts can be modeled as plates for minimum weight design. This is because these parts usually have two fixed dimensions, width and length, obtained from the robot geometry, while their thickness and material can be changed. This is true for most internal mounts, structural walls, top and bottom covers, wedges, shields and armor plates. We'll study these plate-like structural members next.

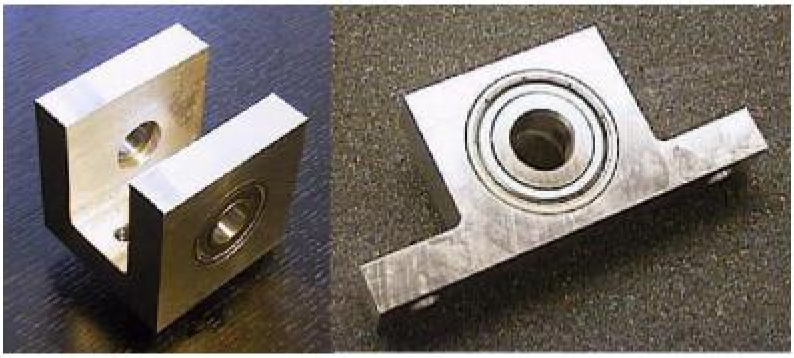
## Minimum Weight Internal Mounts

The most desired property of internal mounts is stiffness. All the impacts they suffer are indirectly transmitted, being relatively damped by the chassis, so KIc is not that important. Usually, internal mounts that have sufficiently high stiffness are made out of plates that are thick enough to satisfy Su and S y requirements.

Therefore, if only the stiffness grades E* are considered, then all Mg alloys are by far the best choice, with grades between 91 and 100, followed by all Al alloys, grading between 73 and 76. Even the low strength 6063-T5 aluminum is a good choice if only stiffness is concerned. But forget about steel internal mounts, their low E* between 36 and 38 will end up adding unnecessary weight to your robot.

But if Su and Sy are also critical, besides stiffness, then we must include them in the selection process. High Su may be important for high stress mounts of heavy weapon motors, such as the 1/2" thick Etek and Magmotor mounts (pictured to the right, which can be found for instance at the Robot Marketplace).

High Sy is also important for internal mounts that support wheel shafts, such as the drivetrain pillow blocks pictured to the right (sold at www.teamdelta.com), which must preserve a relatively accurate alignment without getting permanently bent.



If we (arbitrarily) choose to maximize the average between the grades E*, Su* and Sy*, maximizing a certain grading parameter X* = (E* + Su* + Sy*) / 3, then the best choices are the high strength Mg alloys Elektron 675-T5, ZK60A-T5, AZ31B-H24, Elektron WE43-T5, all of them with X* > 85. The next choices are high-strength Al alloys from the 7000 series, such as 7055-T7751, 7175-T736, 7075-T6, 7050-T7451 and 7055-T74, in that order, all with X* > 77. Steels and even Ti alloys usually result in unnecessarily heavy internal mounts, due to their lower E* and X*.

For instance, the Lexan motor mount pictured to the right only weighs 4 grams, while its 1/2" thickness allows the use of a threaded hole for the 4-40 screw. If the mount was made out of aluminum, it would need to be $(EAl/ELexan)^{1/3}$ ≅ $(72GPa/2.35GPa)^{1/3}$ ≅ 3.13 times thinner to have same stiffness (or $\rho$ Al/ $\rho$ Lexan ≅ 2.8/1.2 ≅ 2.33 times thinner to have the same 4 gram weight). The lower 0.16" thickness for same stiffness would make it impractical to use threaded holes to hold the 0.11" diameter 4-40 screw without compromising strength.

## Minimum Weight Protected Structural Walls

Stiffness is very important for structural walls of robots with active weapons. Large structural deformations can make, for instance, a drum touch the floor when hitting an opponent, a spinning bar hit your own robot during a sloped impact, or even cause mechanism jamming due to severe misalignments.

This is why, unless you're building a passive rammer or wedge (as pictured to the right), making your entire structure and walls out of plastic is a bad idea. For instance, a UHMW plate, despite its good impact toughness, would need to be $(70GPa/0.7GPa)^{1/3} \cong 4.64$ times thicker than an aluminum one to have the same bending stiffness, and it would end up $4.64 \cdot 0.93 / 2.8 \cong 1.54$ times heavier, instead of lighter. A Lexan structure is also a bad idea, the plates would need to be $(70GPa/2.7GPa)^{1/3} \cong 3$ times thicker than aluminum ones, they would end up $3 \cdot 1.2 / 2.8 \cong 1.29$ times heavier. The thicker plates would also require longer screws to be mounted, adding even more weight. Not to mention that Lexan has cracking problems around holes, and plastics in general are easily cut by sawbots. Trust in aluminum! And in magnesium alloys, if available.

If a structural wall is not exposed, such that the opponent cannot hit it directly, or if there's some shock-mounted armor plate over it, then this wall is considered to be protected. Protected walls, besides high stiffness, should have high Su* to support static loads, and high Sy* to avoid getting permanently bent. Since they are protected, KIc* is not that important because they'll only suffer indirect impacts. Therefore, these walls basically behave as high stress internal mounts, being optimized by high strength Mg alloys and aluminum alloys from the 7000 series, as discussed in the previous sub-section. The pictures below show 7050-T7451 inner aluminum walls from our middleweight Touro, which are protected by titanium and Kevlar layers, shown in detail on the right.

Note that most bottom plates (as pictured to the right) can be modeled as protected structural walls, therefore high strength Mg and Al alloys are usually a good option for them.

But, if you have an invertible robot, these bottom plates could get exposed while the robot is upside down, so it is also a good idea to check the optimized materials for integrated structure-armor walls, in the next sub-section. This is especially useful against vertical spinners with large bars or disks, which could flip your robot upside down with one blow, mount on top of it, and then hit again with the blade on the now exposed bottom plate. It is also useful against vertical spinners with small diameter disks, such as K2, which can lift your robot and hit its bottom plate during the same attack as pictured to the right.

We can conclude as well that the best materials for other internal structural components such as gearbox blocks (pictured to the right, from the TWM 3M gearbox) are also high strength Al and Mg alloys, as long as the gearbox is well protected inside the robot, of course.

If you're changing the material of an existing protected wall, you'll need to find its new thickness depending on what property you want to keep constant. If it is stiffness, then we've seen that the scale factor for the thickness in plates is $(Eold/Enew)^{1/3}$. It is also easy to show that the scale factor for the thickness to keep constant the bending strength of a plate is $(Sold/Snew)^{1/2}$, where Sold and Snew are the strengths (either the yield Sy or the ultimate Su) of the old and new materials.

It is necessary to study each material separately, evaluating its particular yield or ultimate strength, and its actual density (although the densities do not vary much within the same alloy family).

It is easy to see that all steels, even high strength steels such as a S7 steel tempered to 54 Rockwell C, are not a good choice for a light weight high strength structure. For instance, to replace a tempered S7 steel plate that works under bending without compromising its ultimate strength, you could use a 7075-T6 aluminum plate $(S_{S7}/S_{7075-T6})^{1/2} = (1965MPa/551MPa)^{1/2} \cong 1.89$ times thicker, weighing $1.89 \cdot 2.81 / 7.83 \cong 68\%$ of the original weight. An almost equivalent choice would be to replace the S7 steel with Ti-6Al-4V. Both 7075-T6 aluminum and Ti-6Al-

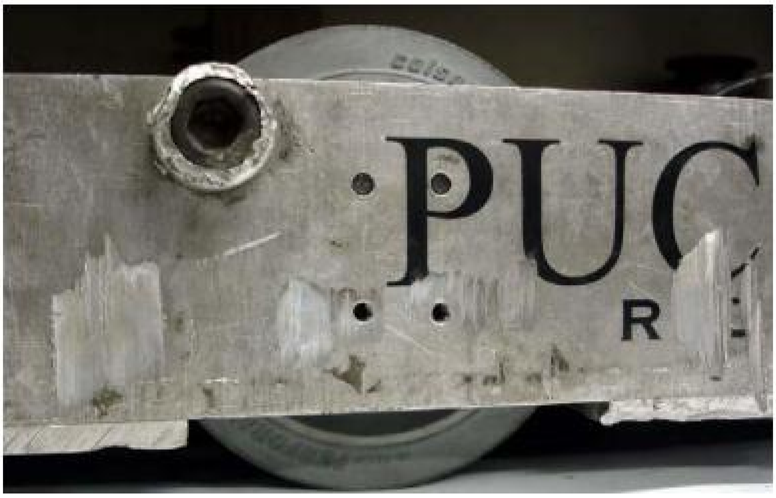
4V would have better ultimate strength-to-weight ratios than tempered S7, so both would be good options to replace any steel alloy in this case, with the high strength aluminum resulting in better values. This can be readily verified from the ultimate strength grade Su* of S7 steel (equal to 55), Ti-6Al-4V (equal to 68) and 7075-T6 aluminum (graded 80). Magnesium alloys would be even better for plates, since ZK60A-T5 has Su* = 93 and Elektron 675-T5 excels at Su* = 100. The use of S7 steel would only be wise if that part needed to remain sharp, which is not the case for structural walls.

But what if you want to increase some property by a factor of n, instead of keeping it constant? Well, the first step is to optimize the material, finding the new material and thickness that keep constant the desired property. After the material has been optimized, you'll need to increase its thickness to improve the property by the n factor. From the analysis of plates under bending, it is easy to show that the scale factor for the thickness is $n^{1/3}$ for improved stiffness, and $n^{1/2}$ for improved yield strength, ultimate strength, or fracture toughness.

For instance, if you want to double the bending stiffness of a 1/4" thick 4340 steel plate, the first step is to switch it to a better material, such as the Mg alloy AZ31B-H24, which has E* = 100, instead of E* = 38 from that steel. The same stiffness of the original plate would be obtained using a Mg alloy plate that was $(E_{4340}/E_{AZ31B\text{-}H24})^{1/3} = (205GPa/44.8GPa)^{1/3} \cong 1.66$ times thicker (0.415" thick). Now, to improve the stiffness by a factor of n = 2 with the same Mg alloy, just multiply the thickness by $n^{1/3} = 2^{1/3} \cong 1.26$, resulting in a 0.523" thick plate. This new plate, even with twice the stiffness of the original 4340 plate, would only have $1.26 \cdot 1.66 \cdot 1.78 / 7.85 \cong 47\%$ of the original weight of the steel version. Clearly, since there is no commercially available 0.523" thick plate, you'll probably have to choose between a lighter 1/2" or a stiffer 5/8" or 9/16" thick plate, or mill it down to the desired thickness.

Note that, if the material is already optimized, then you'll need to add thickness and weight to the plate to improve its mechanical properties. If you can't afford the extra weight, then you'll have to start optimizing the entire geometry, not only the thickness. A simple way to do that is by getting a thicker plate and milling pockets in it, until the final piece has the same weight of the original thinner one. We had to mill very deep pockets in the inner walls of our hobbyweight Touro Jr not to go over its weight limit, as seen on the right. The idea is to make the plate work as an I-beam, with thick outer sections (where the bending stress is maximum) and thinner mid-sections. But to calculate the new stiffness, strengths and toughnesses, you'll probably need the aid of computer software such as Finite Element or even CAD programs.

## Minimum Weight Integrated Structure-Armor Walls




If the external structural walls of your robot are unprotected, working as well as armor (such as in our lightweight Touro Light, pictured to the right), then fracture toughness KIc plays a major role. To be used in the robot structure, the material must have high E* and Sy*, as discussed before. But now KIc* is more relevant than Su*, because while also working as armor the plate will mostly suffer dynamic loads (impacts) instead of static ones.

Top cover plates are also included in this category, because they must have high KIc* to survive the attacks of vertical spinners, hammerbots and overhead thwacks. If they also act as structural elements, helping for instance to support the drive system, then stiffness E* and yield strength Sy* grades are also important, so the following analysis also applies to them.

Since KIc*, E* and Sy* are the most relevant properties for structure-armor walls, we'll (arbitrarily) choose the average of their grades, X* = (KIc* + E* + Sy*) / 3, to evaluate the best materials. We'll also choose only the materials with KIc* > 50, E* > 70 and Sy* > 70, to avoid any distortions that the average X* might carry. For instance, the 5086-H32 aluminum alloy has a relatively good X* = 73.5, however it has an undesirably low Sy* = 60.

It is found that the Mg alloys continue in the lead, with the best alloy from the studied table being ZK60A-T5, followed by AZ31B-H24, Elektron 675-T5 and Elektron WE43-T5. Aerospace aluminum alloys follow in this ranking: 2324-T39 Type II, followed by 7475-T7351, 7175-T736, 7055-T7751 or T74 and 7050-T7451, all of them with X* > 73.

Interestingly, 2024-T3, which is not one of the best options for protected walls, is a good option for structure-armor plates, with X* = 71, despite its lower Sy*. It is almost as good in this application as 7075-T6, which has X* = 72. This is because 2000 series Al alloys have lower Sy than 7000 series, but they usually make it up with better KIc, which is crucial for armor elements.

Forget once again about steels. Although steels have high KIc, their high density results in plates with relatively low KIc-to-weight ratios, with KIc* between 24 and 58 for the ones in the studied table. These low ratios, together with their very low E*, makes them very unattractive, due to their 35 < X* < 47.

Titanium Ti-6Al-4V, despite its relatively good Sy* = 76 and KIc* = 60 (or 66 for the tougher ELI version), is not one of the best choices for an integrated structure-armor because of its relatively low stiffness-to-weight ratio, which results in E* = 54 and thus X* = 63.4. This lower stiffness could be good enough to make a very tough all-titanium rammer or wedge, but it would be a poor choice for an integrated structure-armor robot with active weapons. In fact, even medium strength 6061-T6 is a better choice than titanium, despite its lower Sy* = 68: it combines the same KIc* = 60 of Ti-6Al-4V with a much better E* = 76, resulting in a higher X* = 68.2. In addition, 6061-T6 is much cheaper than high strength Ti and Al alloys, it is easier to machine, it has good weldability, and it is readily available in extrusion forms. No wonder Matt & Wendy Maxham love this material!

## Minimum Weight Wedges

Wedges and integrated structure-armor plates behave in a similar manner. They must have high KIc* to withstand impacts. They must have high Sy* to avoid getting permanently bent, because bent wedges won't remain flush to the ground to scoop the opponents. And they must have high E* to become very stiff and launch the opponents. A very flexible wedge can be effective as an armor element, as a defensive element damping the impact, however it won't be able to effectively use the opponent robot's kinetic energy against it, as an offensive element. Stiff wedges will transmit much higher reaction forces from the arena floor to the opponent.

So, good material choices for wedges must have, similarly to structure-armor plates, a high average grade X* = (KIc* + E* + Sy*) / 3. The main difference here is that wedges must keep their edges sharp to stay effective, so high hardness is also important. We'll choose materials with hardness higher than 32 Rockwell C, which translates to grades HB' > 45. Higher hardness materials will rule out Mg and Al alloys, so we'll need to relax a little the restrictions on the minimum values of the other properties, to be able to find any match. We only choose then materials with KIc* > 25, E* > 35 and Sy* > 40, as well as HB' > 45, that maximize X*.


The result is that Ti-6Al-4V ELI and Ti-6Al-4V (pictured to the right) are by far the best choices from the table, with X* equal to 64 and 63, respectively. High strength steels would be the next choice, the best one being AerMet 100, followed by 18Ni(250), HP-9-4-30, 18Ni(200) 18Ni(300), tempered 4340, AR400 and tempered 5160, all of them with X* > 42.

## Minimum Weight Traditional Armor

If a structural plate only works as armor, such as a rammer shield (pictured to the right), then there are basically three mechanical properties of interest: fracture toughness, impact toughness, and hardness.


The armor needs to withstand impacts, as well as tolerate the cracks that will eventually be formed after receiving some serious hits, therefore KIc is a major concern. Armor plates usually do not carry any static loads besides their own weight, they're just "hanging out" waiting to be hit, so Su is not nearly as important as KIc. Also, they do not lose functionality after yielding, as long as their permanent deformations do not interfere with the inner structure, drivetrain or weapon system,

so Sy is not that important either. And the armor plates are already mounted either over stiff internal structural walls or over shock mounts (as pictured to the right, with shock mounts made out of curled steel cables), therefore they don't need too much stiffness themselves.

Top cover plates can be included in this category if they do not act as structural elements, if they are just plates used to protect the robot interior, without having to support any internal components such as the drivetrain system. So, stiffness and yield strength are not that important, as long as the robot has a few internal supports that will prevent the top cover from bending too much into the robot and smash some critical component. Therefore, non-structural top cover plates that are well supported can be modeled as traditional armor elements, so the following analysis also applies to them.

Note that we're assuming here that the fracture toughness KIc can also be a measure of impact toughness. This is true for most metals, unless they have notch sensitivity problems, explained later. In addition, the value of KIc depends on the loading rate (the impact speed). All K Ic measurements included in the previous table were made under very slow tests, therefore they are also called static KIc. If the tests had been performed at very high load rates, to evaluate the effect of the impact speed, the resulting dynamic KIc values would probably be much lower. For instance, one of the Ti-6Al-4V armor plates from our middleweight


Touro shattered almost like glass due to a high speed impact from the bar spinner The Mortician, during RoboGames 2006. Very little plastic deformation can be seen in the remaining plate (pictured to the right), and the removed portion shattered into tiny pieces. At lower impact speeds, the very ductile Ti-6Al-4V would certainly absorb more energy, meaning that its static (low speed) KIc = 72MPa√m is probably much higher than its dynamic (high speed) KIc.

However, if we assume that the ratio between dynamic and static KIc is similar for all materials (which is not completely true), then we can still compare them directly only using the available static KIc values.

As explained in chapter 2, traditional armors are usually made out of tough and hard materials that try to absorb and transmit the impact energy without getting damaged. They are a good option against very sharp horizontal spinners, since the high hardness will help chipping or blunting the edge of the opponent's weapon. So, in addition to a high grade KIc*, it is desirable that the armor plate has a high hardness grade HB'.

Thus, we'll choose materials that maximize the average X* = (KIc* + HB') / 2, while guaranteeing some minimum toughness and hardness requirements KIc* > 30 and HB' > 45. We find out that the best materials are, in that order, K12 Dual Hardness, AerMet 100, HP-9-4-30, AerMet 310, 18Ni(250), 18Ni(300), Ti-6Al-4V ELI, 18Ni(200) and Ti-6Al-4V, all of them having X* > 50. Tempered 4340 steel is not a bad option, it has X* > 48. Tempered 5160 steel could also be used, but it’s not one of the best choices.

If you have trouble finding or heat treating AerMet, HP-9-4-30 or maraging steel alloys, then your best bet is to go for Ti-6Al-4V armor plates. Note that the above calculations assume that Ti-6Al-4V is in its commercially available annealed condition, because when heat treated to improve its ultimate strength it can end up with KIc lower than 45MPa√m, instead of 72MPa√m. If available, Ti-6Al-4V ELI (Extra Low Interstitial) is even better for armor plates, since KIc = 88MPa√m, despite its 10% lower yield and ultimate strengths. Titanium alloys with higher KIc are usually not commercially available, such as Ti-6Al-2Sn-4Zr-2Mo and Ti-11.5Mo-6Zr-4.5Sn.

If you want a low budget traditional armor, then 304 stainless steel is a reasonable choice. Its KIc* is 58, similar to annealed Ti-6Al-4V, but it is much cheaper. However, due to its low E* and Sy*, it will only be a good choice if backed up by a stiff structure. Touro has a few 304 steel spare armor plates, used when we’re out of Ti-6Al-4V.

Forget about other steels, because their KIc* is usually below 50. With the same weight of the steel armor you can get a 77% thicker Ti-6Al-4V plate that will be much tougher. Even the high strength steels S7, 18Ni(350) and AerMet 340 should be avoided, because of their medium-low toughness grades KIc* ≤ 30. It is true that S7 tempered to 54 Rockwell C is one of the tool steels with highest toughnesses, with KIc = 55MPa√m, however this is a low value compared to most steels: for instance, the low strength 1020 steel can reach KIc = 130MPa√m. Beware, S7 steel is not a panacea! It may only be a good option when sharpness is also required.

## Minimum Weight Ablative Armor

Ablative armors are designed to negate damage by themselves being damaged or destroyed through the process of ablation, which is the removal of material from the surface of an object by vaporization. They’re also made out of tough materials, but with low hardness and low melting point to facilitate the ablation. Most of the impact energy is absorbed by the ablation process, by breaking apart when hit by an opponent, transmitting much less energy to the rest of the robot.

To find out if a material will result in an ablative armor, you must consider its hardness and melting point. If you want a traditional armor, we've seen that a good option is Ti-6Al-4V, which has a 1660$^{O}$C (3020$^{O}$F) melting point and 36 Rockwell C hardness, equivalent to 336 Brinell. But if you want an ablative armor, we'll see that the best options are high toughness Mg and Al alloys, which have low Brinell hardnesses between 60 and 171, and relatively low melting points, close to 660$^{O}$C (1220$^{O}$F). Low hardness helps ablation by making the armor material deform during an impact, while low melting point helps ablation by allowing the armor material to locally melt or even vaporize during high energy impacts.

Ablative armors are a very good choice against blunt or not-so-sharp weapons. But, against very sharp horizontal spinners, very hard traditional armors are a better option, as discussed before. This is because ablative armor materials such as Mg and Al alloys have low hardnesses, not being able to blunt or chip the edge of the opponent's blade during combat. An opponent with a sharp spinning blade during the entire combat is not a pleasant thought. In special because Mg and Al alloys, used in the ablative armor, tend to be easily cut by sharp tools at high speeds, drastically reducing their KIc, Su and Sy, which had been measured under static conditions. It's like cutting butter with a hot knife. Thus, traditional armor materials such as Ti-6Al-4V are better choices against very sharp spinners, their higher hardness and melting point prevent such weakening.

In addition to their ablative properties, high toughness Mg and Al alloys also have better fracture toughness grades KIc* than traditional armor materials. For instance, let's compare Ti-6Al-4V with 5086-H32 aluminum, used in armor plates of light weight military vehicles. In average, 5086-H32 has KIc = 49MPa$\sqrt{}$m, while Ti-6Al-4V has KIc = 72MPa$\sqrt{}$m. Section 3.8 showed that strength and toughness analyses have similar equations because the effect of a crack in a structure is directly proportional to the applied stresses. Therefore, for plates under bending, it is not a surprise that the scale factor between old and new plate thicknesses for a minimum weight design with constant fracture toughness is (KIc,old/KIc,new)$^{1/2}$. Because almost all armor plates don't have restrictions about having their thickness increased, since they are outside the robot, they can be analyzed using a minimum weight design.

So, a Ti-6Al-4V plate would have the same toughness as a 5086-H32 aluminum plate that was (72/49)$^{1/2}$ ≅ 1.2 times thicker. This aluminum replacement would only have 1.2 · 2.66 / 4.43 ≅ 72% of the weight of the Ti-6Al-4V version. In summary, we can conclude that, for weight optimization, high toughness titanium alloys (such as Ti-6Al-4V) are not as good as high toughness aluminum alloys when it comes to fracture toughness.

This conclusion might seem weird, but it is true. Surely a titanium plate would be a better armor than an aluminum one with same thickness, but remember that this is a weight (and not a volume) optimization problem. An aluminum plate with the same weight as a titanium one is about 1.6 times thicker, this is what makes the difference. This is easily seen from the fracture toughness grades KIc* = 60 for Ti-6Al-4V and KIc* = 83 for 5086-H32 aluminum.

But the ultimate ablative armor would be made out of, believe it or not, the Mg alloys ZK60A-T5 (KIc* = 100) and AZ31B-H24 (KIc* = 93). And their very low hardness, between 70 and 77 Brinell (HB' between 10 and 11), helps even more in the ablation process. In summary, the best ablative armor materials are, in that order, the Mg alloys ZK60A-T5 and AZ31B-H24, followed by the Al alloys 5086-H32, 2324-T39 Type II, 7475-T7351 and 7055-T74, all of them with KIc* > 69.

Touro Feather can testify the effectiveness of aluminum ablative armors. At Robogames 2008 it withstood several powerful blows from the featherweight undercutter Relic on its 3/4" thick 7050 aluminum front armor plates (pictured to the right). These scarred plates worked as an ablative armor, slowing down Relic's weapon and allowing Touro Feather to go for the knockout.

Avoid using polymer armor plates, such as Lexan or UHMW, they have KIc* < 45. Wood might be a good option for ablative armor, although its KIc varies by a factor of 10 depending on the impact direction. In average, wood would grade KIc* = 77, a very high score. But hope that your opponent doesn't have a flamethrower, and that the opponent robot doesn't hit you in the brittle transverse direction of the wood fibers.

## Minimum Weight Beams

The previous components were all modeled as plates, because they have by design 2 fixed dimensions (width and length), while only thickness can be changed. However, there are other components (such as shafts) that might only have one fixed dimension, their length, while their diameter can be varied. If a beam basically works under bending and/or torsion, then we've seen in section 3.8 that its mechanical properties are optimized for minimum weight using materials with high $E^{1/2}/\rho$ ratio for stiffness, high $Sy^{2/3}/\rho$ for yield strength, high $Su^{2/3}/\rho$ for ultimate strength, and high $KIc^{2/3}/\rho$ for fracture toughness.

Similarly to what we did for plates, we've normalized all the above ratios using the best materials from the table, resulting in a system of grade points between 0 and 100 for beams. The normalized hardness is still HB', because it is a local property, while the grades for minimum weight beams are represented by the property followed by the ** symbol, namely E**, Sy**, Su** and KIc**, shown in the table below. Note that the beam grades can differ a lot from the plate grades. For instance, the best material from the table for a beam with high yield strength is not a Mg alloy, as it was for plates, but the 7055-T7751 Al alloy, grading Sy** = 100. Note that steels are poor choices for high stiffness elements not only for plates, but also for beams, with E** < 50.

In the table there are also properties followed by the *** and ’ symbols, they will be used respectively in minimum weight truss design and in minimum volume design, discussed later.

| | | min. weight beam | | | | min. weight truss | | | | minimum volume | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | material | E** | Su** | Sy** | KIc** | E*** | Su*** | Sy*** | KIc*** | E' | Su' | Sy' | KIc' | HB' |
| ys | AZ31B-H24 | 100 | 80 | 63 | 90 | 94 | 47 | 28 | 57 | 22 | 10 | 6 | 13 | 11 |
| | ZK60A-T5 | 97 | 88 | 74 | 100 | 92 | 55 | 36 | 68 | 22 | 13 | 8 | 15 | 10 |
| M | Elektron WE43-T5 | 96 | 76 | 69 | 60 | 90 | 45 | 32 | 32 | 21 | 10 | 7 | 7 | 14 |
| g | Elektron 675-T5 | 90 | 100 | 93 | 57 | 85 | 69 | 53 | 30 | 21 | 17 | 13 | 7 | 17 |
| | Al 6063-T5 | 82 | 43 | 40 | 55 | 96 | 23 | 18 | 34 | 33 | 8 | 6 | 11 | 9 |
| | Al 6061-T6 | 82 | 60 | 62 | 58 | 96 | 38 | 34 | 37 | 33 | 13 | 11 | 12 | 14 |
| | Al 2024-T3 | 82 | 78 | 70 | 63 | 99 | 57 | 41 | 42 | 35 | 20 | 14 | 15 | 18 |
| | Al 2324-T39 Type II | 82 | 78 | 74 | 83 | 98 | 56 | 44 | 63 | 35 | 19 | 15 | 22 | 18 |
| s | Al 5086-H32, H116 | 84 | 58 | 52 | 88 | 100 | 36 | 26 | 67 | 34 | 12 | 8 | 22 | 12 |
| | Al 7050-T7451 | 80 | 81 | 84 | 61 | 95 | 61 | 55 | 41 | 35 | 21 | 19 | 14 | 21 |
| | Al 7055-T74 | 79 | 80 | 84 | 71 | 94 | 60 | 54 | 51 | 35 | 21 | 19 | 18 | 21 |
| m | Al 7055-T7751 | 79 | 92 | 100 | 56 | 94 | 73 | 71 | 35 | 35 | 26 | 25 | 13 | 26 |
| | Al 7075-T6 | 80 | 85 | 86 | 53 | 96 | 64 | 56 | 32 | 35 | 22 | 19 | 11 | 22 |
| | Al 7075-T73 | 80 | 80 | 81 | 60 | 96 | 59 | 51 | 39 | 35 | 20 | 18 | 14 | 20 |
| | Al 7175-T736 | 81 | 85 | 87 | 65 | 96 | 64 | 57 | 44 | 35 | 22 | 20 | 15 | 22 |
| | Al 7475-T7351 | 80 | 79 | 79 | 79 | 96 | 58 | 49 | 58 | 35 | 20 | 17 | 20 | 20 |
| Ti | Ti-6Al-4V (36HRc) | 63 | 79 | 85 | 68 | 93 | 73 | 69 | 59 | 53 | 40 | 38 | 33 | 50 |
| | Ti-6Al-4V ELI | 63 | 74 | 79 | 78 | 93 | 66 | 62 | 73 | 53 | 36 | 34 | 40 | 49 |
| | 1020 steel | 48 | 26 | 21 | 57 | 97 | 18 | 11 | 60 | 98 | 18 | 11 | 59 | 16 |
| | 304 stainless | 46 | 32 | 21 | 79 | 90 | 25 | 11 | 100 | 93 | 25 | 11 | 100 | 23 |
| | 4340 (43HRc) | 49 | 58 | 61 | 44 | 98 | 60 | 57 | 41 | 99 | 59 | 55 | 40 | 60 |
| | 4340 (39HRc) | 49 | 54 | 57 | 54 | 98 | 55 | 51 | 56 | 99 | 53 | 49 | 55 | 54 |
| | 4340 (34HRc) | 49 | 50 | 53 | 62 | 98 | 49 | 45 | 69 | 99 | 48 | 44 | 67 | 48 |
| | S7 (54HRc) | 49 | 71 | 67 | 32 | 99 | 82 | 64 | 26 | 100 | 80 | 62 | 25 | 81 |
| | AerMet 100 (53HRc) | 47 | 70 | 72 | 53 | 92 | 82 | 72 | 55 | 94 | 80 | 70 | 54 | 79 |
| ls | AerMet 310 (55HRc) | 47 | 75 | 77 | 38 | 92 | 90 | 80 | 33 | 94 | 88 | 78 | 32 | 84 |
| | AerMet 340 (57HRc) | 47 | 80 | 81 | 25 | 92 | 99 | 87 | 17 | 94 | 96 | 85 | 17 | 89 |
| | HP-9-4-30 (51HRc) | 49 | 62 | 60 | 57 | 97 | 67 | 55 | 59 | 97 | 64 | 52 | 57 | 74 |
| | 18Ni(200) (46HRc) | 45 | 58 | 62 | 59 | 86 | 61 | 58 | 65 | 88 | 61 | 57 | 65 | 64 |
| | 18Ni(250) (51HRc) | 46 | 63 | 71 | 53 | 89 | 71 | 70 | 55 | 92 | 70 | 70 | 55 | 73 |
| | 18Ni(300) (54HRc) | 46 | 72 | 79 | 40 | 89 | 85 | 83 | 37 | 92 | 84 | 82 | 36 | 81 |
| | 18Ni(350) (61HRc) | 47 | 80 | 89 | 26 | 93 | 100 | 100 | 19 | 97 | 100 | 100 | 19 | 100 |
| | K12 Dual Hardness | 48 | 66 | 70 | 38 | 98 | 74 | 68 | 33 | 99 | 72 | 66 | 33 | 100 |
| | Delrin | 33 | 45 | 44 | 26 | 8 | 18 | 15 | 8 | 1 | 3 | 3 | 1 | 1 |
| m. | Lexan | 34 | 48 | 51 | 25 | 7 | 18 | 17 | 7 | 1 | 3 | 2 | 1 | 1 |
| | UHMW-PE | 24 | 44 | 33 | 26 | 3 | 14 | 8 | 6 | 0 | 2 | 1 | 1 | 1 |

To decide which material to choose from the table for a light weight beam, we must know which of the E**, Sy**, Su**, KIc** and HB' properties are more important, which depends on its functionality in the robot. We'll study these beam-like structural members next.

## Minimum Weight Shafts and Gears

Shafts are, basically, beams with circular cross-section under bending and torsion. They must have high KIc** grade to withstand impacts, high stiffness grade E** to prevent vibration and gear misalignment, and certainly high Sy** grade not to get bent. We'll look then at the average grade X** = (KIc** + E** + Sy**) / 3 to evaluate the fitness of each material.

It is easy to see that high strength Mg and Al alloys would be the best choices, with X** between 72 and 90. This is true for most beams, but not for shafts. It is true that Mg and Al shafts would have the best minimum weight properties, however they would need to have a much larger diameter than an equivalent one made out of steel or titanium, which would imply in larger bearings, larger gears and pulleys, and larger gearboxes, increasing the robot weight.

So, to avoid shafts with very large diameters, we'll limit our choices to denser materials such as steels and Ti alloys. We can easily do that by adding another restriction, which is HB' > 45. This medium-high hardness requirement will not only filter out polymers, Mg and Al alloys, but it will also help in the mounting process, since low hardness shafts would easily become dented, making it difficult to mount, for instance, a tight tolerance roller bearing. Also, higher hardness shafts will prevent wear due to, for instance, bronze bearing friction.

Also, to avoid distortions in the X** average, we'll also limit the choices to materials with KIc** > 25, Sy** > 40 and E** > 40. It is found that the best shaft materials from the studied table are Ti-6Al-4V ELI (with X** = 73) and Ti-6Al-4V (X** = 72, see the shaft pictured on the right). The next choices are, in that order, AerMet 100, 18Ni(250) 18Ni(200), HP-9-4-30, 18Ni(300), tempered 4340, AR400, and tempered 5160, all of them with X** between 50 and 58. Avoid using S7 steel shafts, they only grade X* = 49, and they're more expensive and with lower KIc** than 4340 steel.

Therefore, hardened steel shafts are better than Mg or Al ones. Note that high strength titanium is only better than high strength steels if the weight saved by the shaft is not gained by the slightly larger bearings, gearboxes, etc.

Note that minimum weight gears also fall in this very same category, if their thickness is a free parameter that can be changed. They also need high KIc**, E** and Sy**, for the same reasons. And a higher hardness grade HB' > 45 will prevent wear on the gear teeth. So, if the volume of the gear is not important, the best choice for minimum weight would be high strength Ti alloys. If you need more compact gears and with less tooth wear, go for the same high hardness steels chosen for shafts (such as in the hardened steel gear pictured above, from the TWM 3M gearbox).

## Minimum Weight Spinning Bars and Eggbeaters

The material choice for the bars (blades) of horizontal and vertical spinners is very critical. Spinning bars can be modeled as beams or plates, depending on your design requirements. If their width and thickness are not restrained, which is usually true, then they can be analyzed as beams for minimum weight design. Eggbeaters (pictured to the right) also fall in this category, because they are basically two vertical spinning beams connected by two horizontal beams.

Note that minimum weight design does not mean that your spinning bar will have a low inertia, it only means that it will have high ratios between mechanical properties and weight. After optimizing your material, you'll be able to increase the bar thickness until reaching the desired weight or moment of inertia, and still have optimized mechanical properties.

All spinning bars need to have high KIc** grades, since they'll have to withstand their own inflicted impact, high E** grades to avoid hitting themselves due to excessive deflection at a sloped impact, and high Sy** not to get warped and therefore unbalanced.

There are several different material choices depending whether the bar itself needs to be sharp, blunt, or if it will have inserts made out of a different material at its tips, as discussed next.

### Sharp one-piece spinning bars and eggbeaters

Sharp one-piece spinning bars (such as the one from the antweight Collision, to the right) and eggbeaters must have high hardness, to retain their sharpness. If we only select materials with HB' > 75, then we only have steels to choose from. The E** of steels is basically constant (it only varies between 45 and 49 for them). And all steels with very high hardness also have high yield strength, so we don't have to worry too much with Sy**, they would break before the yield deformations were high enough to cause unbalancing. We then decide to maximize the remaining grade, KIc**.

The result is that the best materials are AerMet 100 (KIc** = 53), 18Ni(300) (KIc** = 40) and AerMet 310 (KIc** = 38). Other good choices are S7 steel at 54HRc (as in Hazard's sharp bar pictured to the right), 18Ni(350) and AerMet 340, but only if the bar or eggbeater is not heavily notched, because of their lower KIc** < 33.

If the bar or eggbeater is notched, it would probably be safer to use 5160 steel tempered to 46 HRc instead of S7, you will have a lower hardness (HB' = 65) but higher impact toughness. Note that these results also apply to sharp one-piece spears.

**Blunt one-piece spinning bars and eggbeaters**

If you want a minimum weight blunt one-piece spinning bar or eggbeater, then your hardness requirements can be somewhat relaxed. You still need medium-high hardness to be able to inflict damage, but it does not need to be too high since the weapon doesn't need to be sharp. This reasoning would also apply to one-piece hammers for hammer, thwack or overhead thwack bots.

We'll then choose materials with medium-high HB' > 45, with grade KIc** > 30, and order them by the average between these two grades, X** = (KIc** + HB') / 2, since both are important.

The result is that the best materials are AerMet 100, HP-9-4-30, 18Ni(250), Ti-6Al-4V ELI, 18Ni(200), 18Ni(300) and AerMet 310, all of them grading X** > 60. Ti-6Al-4V is the next choice (X** = 59). And 4340 steel is not too bad, as long as it is tempered to lower hardnesses between 34 and 39HRc to improve toughness (despite losing strength), instead of the usual 40 to 43HRc. But note that 4340 steel is usually sold in bar form, you might need to look for AR400 or 5160 steel plates.

**Spinning bars and eggbeaters with inserts**

If you want to improve the impact and fracture toughness of your spinning bar or eggbeater, then it is a good idea to use two different materials: a softer one for the bar itself, and a very hard one for inserts to be attached at its tips.

Now we have to worry again with E** and Sy**, since we won't be limiting our search to high hardness materials. So, to minimize the weight of spinning bars and eggbeaters with inserts, we'll choose materials with KIc** > 50, E** > 60 and Sy** > 60, and order them by the average grade X** = (KIc** + E** + Sy**) / 3.

Other good options are Elektron WE43-T5, 7075-T73 or T6, Ti-6Al-4V ELI, Ti-6Al-4V and 2024-T3, all with X** > 70. Avoid using steels (X** < 58) or polymers (X** < 40).

The use of Mg and Al alloys has also the advantage of increasing the moment of inertia of the bar for a given weight. This is because you'll have a lighter material close to the spin axis, leaving more weight for heavier steel inserts at the tips, which will contribute much more to the moment of inertia due to their higher distance. Remember that the moment of inertia is proportional to the square of the distance of a certain mass to the spin axis. The aluminum spinning bars pictured to the right, from the middleweight The Mortician, not only have heavy steel inserts at their tips, but they also have pockets milled close to the spin axis or through-holes to optimize the weight distribution.

Note that the above optimum materials also apply to hammer handles (as pictured to the right), thwack or overhead thwack handles, and spears that have inserts.

Lifter and launcher arms would also be lighter if made out of these materials, since such arms are basically beams under bending stresses. But if using Mg or Al alloys in the lifter/launcher arm, make sure you'll have high hardness inserts at its tip to help wedge and scoop the opponent.

**Low maintenance spinning bars and eggbeaters with inserts**

As seen above, Mg and Al alloys make great spinning bars that have inserts. But, unless your inserts are large enough to shield and prevent any direct hits on such low hardness bar, you'll realize that the bar itself will need to be changed very often, due to ablation.

A low maintenance bar would need to have a higher hardness grade, for instance HB' > 45, in addition to the high average grade

X** = (KIc** + E** + Sy**) / 3.

But these are exactly the requirements we used for minimum weight shafts and gears, so the optimum materials are the same: high strength Ti alloys are the best choice, followed by AerMet 100, 18Ni(250), 18Ni(200), HP-9-4-30, 18Ni(300), tempered 4340 (or AR400), and tempered 5160. Once again, avoid using S7 steel in the bar, leave it for the inserts. The spinning bar from the middleweight Terminal Velocity (pictured to the right) is an excellent example of optimum material choice: Ti-6Al-4V with S7 inserts.

Note that these materials also apply to low maintenance hammer, thwack or overhead thwack handles, to low maintenance spears that have inserts, and to low maintenance lifter and launcher arms, such as in the titanium hammer handle from the middleweight Deadblow (pictured to the right).

**Spinning bars with minimum width restrictions**

In all the above spinning bar analyses, it was assumed that both the bar width and thickness could be changed. But the bar must have a minimum width of, for instance, twice the diameter of its center hole, where the weapon shaft goes through. Smaller widths will probably compromise strength, as it will be shown in chapter 6. So, if the above calculations for minimum weight beam design result in a bar width that is smaller than, for instance, twice the center hole diameter, then the design strategy must be changed.

If this happens, then the bar width must be kept constant at this minimum value, while only the bar thickness can be changed in the design process. Thus, the problem is now a minimum weight plate design, instead of a minimum weight beam design. We'll have to use the plate grades KIc*, E* and Sy* instead of K Ic**, E** and Sy**. The material choice for this bar with fixed width will then be the same as for a minimum weight spinning disk, as shown next.

## Minimum Weight Spinning Disks, Shells and Drums

Spinning disks and shells usually have their diameter defined by the robot design, while only their thickness is a variable design parameter. The same is valid for drums, their external diameter and width are defined by the design of the robot structure, only leaving the drum thickness as a variable value. So, spinning disks, shells and drums are modeled as plates. Spinning bars with fixed width also fall in this category, as explained above.

**Sharp one-piece spinning disks, shells and drums**

One-piece spinning disks, shells and drums (pictured below) are usually a good option to maximize tooth strength and to minimize the number of parts.

The analysis is very similar to the one for sharp one-piece spinning bars, except that plate grades are used, instead of beam grades.

The disk, shell or drum also needs to retain its sharpness, so we choose materials with grades HB' > 75, KIc* > 20, Sy* > 50 and E* > 30, trying to maximize KIc*.

The best materials are then AerMet 100 (KIc* = 43), 18Ni(300) (KIc* = 35) and AerMet 310 (KIc* = 34). Other good choices are S7 steel at 54HRc, 18Ni(350) and AerMet 340, but only if the disk, shell or drum is not heavily notched, because of their lower KIc* ≤ 30. Note that these materials are exactly the same as the ones from the one-piece bar analysis, which is a coincidence, since different grades were used.

**Blunt one-piece spinning disks and shells**

Blunt one-piece spinning drums are not a good idea, they will have a hard time grabbing and launching the opponent. Sharpness is important for drums. But blunt one-piece spinning disks may be useful, in special if the one-piece disk has large teeth, and if it spins horizontally. Blunt one-piece spinning shells might also be useful.

We can use the same material selection criteria from blunt one-piece spinning bars, as long as we change beam grades to plate grades, so we need HB' > 45 and KIc* > 30, ordered by the average X* = (KIc* + HB') / 2. Interestingly, these are exactly the same criteria that optimize traditional armor plates, resulting in almost the same materials.

So, the best materials are then K12 Dual Hardness, AerMet 100, HP-9-4-30, AerMet 310, 18Ni(250), 18Ni(300), Ti-6Al-4V ELI, 18Ni(200) and Ti-6Al-4V, all of them with X* > 50. Tempered 4340 or 5160 steels are not bad options, but not one of the best. Avoid low hardness steels such as 1020 (which will yield very easily, as seen on the spinning disk tooth on the right), and medium-low toughness steels such as S7.

Note that the K12 Dual Hardness steel is probably a bad idea for disks. Although one of the disk surfaces would have HB' = 100, the other one, which is also exposed, would only have HB' = 73. K12 would be fine for shell spinners, as long as the harder surface is facing outwards.

**Spinning disks, shells and drums with inserts**

If your disks, shells or drums have inserts (as pictured below), then they can have a lower hardness to improve fracture toughness.

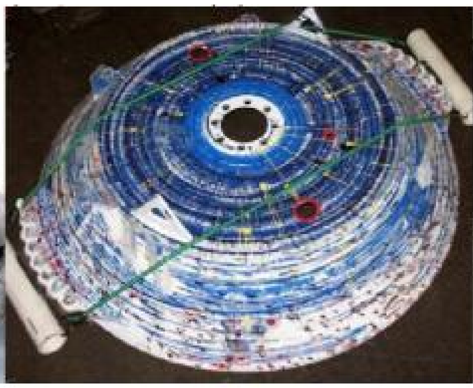
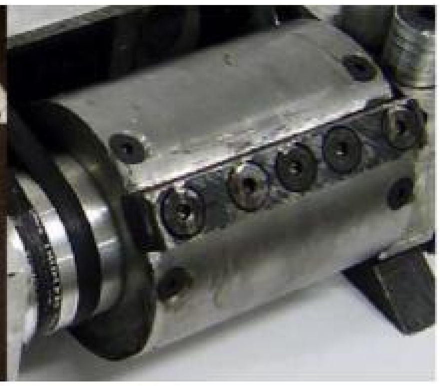
We can use material selection criteria similar to the ones for spinning bars with inserts, if the beam grades are changed to plate grades. So, we'll choose materials with KIc* > 50, E* > 70 and Sy* > 70, and order them by the average grade X* = (KIc* + E* + Sy*) / 3. These are the same criteria used for integrated structure-armor plates, resulting in the same material choices: ZK60A-T5, AZ31B-H24, Elektron 675-T5, Elektron WE43-T5, 2324-T39 Type II, 7475-T7351, 7175-T736, 7055-T7751 or T74 and 7050-T7451, all of them with X* > 73. The aluminum alloys 7075-T73 or T6 and 2024-T3 would be the next options. As we did with integrated structure-armor plates, avoid Ti alloys, steels and polymers.

Note that Ti-6Al-4V ELI is as good as most aerospace aluminum alloys for spinning bars with inserts, but it is significantly worse for spinning disks and drums with inserts. This is not an obvious conclusion, only after the above analyses we were able to show that.

So, the best spinning disks, shells and drums with inserts are made out of high toughness Mg and Al alloys. But these materials result in a high maintenance disk, shell or drum, due to ablation. The picture to the right shows that the aluminum drum of our featherweight Touro Feather, although still functional, has suffered a lot of ablation. This loss of material ends up unbalancing the drum, requiring it to be changed after a few tournaments. On the other hand, its tempered S7 steel teeth are high hardness inserts, with very little loss of material (despite some brittle chipping that can be noticed around their countersunk holes).

**Low maintenance spinning disks, shells and drums with inserts**

If you want a low maintenance disk, shell or drum, such as the ones pictured below, then you need to select a material with a higher hardness grade, for instance HB' > 45, in addition to the high average grade for plates X* = (KIc* + E* + Sy*) / 3.

If we also only choose materials with KIc* > 25, E* > 35 and Sy* > 40, to avoid distortions in the X* average, then we end up with exactly the same criteria for wedges. So, after having ruled out Mg and Al alloys due to their low hardness, the best materials would be Ti-6Al-4V ELI and Ti-6Al-4V, with X* equal to 64 and 63, respectively. The next choices would be AerMet 100, followed by 18Ni(250), HP-9-4-30, 18Ni(200), 18Ni(300), tempered 4340, AR400 and tempered 5160, all of them with X* > 42.

## Minimum Weight Weapon Inserts

The most important properties of weapon inserts are high impact and fracture toughnesses. If they must remain sharp, then high hardness is also important. Three types of inserts are studied below.

**Sharp plate-like weapon inserts**

Clampers, lifters and launchers usually use sharp inserts at the tip of their arms to help scoop the opponent. These scoops are basically plates under bending, working as wedges. Therefore, the wedge design analysis can be used here, resulting in Ti-6Al-4V ELI and Ti-6Al-4V scoops. But the lower HB' between 49 and 50 of these alloys might require high maintenance to keep them sharp at every combat.

So, for a low maintenance scoop, a higher hardness is desired, for instance HB' > 75. With this new restriction, the same analysis used for sharp one-piece spinning disks can be applied for these scoops, resulting in AerMet 100 as the best material, followed by 18Ni(300), AerMet 310, S7 steel at 54HRc, 18Ni(350) and AerMet 340. Alternatively, 5160 tempered at 46HRc can be used, but it has a lower HB' = 65 than the other high strength steel options.

**Sharp beam-like weapon inserts**

Most weapon inserts, such as drum, disk, shell or bar teeth (pictured to the right), spear tips, or sharp thwack, overhead thwack or crusher tips, can be modeled as beams. This is because they usually have both their width and thickness (or their diameter) as free parameters.

To retain their sharpness, we need to select high hardness materials. Forget about Ti-6Al-4V inserts, its grade HB' = 50 won't stand a chance to keep sharp against hard traditional armor or wedge materials such as AR400, with HB' = 60. You'll need something harder than that, preferably with HB' > 75. These hardness and toughness requirements are then similar to the ones used for sharp one-piece spinning bars, resulting in the same optimal materials: AerMet 100 is the best, followed by 18Ni(300), AerMet 310, S7 steel at 54HRc, 18Ni(350) and AerMet 340, coincidently the same materials selected for sharp plate-like inserts.

Inserts usually have complex geometries, such as the puzzle-like fitting between the aluminum spinning bar from The Mortician and its hardened steel inserts, pictured to the right. These fittings are essential to guarantee a strong connection during high energy impacts, helping to avoid sheared bolts. Note, however, that sharp notches should be avoided in the insert, because the high hardness steel in general does not have a very high fracture toughness, typically

KIc** < 33. So, if intricate geometries are necessary, use large notch radii (typically of a few millimeters) to avoid high stress concentration factors (denoted by Kt), which might lead to the fracture of the insert.

For instance, the Kt of an 8mm deep notch with a sharp 0.5mm radius can be roughly estimated by $Kt = 1 + 2 \cdot (8mm / 0.5mm)^{0.5} = 9$, meaning that any stresses near this notch will be locally multiplied by 9. For very ductile and low hardness metals (such a 304 stainless steel) this may not be a problem, because these 9 times higher stresses will probably cause the notch to plastically deform and get blunt. This would increase the notch radius and thus decrease the Kt from 9 to much lower values, even lower than 2. But high hardness metals usually don't have enough ductility to blunt the sharp notch, keeping in this example the Kt in its original high value equal to 9.

Even though the bar is usually made out of a softer material than its insert, it is also a good idea to avoid sharp notches as well in the bar (or disk, drum, handle). In special if the notch is very close to a threaded hole, which can have Kt of up to 7, because both Kt would get multiplied. For instance, if the sharp notch from the previous example (with Kt = 9) was very close to a threaded hole, the resulting Kt could be as high as $9 \times 7 = 63$. The amazing 63 times higher notch root stress would certainly break a very hard low ductility material. Tougher materials such as the ones used in the bars would be able to lower this Kt through blunting, but maybe it would still be high enough to cause fracture. So, avoid sharp notches at all costs. And never thread any hole from high hardness inserts, always leave the threads, if necessary, to the lower hardness bars, disks, drums and handles.

Using plain through holes can be a good option to avoid the stress concentration from the threads, as seen on the bar to the right, where nuts are used to hold the two bolts from the insert. Note, however, that through holes such as the ones shown in the picture should only be drilled in a very thick bar, otherwise they'll significantly lower its cross section area, compromising strength.

If your inserts are still breaking even after removing all sharp notches from their geometry, then you'll probably need to sacrifice hardness a little bit to improve the impact and fracture toughnesses, by changing the material or the heat treatment. Earlier versions of the S7 steel drum teeth of our middleweight Touro had been tempered to hardnesses between 57 and 59 Rockwell C (HRc), to guarantee their sharpness. However, as seen to the right, this led to their premature fracture in combat. The newer teeth now have a slightly lower 54 HRc hardness, but with a much better impact toughness.

**Blunt beam-like weapon inserts**

Hammer heads (as pictured to the right), which may be used in hammer, thwack or overhead thwack robots, are usually made out of blunt inserts, which do not need to be sharp. Medium-high hardness is still important, but now we can lower our minimum HB' grade requirement from 75 (for sharp inserts) to, for instance, 45, allowing us to have more material options and also improve other properties such as fracture toughness.

Since the diameter (or other cross-section dimensions) of hammer heads is a design parameter that can be varied, we conclude that these blunt inserts can also be modeled as beams. It is easy to see that these blunt inserts with HB' > 45 have basically the same requirements of blunt one-piece spinning bars, resulting in the same material choices: AerMet 100 as the best, followed by HP-9-4-30, 18Ni(250), Ti-6Al-4V ELI, 18Ni(200), 18Ni(300) and AerMet 310. Other good choices are Ti-6Al-4V, 4340 (at 34HRc) and 4340 (at 39HRc). So, if sharpness is not important, then high toughness titanium alloys are also good choices for inserts, together with high toughness hardened steels.

## Minimum Weight Clamper and Crusher Claws

Since clamper and crusher robots have relatively slow active mechanisms, acting without impacts, it is more important to have claws with high Su and Sy than high KIc. Claws are basically beams working under bending, therefore to minimize their weight it is important to choose materials with high Su** and Sy** grades.

If high hardness inserts are used at the tips of the claws, as pictured to the right, then the choices for the claw material can include low hardness alloys. We then select the materials with a high average grade X** = (Su** + Sy**) / 2, resulting in Elektron 675-T5 as the best, followed by 7055-T7751, 7175-T736 and 7075-T6, all of them with X** > 85. Other reasonable choices are, in that order, 18Ni(350), 7050-T7451, Ti-6Al-4V, 7055-T74, ZK60A-T5, AerMet 340 and 7075-T73, all of them with X** > 80.

Note that these material choices didn't consider the possibility of the claws receiving impacts, in special from spinners. Otherwise, you'll need to choose claw materials with high KIc** as well. So, if the claw must withstand high impacts as well, the best material choices would be the same as for spinning bars with inserts, such as the Mg alloys ZK60A-T5 and AZ31B-H24, which have high KIc** grades for beams.

Note also that the Mg and Al alloy options may require high maintenance, due to their low hardness. If low maintenance is also desired, then the best material choices would be the same as for low maintenance spinning bars with inserts, such as Ti-6Al-4V ELI.

Finally, if you want to use one-piece claws (as pictured to the right), without tip inserts, then very high hardness is required. The best choices would then be the same as for sharp one-piece spinning bars, such as AerMet 100 or 18Ni(300).

## Minimum Weight Trusses

The weight optimization analysis of trussed elements, which can be used in the structure of trussed robots (as pictured to the right, using welded steel tube trusses), is relatively simple.

Besides composites and Be alloys, we've shown that all steels, Al, Ti and Mg alloys result in similar stiffness-to-weight ratios for trusses, which depend on E/ρ. To find the best materials, it is then a matter of looking for the ones that maximize Sy/ρ, Su/ρ and KIc/ρ at the same time, since a trussed robot structure needs high Sy not to get bent, high Su to bear static loads and avoid fatigue, and high KIc to withstand impacts and cracks. The previous table shows the minimum weight truss grades E***, Sy***, Su*** and KIc*** for several materials, obtained by normalizing the E/ρ, Sy/ρ, Su/ρ and KIc/ρ ratios using the best materials in the table.

Most trussed robot designs have their trusses exposed or only partially covered by armor plates, allowing them to take direct hits. So, we'll give more importance to KIc*** than to Su***. We choose then the materials that have higher average grade X*** = (KIc*** + Sy***) / 2, requiring as well that KIc*** > 40 and Sy*** > 50.

The best truss material from the table is Ti-6Al-4V ELI, followed by Ti-6Al-4V, AerMet 100, 18Ni(250) and 18Ni(200), all with X*** > 60. Other good choices are HP-9-4-30 and 4340 tempered to 39HRc, both with X*** > 50. Note that 304 stainless steel wasn't chosen, despite its high toughness, due to its low Sy that will allow the frame to easily get warped. And S7 and 18Ni(350) weren't chosen either, because of their insufficient fracture toughness.

The above options (with X*** > 50) are fine if the robot trusses will be bolted together. But if you want to use welds to join them, then their material will also need to have a high weldability. The above Ti alloys are still the best choice, but you might have trouble welding the presented high strength steel options, even the 4340 steel. There's no point in having high strength trusses if they're joined by weak welds. So, a good alternative to 4340 would be 4130 steel which, despite its lower Sy and Su, results in stronger welds due to its lower 0.3% carbon content, instead of 0.4% from 4340. But note that, after welding the 4130 steel trussed frame, it needs to be heat treated to relieve residual stresses from the welds and to achieve higher Sy and Su through temper. This means that repaired 4130 welds at the pits during a competition will probably be weak spots in the following fights, unless they're somehow heat treated.

Ti-6Al-4V and Ti-6Al-4V ELI, on the other hand, in addition to their highest X*** grades, don't need to be hardened after welding, resulting in a much better choice for repairs if proper welding equipment is available at the pits. Their only disadvantage is the higher cost.

Note that bamboo is not represented in the table, however it has a great stiffness-to-weight ratio for trusses, comparable to the performance of metals, grading E*** = 94. Its fracture toughness grade is not too bad, KIc*** = 31, comparable to low toughness aluminum alloys. The strength grades for trusses Su*** = 19 and Sy*** = 19 are relatively low compared to high strength metals, however they are actually higher than the grades from 1020 steel, used in civil engineering. So, it's not a surprise to see that China is using bamboo-reinforced concrete to build high-rises. Note however that bamboo has only about half the KIc*** of 1020 steel, which might mean bad news during an earthquake. For combat, bamboo is not a good option, because most high strength metals will result in much better strength and toughness grades. Also, bamboo trusses, despite being light, would end up with a very high volume, leaving a limited room inside the robot to mount its components. Not to mention the challenge in putting together the bamboo trusses with strong and light joining elements.

## Minimum Volume Design

All minimum weight problems presented in the previous section can be used to choose materials that make your robot lose weight without losing stiffness, strength or toughness. But what if a component needs to have its mechanical properties improved? Well, if there's space to increase the volume of the component (such as in most structural or armor elements), then this shouldn't be a problem, it is just a matter of weight optimization, using the grades from minimum weight design. If the material has not yet been optimized, then you should first change it depending on the functionality of the component, as explained before. After that, you only need to increase the component thickness (for plate elements) or cross section area (for beam and truss elements) until the desired improved properties are obtained.

But there are other components that cannot (or should not) have their volume increased. For instance, a gear that keeps breaking cannot be replaced by a thicker one without modifying the gearbox. A shaft that keeps yielding cannot have its diameter increased without changing its bearings and collars. These examples are volume optimization problems, requiring a minimum volume design, instead of minimum weight, as described next.

Minimum volume design has the goal to find the best materials to optimize the performance of a component while minimizing its volume. It assumes that the weight of the component can be increased, if necessary, but in most cases its dimensions cannot be changed. The idea is to design a component for a desired functionality with the lowest possible volume. Alternatively, if a component is failing in combat and its dimensions should not be changed, then the idea is to improve its mechanical properties only by switching its material, without changing its dimensions, while adding as little weight as possible.

Minimum volume design is quite straightforward in the case where the dimensions must be kept constant. Since the volume is not changed, it is just a matter of directly comparing the material properties. This is more easily performed if we normalize the mechanical properties using the best materials from the presented table, resulting in a system of grade points between 0 and 100 for minimum volume. These grades are represented by the property followed by the ' symbol, namely

E', Sy', Su' and KIc', shown in the previous table.

Note that minimum volume grades are completely different than minimum weight grades. Polymers are always the worst choice, by far, for minimum volume parts, with grades lower than 4 (out of 100). Al and Mg alloys are also very bad options, none of their grades is higher than 35. Even Ti alloys are not good, their highest grades only go up to 53.

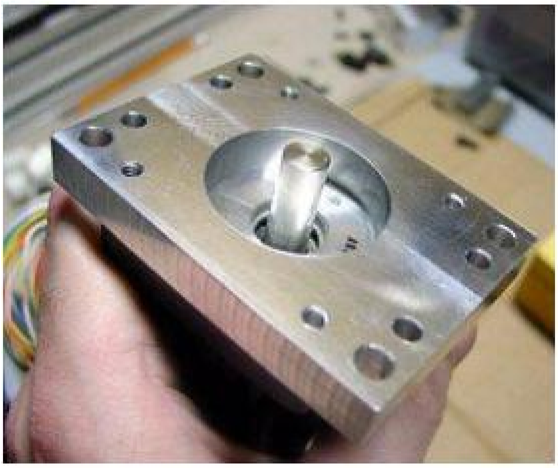
Therefore, steels are always the best choice if you need to minimize volume. Their E' grades are always between 88 and 100. The best material from the table for a minimum volume component with high yield and ultimate strengths is the 18Ni(350) maraging steel, with Sy' = 100 and Su' = 100. The best choice to maximize fracture toughness is the 304 stainless steel, with KIc' = 100.

Note that, except for titanium alloys, almost all Su' grades are only within 4 points from HB' grades. This is no surprise, because there are good correlations between Su and hardness for different metal alloy families, as mentioned before. For instance, you can estimate Su ≅ 3.4 · HB for steels within a few percent. So, in most metals, high hardness and high Su usually come together for minimum volume design. This trend is also true for titanium alloys, but the correlations are not as good.

Note also that the Su grades are very different than HB grades for minimum weight design, because the strength of the component depends not only on its material but also on its shape and functionality, while hardness is a local property that only depends on the material.

The main minimum volume design problems in combat robots are presented next.

### 3.10.1. Compact-Sized Internal Mounts



Very compact robots sometimes need to minimize the volume of internal mounts so they can fit inside. For instance, an internal mount attached to the face plate of a drive system motor may have thickness limitations, in special if the motor cannot be shifted too much inside the robot or if its output shaft is not too long, as pictured to the right. If the 6061-T6 aluminum motor mount in the picture didn't have enough stiffness or strength, you'd probably have to switch its material. Minimum weight design would tell you to use magnesium alloys, but their higher thickness (despite their lower weight) would make it hard to mount any wheel or pulley in such short output shaft. This is a problem of minimum volume design.

So, to improve the properties of the internal mount, we'd need to choose materials with better minimum volume grades. Since internal mounts should have high stiffness as well as high ultimate and yield strengths, we'll select materials with highest average grade X' = (E' + Su' + Sy') / 3.

The best material to minimize volume would then be 18Ni(350) maraging steel, followed by AerMet 340, AerMet 310, 18Ni(300), AerMet 100 and S7 tempered at 54HRc, all of them with average grade X' > 80. Other options would be 18Ni(250), HP-9-4-30, and 4340 tempered to 43HRc, all with X' > 70. But note that all these steels will result in heavier mounts. This is the price you pay to minimize volume.

If you're also concerned with weight, then you'll have to compromise a little the minimum volume requirement. The idea is to find the lowest density material that will satisfy your X' requirement, without significantly increasing the volume of the component.

For instance, in the above example, the 6061-T6 aluminum has X' = 19 and density ρ = 2.7. We won't even bother looking for polymers or Mg alloys, because mounts with same volume would have much worse mechanical properties since their X' is always below 3 and 17, respectively. For polymer or Mg alloy mounts to have similar or better mechanical properties than our 6061-T6 mount, they would need to have a much higher thickness, due to their lower density.

We'll then start looking among all aluminum alloys, which have approximately the same density ρ, between 2.66 and 2.86. The highest X' among them is 28.5, for the 7055-T7751 alloy, which would result in a better mount with about the same weight and volume as the 6061-T6 version.

If this X' is still low for your application, or if you still need to decrease the thickness (and therefore the volume) of the mount, then look into Ti alloys. Their density ρ between 4.4 and 4.6 is not too much higher, and you'll be able to achieve X' = 43.7 for the alloy Ti-6Al-4V.

Finally, if you still need a higher X' or a lower thickness, look into steels. You'll end up with a heavier mount, due to their higher density ρ between 7.7 and 8.0, but you'll be able to achieve up to X' = 98.9 for high strength alloys such as 18Ni(350). And you'll be able to get a much thinner mount, such as the steel motor mount pictured to the right.

## Compact-Sized Drums

Spinner bars and disks naturally have a high moment of inertia. Therefore, usually the inertia and strength requirements can be met just by switching the material and changing the bar or disk thickness, which was already studied in minimum weight design. On the other hand, designing a compact drum is a little trickier, as seen next.

**Compact-sized drums with inserts**

If we assume that the drum thickness can be changed (changing the drum internal diameter), then we're facing a minimum weight design problem. It was already seen that Mg and Al alloys with high strength and toughness are the best options for drums with inserts, optionally using Ti-6Al-4V for low maintenance versions.

This could be fine for very fast spinning drums, such as the aluminum drum of our featherweight Touro Feather, which compensates its low moment of inertia with a high spin. Or it could be fine for drums with large outer diameter, such as the aluminum drum from the middleweight Stewie, which can reach a large moment of inertia despite its low density material.

But our low profile drumbot Touro has limited values for the drum outer diameter D (about 5", without its S7 teeth inserts), as well as for its mass m (about 11.6kg or 25.6lb) and length L (180mm, a little over 7"). These values cannot be arbitrarily increased without changing the design of the rest of the robot. A minimum weight design would select the low density Mg or Al alloys, which would result in a drum with high thickness and therefore low internal diameter d. For a drum material with density ρ, it is easy to show that $d^2 = D^2 - 4m/\rho\pi L$, which lowers as ρ decreases.

But, for a given drum mass m and outer diameter D, a very low internal diameter d would lower the moment of inertia $I_{zz} \cong m \cdot (D^2 + d^2)/8$. For Touro, we decided that the resulting lower Izz, combined with a moderate 6,000RPM drum speed, would make an Al or Mg drum have low energy. To maximize Izz, we had to use a material with the highest possible density. A natural choice was steel, due to its ρ between 7.7 and 8.0. Denser metals would be either too expensive (such as tungsten, tantalum, silver, gold, platinum), too brittle if unalloyed (such as molybdenum, cobalt), or too soft (such as lead).

By selecting steels, we were able to get a 1” thick drum wall, which was thick enough to mill channels to hold the teeth without compromising its strength. If the resulting thickness was too thin, we would probably need to use the lower density Ti-6Al-4V for the drum, reducing somewhat the Izz but adding enough thickness to be able to mill the channels without compromising strength.

But now, which steel should we use? We once tried a hardened 410 stainless steel for the drum body, trying to achieve a low-maintenance drum. This was not a good choice, because this high strength steel has only a moderate fracture toughness, while the drum body has several stress risers such as milled channels and threaded holes. Not surprisingly, the drum not only fractured along the threaded holes, but also sheared at the notch root of its tooth channel (as seen on the right), all at the same time during its first impact test against a dead weight.

We had to change the material to improve the impact toughness. Since it is a minimum volume problem, we had to look at the E', Sy', Su' and KIc' grades of the material candidates. We know that the drum does not lose functionality if it yields locally, so Sy’ is not that important for drums that have teeth inserts (unless there’s some major yielding that might compromise the tooth support or unbalance the drum). The grade E’ is almost the same for all steels, so it doesn't need to be considered.

Most of the loads on the drum are due to impacts, related to the grade KIc'. The static loads, related to the grade Su', are relatively small, they're mostly due to the centrifugal forces of the drum teeth. For instance, each of the 0.63kg (1.39lb) teeth from the 2007 version of Touro's drum, which spin at 6,000RPM (628 rad/s) from a radius 0.065m (2.56"), generates a centrifugal force equal to $0.63 \cdot 628^2 \cdot 0.065 = 16{,}150$N, equivalent to 1,646 kgf or 3,629 lbf. This might seem a large static force, but it is small compared to the dynamic loads generated when hitting a stiff opponent. So, the grade Su' is not as important as K Ic'.

So, this is a volume optimization problem to maximize KIc'. The best option among the studied materials is the 304 stainless steel, with KIc' = 100. Other good options are, in that order, 4340 tempered at 34HRc, 18Ni(200), 1020 steel, HP-9-4-30, 18Ni(250), 4340 at 39HRc and AerMet 100, all of them have KIc' > 50.

Avoid using S7 steel, its KIc' at 54HRc is only 25, it could break in a similar way as shown above, near the notches. If the drum has inserts, there is no need to make the drum body out of a very hard material, lowering its impact toughness. Use hard materials only where they are needed, such as on the drum teeth, which must remain sharp. Avoid as well using other steels that might have KIc' < 50.

Avoid using as well polymers, magnesium, aluminum and titanium alloys, not only due to their low density, but also due to their KIc' < 50.

This is why Touro's drum body is made out of 304 stainless steel (KIc' = 100), to hold the sharp tempered S7 steel teeth. The only downside is the low yield strength of 304, but this is not much of a problem for the body of a drum. It easily yields, but it also withstands huge impacts, such as the one that broke the spinning bar of Terminal Velocity at Robogames 2007 (the resulting indentation is pictured to the right).

The drum body of our lightweight Touro Light had already been machined using 410 stainless steel, the same material from Touro's fractured drum, before that fracture happened.

Instead of machining another drum out of 304 stainless steel, we've decided to save money by keeping the 410 version, but without hardening it through heat treatment. Without tempering the 410 steel, it ended up with a much higher impact toughness than the tempered version, and the much lower yield strength wouldn't be a problem for the drum body. The 304 steel would be a better choice, but the 410 steel without temper was almost as good, surviving Robogames 2007 while leading Touro Light to a gold medal.

**Compact-sized sharp one-piece drums**

Sharp one-piece drums have their body and teeth milled out of a single bar or block, as a single piece. They are not very popular with the heavier robots, because they're not easy to machine, and if a tooth breaks they need to be entirely replaced.

But they're a good option for lighter robots, such as insects. Teeth inserts for insect classes are very delicate to machine and temper, and they're not simple to attach to the tiny drum body. Teeth made out of hardened flat-headed allen bolts are a popular choice, but their hardness never exceeds 44 Rockwell C, even if using class 12.9 bolts. A one-piece drum can be hardened between 51 and 55 Rockwell C and still have a high toughness, if its material is wisely selected.

To maximize the one-piece drum moment of inertia, it is important to choose a dense material such as steel. So, if the drum outer diameter and width cannot be changed, then we end up facing a minimum volume problem.

We'll choose then steels that have minimum volume grades HB' > 70 to guarantee tooth sharpness, KIc' > 20 to avoid drum body or tooth fracture, and Sy' > 60 to avoid bent teeth. By choosing the average X' = (KIc' + HB') / 2 as a grading criterion, the best materials are AerMet 100, 18Ni(250), 18Ni(300), and AerMet 310, all of them with X' > 55. Another good choice is S7 steel tempered at 54HRc. Avoid using polymers, Mg, Al or Ti alloys, or steels with low hardness or with X' < 45.

## Compact-Sized Shafts, Gears and Weapon Parts

Shafts, gears and most weapon parts are subject to impacts. If their volume cannot be increased but their mechanical properties must be improved, then we face again a minimum volume problem.

For instance, the weapon system of our middleweight spinner Titan originally used a TWM 3R2 gearbox. This nicely crafted sturdy gearbox is made out of a solid aerospace aluminum block, with tempered steel gears and a special titanium shaft adapted for spinning weapons. After very severe tests and a lot of abuse, we ended up bending the titanium shaft (pictured to the right). The shaft dimensions cannot be increased, otherwise it won't fit in the gearbox, so it's a minimum volume problem. We thought that an S7 steel shaft tempered to 54 Rockwell C (HRc) would be a good replacement, despite its higher weight. It has more than twice the ultimate and yield strengths of Ti-6Al-4V, which would certainly prevent it from getting bent. But our S7 steel shaft ended up breaking in similar tests (see picture above). Experiments don't lie. So why did it happen?

S7 steel already has lower toughness than Ti-6Al-4V in specimens without notches, as seen from their minimum volume grades KIc' equal to 25 and 33, respectively. It is not much of a difference, but this difference is exacerbated if sharp notches are present. By notch we mean any change in the geometry of the part, such as holes, grooves, fillets. Sharp notches should always be avoided because they are stress risers. But sometimes they are inevitable, such as in keyways.

Our titanium shaft was so ductile (with $\varepsilon f$ = 45%) that it was able to blunt its sharp notches during the impact and avoid the effects of stress concentration. It's true that it got bent, but at least it withstood the impact without breaking (a broken shaft in your bot will award your opponent many more damage points from a judge than a bent one). But the lower ductility of the S7 steel wasn't able to blunt the sharp notches from its keyway, concentrating the impact energy on that point and making it break. In summary, S7 is notch-sensitive, it exhibits relatively high impact strength in the unnotched condition or if it has notches with generous radii, but it has a very severe degradation in its impact absorbing ability if it has sharp notches. So, S7 steel was a poor choice.

One alternative would be to change the keyway geometry to increase the notch radius, switching the square key to a round one. Another option would be to change the material to 4340 steel tempered to 43 Rockwell C, which would result in about the same ductility as Ti-6Al-4V ($\varepsilon f = 45\%$) and a much higher Su = 1450 MPa. This combination would result in a much better impact strength than both S7 and Ti-6Al-4V, even in the presence of notches, due to 4340's relatively high ductility, preventing it from breaking. And its higher ultimate and yield strengths would prevent it from getting permanently bent as it happened with the Ti-6Al-4V shaft.

But there are even better options than 4340 steel. Let's look for materials with minimum volume grades KIc' > 30 to avoid fracturing, and Sy' > 50 to avoid getting bent, ordering them by their average grade X' = (KIc' + Sy') / 2. Hardness and stiffness are also important in shafts, as discussed before, so let's look as well for HB' > 45 and E' > 85.

So, the best materials for compact-sized shafts are, in that order, 18Ni(250), AerMet 100, and 18Ni(200), all of them having X' > 60. Other good options are 18Ni(300), AerMet 310, HP-9-4-30, 4340 (tempered to 40-43HRc), and 5160 (tempered to 44-46HRc), all of them with X' > 45. Avoid using polymers, Mg, Al or Ti alloys, medium-low strength steels (such as 1020, 1045 and 304), and medium-low toughness steels (such as S7, 18Ni(350) and AerMet 340)

The above material choices are also applicable to compact-sized gears, which must also have high KIc' and Sy', together with high HB' to prevent tooth wear, and high E' to prevent excessive deflections.

Compact-sized weapon parts that do not get in touch with the opponent can also be included in this category.

But if the weapon part touches the opponent, then its material choice should be the same one used for compact-sized one-piece drums, to retain sharpness due to HB' > 70 instead of only requiring HB' > 45, resulting in AerMet 100, 18Ni(250), 18Ni(300), AerMet 310 and S7 steel tempered at 54HRc, and excluding lower hardness options such as 4340 and 5160.

## Conclusions on Materials Selection

The main conclusions from the material optimization analyses presented in this chapter are:

- aluminum and magnesium alloys in general, especially the high strength ones, are a very good choice for protected structural walls, integrated structure-armor, structural top covers, bottom covers, ablative armor and internal mounts. They're also a good choice for the body of weapons that have inserts, such as spinning disks, shells, drums, bars and eggbeaters with inserts, hammer, thwack or overhead thwack handles, spears with inserts, lifter and launcher arms with inserts, and clamper and crusher claws with inserts. In all the above applications, avoid using steels, even high performance steel alloys.

- Ti-6Al-4V titanium, in special the ELI version, is the best material for wedges and for minimum weight shafts, gears and trusses. It is a very good option for the body of low maintenance weapons that have inserts, such as low maintenance spinning disks, shells, drums, bars and eggbeaters with inserts, and low maintenance hammer, thwack or overhead thwack handles. It is very good as well for blunt weapons such as blunt one-piece spinner disks, shells, bars and eggbeaters, blunt hammer heads, and blunt thwack or overhead thwack tips. It is also a good option for traditional armor, rammer shields and non-structural top covers.

- steels that combine high toughness, high strength and high hardness are the best materials for traditional armor, rammer shields, non-structural top covers, as well as compact-sized shafts, gears and weapon parts. They are also the best option for sharp weapon parts such as one-piece spinning disks, shells, drums, bars and eggbeaters, one-piece spears, and sharp weapon inserts (such as teeth, spear tips, clamper, lifter or launcher scoops). Together with Ti-6Al-4V, they're also a good option for blunt one-piece spinner disks, shells, bars and eggbeaters, blunt hammer heads, blunt thwack or overhead thwack tips, and minimum weight trusses.

- because shafts are basically beams under bending (and torsion), theoretically aluminum and magnesium alloys would be better candidates than steels for minimum weight shafts. However, an aluminum shaft would need to have a much larger diameter than an equivalent one made out of steel, which would imply in larger bearings, larger gears and pulleys, and larger gearboxes, increasing the robot weight. Therefore, hardened steel shafts are better than aerospace aluminum ones. Ti-6Al-4V titanium is the best option for minimum weight shafts, as long as the weight saved by the shaft is not gained by the slightly larger bearings, gearboxes, etc, when compared to the ones from a steel shaft. As a reference, steel shafts that drive the wheels of robust middleweights usually have diameters between 15 and 20mm (0.59" and 0.79", but it depends on the robot type and number of wheels it uses), and the main steel shafts for spinning weapons may vary from 25 to 40mm in diameter (0.98" to 1.57", but it depends, of course, on the weapon type).

- avoid using plastics such as Lexan in the robot structure, even as armor plate. Even relatively tough polymers such as Lexan and UHMW are not recommended to be used as structural parts. Structural plates made out of the best polymers can achieve higher stiffness-to-weight, strength-to-weight and toughness-to-weight ratios than most steels, however high strength aluminum and magnesium alloys are much better in all those cases. In addition, polymer plates need to be very thick to outperform steels, which will significantly increase the volume of the robot. Lexan used to be an attractive armor material due to its transparency to radio signals, because an all-metal robot used to suffer from the Faraday cage effect. However, the high frequency radios used nowadays, such as the 2.4GHz ones, do not have much problem with all-metal robots. So, plastics should be avoided in structural parts.

The table in the next page summarizes all the weight and volume optimization analyses performed in this chapter.

It is interesting to note that the know-how of experienced builders, coupled with the "survival of the fittest" principle from the theory of evolution, has made several combots converge to very good if not the best material choices studied in this chapter, for instance:

- AR400 (or 4340 steel) for very hard wedges, or Ti-6Al-4V for not-so-hard wedges, both used by Devil's Plunger;
- spinner bars made out of aerospace aluminum and lightly notched S7 steel inserts, used by Last Rites and The Mortician;
- shock mounted Ti-6Al-4V top covers against vertical spinners, used by Pipe Wench;
- Ti-6Al-4V for very light shafts, such as the ones used in the TWM 3M gearboxes;
- aluminum alloys as integrated structure-armor elements, such as Team Plumb Crazy's 6061-T6 extrusions for the unprotected walls (which in theory are unprotected, as long as we do not define red wheels as armor elements!); and
- trussed robots made out of welded and tempered 4130 steel tubes, as in Last Rites and The Mortician (noting that 4130 steel is not the best truss option, but it is the cheapest and most easily weldable among the good ones).

On the other hand, this chapter has shown that there's still a lot to evolve, such as:

- making more use of high strength magnesium alloys for structural parts;
- using high toughness magnesium and aluminum alloys as ablative armor plates;
- using AerMet and maraging alloys in weapon inserts, replacing S7 steel, as well as in compact-sized shafts, replacing 4340 steel, and even in traditional armor plates, replacing Ti-6Al-4V; and
- replacing Ti-6Al-4V with Ti-6Al-4V ELI to improve impact toughness.

Finally, one might think that several high performance materials discussed in this chapter aren't used in combat because of high cost, but this is not entirely true. Most of them are not used because they're not very well known or understood. Magnesium alloys are the third most used structural metal in the world, it is not difficult to find high strength Mg alloys in surplus dealers at a low cost. The ELI version of Ti-6Al-4V, with improved impact properties, is not too difficult to find either. Maraging steels are expensive, but they can be bought in small quantities, they're worth using in critical compact shafts. AerMet alloys such as AerMet 100, on the other hand, are not only expensive, they're difficult to buy in small quantities, they're difficult to machine, and their heat treatment is very complicated, but it is worth the trouble if you want a steel as hard as S7 with 2.15 times higher impact toughness.

I hope that this chapter will, among other things, help making these high end materials more popular in combat robot design.

In the following chapter, the joining elements are studied, necessary to join the presented materials with enough stiffness and strength.