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September 2009

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Pacman charges up his blade and tests his metal against the titanium tank Fir Darrig. Photo by Kevin Berry.

then I drilled and tapped additional holes to connect the blade to the gear. Volià! A sturdy hub to mate the two objects together.

After some decorations, the robot named "Pacman" was ready just in time for the competition. While it was not the best, it was a favorite to the audience, as they chanted "Wakka wakka wakka!" when Pacman was called to compete. The serpentine belt system worked like a charm, the robot drove with great control, and I was relieved to know that I had survived the two-day gauntlet with a record of five wins and two losses.

Robot building is similar to school work. There are deadlines, there are excuses, and there are lessons to be learned in both. Just remember your robot building basics and there will be no pressure when your robot is due! SV

MANUFACTURING: RioBotz Combat Tutorial Summarized — Materials

● Original Text by Professor Marco Antonio Meggiolaro; Summarized by Kevin M. Berry

Professor Marco Antonio Meggiolaro of the Pontifical Catholic University of Rio de Janeiro, Brazil, recently translated his popular book, the *RioBotz Combot Tutorial* into English. In June and July, *SERVO* summarized Chapter 2, "Design Fundamentals." This month, we continue the series with a summary of the first part of Chapter 3, "Materials," focusing on commonly used metals in combat bot building. Marco's book is available free for download at: **www.riobotz.com.br/en/tutorial.html**, and for hard copy purchase — at no profit to Marco — at **www.lulu.com/content/7150541**. All information here is provided courtesy of Professor Meggiolaro and RioBotz.

Mechanical Properties

There are several terms needed to understand the properties of materials. Most materials start off deforming in an elastic manner, meaning they spring back after being bent. This is dependent on the stiffness, or "Young Modulus." After some point, the elasticity is lost. The material begins to yield, meaning it no longer springs back to its original shape. This is called "plastic deformation." It continues yielding (bending) until it reaches a value called the ultimate strength, where it breaks. Ductility is another term related to how well it deforms without breaking, related to the above terms in a way requiring a lot more explanation that we can do here.

The above values are usually tested in a slow manner. Dynamic, or "fast" loads use the terms resilience and impact toughness. Resilience is how much impact energy it can take before it starts to yield, or bend. Toughness tells how much impact energy it absorbs before breaking.

How do we use this information? A tough material is not necessarily resilient, and vice versa. For instance, the stainless steel (SS) type 304 — the most used SS — tolerates large deformations but it is easily yielded. It is very tough, being good for armor plates that can be deformed. However, it has low resilience, 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, with a very high yield strength, and thus it has a high resilience. However, 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.

Fracture toughness is another useful term which means how well it resists propagation of cracks. This is related not only to the material itself, but the geometry of the actual piece being used.. Thinner plates, for example, can deform more easily than thick ones, and absorb more energy per unit volume.

Hardness is the resistance to penetration by other 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.

Among all the properties presented here, 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. Let's look at some specific types of materials.

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 the average being 7.8 (which means 7.8 times the density of water, or 7.8 kg per liter of the material).

Their stiffness also varies very little. 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

TABLE 1

TYPE	ALLOY CONTENT	STRENGTH (BREAKING)	STRENGTH (YIELDING)	IMPACT TOUGHNESS	RECOMMENDED HARDNESS (AFTER HT)	COST	GOOD USES	POOR USES
1018, 1020 Steel	Low Carbon (0.18-0.20%)	Low, breaks easily	Low, bends easily	High	Low (108HB), only its surface can improve hardness with HT	Low	Inexpensive structure, light duty shafts	Weapons, armor
1045 Steel	Medium Carbon (0.45%)	Medium, after HT	Medium after HT	Medium	Medium-Low, 27HRc	Low	Gears, shafts, machine parts	Weapons, armor
1095 Steel	High Carbon (0.95%)	Medium-High after HT	Medium-High after HT	Low, brittle	Medium-High, more than 39HRc	Medium-Low	Springs, cutting tools	Weapons, armor
4130 Steel	Medium-Low Carbon (0.30%) plus Chromoly	Medium-High after HT	Medium-High after HT	Medium-High	Medium, 36HRc	Medium-Low	Trussed structure, welding	Weapons, armor
4340 Steel	Medium Carbon (0.40%) plus Chromoly and Nickel	High after HT	High after HT	High	Medium-High, 40-43HRc	Medium	Shafts, gears, weapons, armor	Lightweight structure
AR400 Steel (Abrasion Resistant)	Similar to 4340	High after HT	High after HT	High	Medium-High, 43HRc	Medium	Armor, wedges	Lightweight structure
5160 Steel (Spring Steel)	Medium-High (0.60%) plus Chrome and Manganese	High after HT	High after HT	High	Medium-High, 44-46HRc	Medium	Weapons	Lightweight structure
304 Stainless Steel	18% Chrome plus 8% Nickel	Medium-low	Low, bends easily	Highest	Low, 153HB, does not harden with HT	Medium	Armor	Shafts
S1 and S7 Tool Steel	Medium Carbon (0.50%) plus several alloy elements	Very high after HT	Very high after HT	Medium	High, 54HRc	Medium-High	Weapon teeth	Heavily notched parts
AerMet 100	Nickel and Cobalt	Very high after HT	Very high after HT	High	High, 53HRc	Very High	Shafts	Large parts, it's VERY expensive
Maraging Steel	18% Nickel, plus Cobalt and Molybdenum, Low Carbon	Very high after HT	Very high after HT	High	High, 46-61HRc depending on the alloy	High	Shafts, weapons, weapon teeth, armor, wedges	Large parts, it's expensive
K12 Steel (Dual Hardness)	High Carbon plus Chromoly and Nickel (Front)	Very high after HT	Very high after HT	Medium-High	Very High, Front 58-64HRc, Back 48-54HRc	Very High	Armor	Non-flat parts
Cast Iron	High Carbon (>2.5%)	Low	Low	Very Low	Depends on the type, 11-65HRc	Low	Bearing housings	Impact applications

TYPE	STRENGTH (BREAKING)	IMPACT TOUGHNESS	FABRICATION	COST	GOOD USES	POOR USES
6063-T5 (Architectural)	Low	Medium-Low	Weldable	Low	Internal Structure	External Structure
6061-T6	Medium	Medium	Weldable	Medium	Structure	Shafts, Wedges
5083-H131, H116, H32	Medium	High	Weldable	High	Thick Armor	Structure
2024-T3, 7050-T7451, 7075-T6, 7475-T7351 (Aerospace)	High	Medium-High	Hard to weld	High	Structure	Wedges
Alusion foam	Very Low	High (per weight)	Hard to weld	High	Ablative armor	Structure

TABLE 2

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°C, or 1,472 to 1,652°F, but it varies a lot with the steel type), 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°C, or 392 to 1,112°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 larger reliability in the resulting mechanical properties. **Table 1** shows a few of the main types of steel used in combat robots.

Aluminum

Aluminum is a very light metal, with about 1/3 of the density of steels — about 2.8 — which makes it very attractive for robot structures. Its stiffness is also around 1/3 of steel. Many types of aluminum exist, usually denominated by a four 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; it should be avoided.

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 Yield and Ultimate strengths, they are naturally the most expensive. The 7000 series alloys usually have higher strength than the 2000 series, but sometimes this comes along with a lower fracture toughness.

Aluminum alloys already come heat treated from the factory, which saves us time and money when building a combat robot. Be careful with the letter T in the denominations; the number after it indicates which heat treatment was used. For instance, the aluminum 6061-T6 has much higher strength than 6061-T4, which underwent a different HT. The main types of aluminum alloys are listed in **Table 2**.

Titanium

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. This makes their strength-to-weight ratio so attractive that they're used in 42% of the F-22 fighter aircraft. Its stiffness is about half the one of steels. They are non-magnetic, non-toxic, and extremely resistant to corrosion.

Titanium generates beautiful white sparks when it is ground (or hit by weapons in the box, making it a crowd pleaser). Care should be taken with titanium chips from machining; they are flammable. We've carefully made several mini-bonfires with titanium chips in the lab; they generate a very intense white light. (Note: I've burned up TWO table saws this way. Literally burned up. Note to self: Don't cut titanium on the same saw you use for wood!)

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 hand drill). 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, so 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.

It is possible to color titanium, using a process which will be covered in a future *SERVO* "Parts Is Parts" article.

Commercially pure titanium — the most common of which is grade 2 — 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.

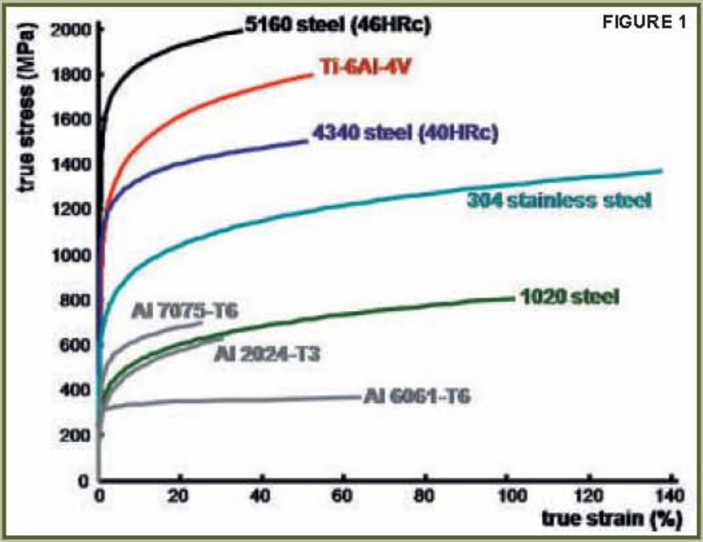
FIGURE 1

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 can be heat treated, however the increase in ultimate strength is small. 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. Unfortunately, titanium grade 5 is expensive, and builders usually obtain it from resellers or scrap yards.

If you need 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 about 10% in the yield and ultimate strengths.

Titanium is usually reserved for armor, but sometimes structural or mechanical parts are made from it.

The graph in **Figure 1** compares properties of common aluminum, steel, and titanium alloys.

These stress-strain 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 fracture strain. 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. Note from the areas under the curves that Ti-6Al-4V has similar impact toughness to 5160 steel, but with almost half the weight.

Other Materials

This book also covers less popular materials such as magnesium, copper, nickel, beryllium, Tungsten, and even more exotic materials from the bottom of the periodic table. Metallic glasses are also covered. In the spirit of condensing the data, the reader is referred to the source for these discussions.

Summary — Metallic Materials

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 Team Plumb Crazy's bots.
- 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!).
- 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, 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.
- Replacing Ti-6Al-4V with Ti-6Al-4V ELI to improve impact toughness.

Non-metals — very popular material in combat bots — will be discussed in Part 2 of this article in an upcoming issue of *SERVO*. SV