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Materials Selection

Materials for mechanical watches

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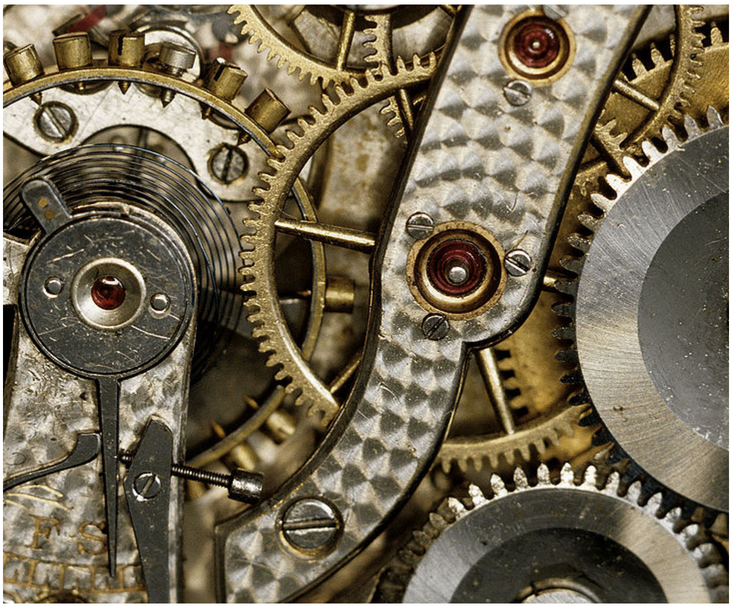

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Chapter 1

Introduction

In close relationship with the course of Materials Selection, we will study the best-suited materials for mechanical watches. To do so, we will introduce what are mechanical watches and how they work. Then, we will focus on existing solutions, from where we will look after new and/or innovative solutions. This, thanks to a computer software (CES) and additional resources. We will finally discuss about all selective criteria we are choosing from to get the most optimized watch we could.

Chapter 2

About mechanical watches

2.1 What are mechanical watches made of?

Mechanical watches are complex systems that can be divided into an external part and an internal part. The internal part is made of mechanisms that are swinging a spring whose goal is to indicate the time thanks to a set of wheels called the *geartrain*. The external part is everything containing the mechanism, such as e.g. a protective layer over the display, some matter around the watch, or a wristband.

2.1.1 Internal part

A mechanical watch is made of different toothed wheels, or *gears*, illustrated on Fig.2.1 and described below.

The main wheel, sitting on a barrel, contains a spring, called the *main spring* or *barrel spring*, that gives energy to a swinging mechanism. The barrel contains an arbor that moves freely inside the barrel. The main spring is fixed to the arbor thanks to a hook on one side, and to the internal face of the barrel on the other side.

Over the main wheel, coïnciding whith the same axis, we find the *ratchet* whose movement is controlled by a *click*. The ratchet is linked to the crown wheel, and the click forbid the ratchet of moving counterclockwise while winding up the main spring. The crown can be manipulated by the watch-user to wind it up, or change the time.

We can also find a couple of light wheels, called *center wheel*, *third wheel* and *fourth wheel*, which are linking together the main spring whith the swinging mechanism. On each one, a pinion is attached; as such, the wheels are connected one another through their pinions.

At the end of the chain, we find the swinging mechanism, or precisely *escapement*, a part where an escape wheel, pallets and a balance wheel are brought together. The entry and exit pallets are fixed on the main pallet. The balance wheel is not perfectly circular and is fitted with some weights, whose goal is to set the wheel swinging movement with a given period.

The balance spring is fixed underneath the balance wheel thanks to a staff and a stud.

2.1.2 External part

As we now have a mechanism, it needs to be fit into some case. We all know what watches look like from the outside. Old watches were quite heavy and hanged by a chain coming from a pocket. Nowadays, watches are light and worn on the wristle. The materials that may be used and their application will be discussed later in this chapter.

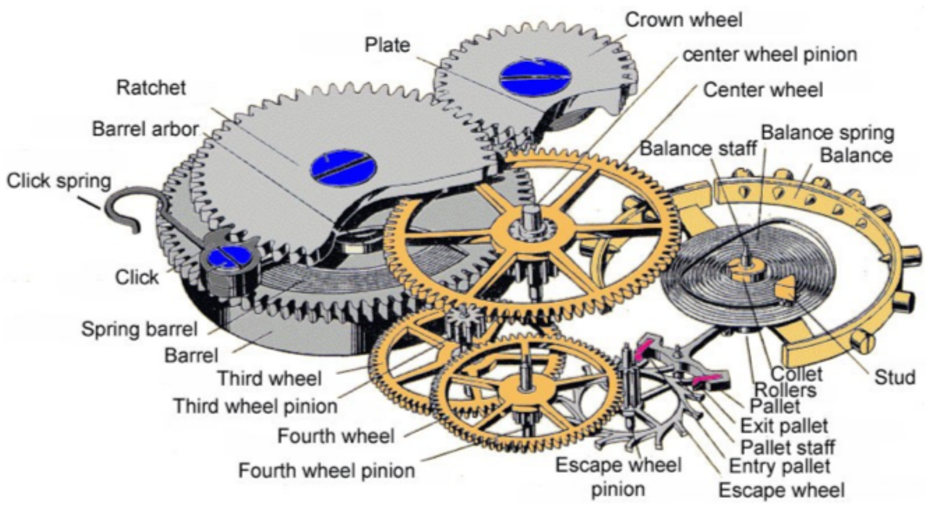

Figure 2.1: Wheels in a mechanical watch

2.2 How do mechanical watches work?

To initiate the watch movement, the user has to wind up its watch. This has for effect to wind up the main spring which contracts itself and gets more strain energy.

As the spring would like to get back to its initial position, it pulls the barrel drum that, in turn, transmits a radial force to the geartrain. From one wheel to another, the force transmits to the escapement.

The escape wheel is not shaped as every other toothed wheels. It has a design that makes it moving only step by step. In a first move, the escape wheel touches the first pallet, called the exit pallet, which in turn moves the main pallet, pushing the roller on one side and so swinging the balance wheel. While the balance moves, the exit pallet blocks the escape wheel. As the balance wheel is linked to its spring, it gets back, pushes on the main pallet on the other side while at the same time the escape wheel turns and gives another pulse.

The main pallet moves the balance wheel back and forth : the movement we just created gets self-sustained at a given period. One can hear the pallet contact with the roller through the "tic, tac" sound, familiar with watches or even cheap clocks.

2.3 Review of materials in nowadays watches

Early watches are mainly made of several kind of steel. For coatings, a thin layer of stainless steel can be deposited.

Watches nowadays make a big use of materials such as plastic and alloys. We can find other materials, sometimes precious and expensive for crucial mechanical parts. Wristbands are very different from one watch to another : It can be made of leather, steel, plastic or even cardboard for low-value watches.

The mechanism is mainly made of metallic parts, the matter depending on the quality and/or the manufacturer. For **springs** [1], we usually use low-carbon steels or alloys based on Nickel, Cobalt or Titanium (e.g. Elgiloy, a Cr-Co-Ni-Fe-Mo-based alloy, or Nivarox, a Fe-Ni-Cr-Ti-Al-alloy). For **gears** [2], we use cast-iron or low-carbon steel alloys (hardened and tempered) because they are easily machinable; we can also use Brass, because it absorbs the gears noise.

To have watches looking more precious, manufacturer sometimes add some jewelry artifices, that can range from low-carats jewel to beautiful rubys.

The display are made of a glasses or polymers, which one having their qualities and defaults. Glasses are tough but fragile and can be easily ripped, while polymers can resist to shocks and ripping if attention is given in the design process.

2.4 Innovative materials

The quest for optimum materials for watch components is one of the branches of research at the forefront of watch innovations. Watch manufacturers are always on the search for exciting new materials. The goal of lots of these material innovations is to minimize the weight and friction losses without the use of oil which implies greater accuracy in mechanical movement and at the same time longer durability.

Several watch brands, such as *Ulysse Nardin*, *Omega* and *Patek Philippe*, produce watches with silicon pieces. For instance, *Patek Philippe* developed Silinvar (a patented substance derived from oxidising the constituents of pure silicium in a vacuum) to make several timepieces: an escape wheel that requires no lubrification, a balance spring which improves isochronism of the movement and an escapement which has a more efficient power transmission.

Patek Philippe has recently developed a new balance in gold and Silinvar. This choice of materials results from two criteria to optimize in a balance: to be as light as possible and to have a big inertia. Its chassis is etched in Silinvar for its low density while two inertial masses made in 24K gold are put at the periphery. This is, we minimize the mass near the axis of the balance and we increase its inertia.

Moreover, due to the high density of gold, the volume, and so the aerodynamic drag, can be minimized. But it requires an excellent manufacture precision. Indeed, by concentrating the mass on the outside of the balance, a default of mass positioning, i.e. an unbalance, would generate a harmonic excitation of high amplitude and would result in an unwanted dynamic response.

The key physical properties of Silinvar are :

- Its low density (3.6 times less density than conventional balance materials);
- Homogenity (uniform mass distribution);
- Antimagnetism;
- Resistance to corrosion;
- Hardness;
- Resistance to shocks;
- Manufacturing precision;
- Non susceptibile to temperature fluctuations.

From the above, this material is really the must for manufacturing timepieces.

Another watch manufacturer, *Omega*, has also created a balance spring in silicon. The balance spring is a critical element for precision. Indeed, it is extremely sensitive to shocks as well as to magnetic fields. Silicon allows to increase shock absorbency and stability while increasing resilience. It also eradicates the effects of any magnetic fields. So, this material contributes to the higher rate accuracy, lifespan, efficiency and reliability of watches.

Other brands target the lightness of watches. For instance, *Richard Mille* has developed a new material, called *Alusic*, to produce the case. It is a super light hybrid material – aluminum AS7G, silicon and carbon used for the production of ultra-light satellites, and another aluminum-lithium alloy for the tourbillion skeleton movement.

Finally, *Audemar Piguet* use carbon for its lightness and shock resistance.

Even if these materials are very innovative and functional, the traditional ones are still favored in watch productions for several reasons. First, steel pinions and brass wheels still provide the best friction coefficient. Secondly, these materials are familiar to watch manufacturers and watch repairers.

Chapter 3

Materials selection

3.1 Introduction

In this study-case, we will focus on the main parts contained in mechanical watches.

We will therefore consider the following parts, respectively **springs** (mainspring and balance wheel), **wheels** (gearbox, escapement, barrels and so on), **pallets**, **shafts** (wind-up mechanism), **case**, **gaskets**, **hands** (hours and minutes), **dial** and **wristbands**.

3.2 Springs

For the springs, our objective is to store as much energy as possible without failure while minimizing cost.

On one hand, the deformation energy of a spring is given by $W = \int \sigma \varepsilon dV$. On the other hand, the spring is submitted to the constraint :

$$\sigma = \frac{6M}{bt^2} \leq \sigma_f$$

where M is the couple applied on the spring, b the width and t the thickness. We can also deduce a free variable $\varepsilon = \frac{\sigma_f}{E}$.

Combining these three last expressions, it comes :

$$W = \int \frac{\sigma_f^2}{E} dV = \frac{\sigma_f^2}{E} \int dV = \frac{\sigma_f^2}{E} \frac{m}{\rho}$$

Therefore, we have to maximise one of the following expression :
- the elastic energy per mass unit $W = \frac{\sigma_f^2}{\rho E}$
- the elastic energy per volume unit $W = \frac{\sigma_f^2}{E}$.

The cost of the spring can writes $C = \rho c V$ where C is the total material cost, ρ the density of the material, V the volume of the spring and c the material cost per mass unit.

Since the stored energy U is assumed known, we can isolate the volume $V = \frac{UE}{\sigma_f^2}$ so that our expression becomes :

$$C = \frac{\rho c U E}{\sigma_f^2} = \underbrace{\frac{\rho c E}{\sigma_f^2}}_{\text{material}} \underbrace{U}_{\text{energy}}$$

Thus, we have to maximize :

$$W = \frac{\sigma_f^2}{E} \tag{3.1}$$

which gives in logarithmic scales :

$$\begin{aligned} \log W &= 2\log\sigma_f - \log E \\ \Leftrightarrow \log E &= 2\log\sigma_f - \log W \\ \Leftrightarrow y &= 2x - \log W \end{aligned}$$

From the last equation, we can draw an Ashby diagram in the software CES. This diagram shows which materials are maximizing the deformation energy with respect to the Young's modulus (see Fig. 3.1).

We also have to minimize the following expression :

$$M = \frac{\rho c E}{\sigma_f^2} \tag{3.2}$$

which gives in logarithmic scales :

$$\begin{aligned} \log M &= \log(\rho c E) - 2\log\sigma_f \\ \Leftrightarrow \log(\rho c E) &= 2\log\sigma_f + \log M \\ \Leftrightarrow y &= 2x + \log M \end{aligned}$$

Once again, we represent in CES an Ashby diagram that shows the materials which are minimizing the cost with respect to the stored energy (see Fig. 3.2).

By taking, say, the ten first materials suggested by CES and comparing them using the AND-method (see Tab. 3.1) with a weighted factor of 1, we have to convert the maximum criteria for stored energy into a minimum criteria. This is simply done by inverting the maximum criteria : $M_1 = \frac{1}{W} = \frac{E}{\sigma_f^2}$.

From Tab. 3.1, we see that the low carbon-steel alloys fullfit the imposed requirements. If we want to maximize the internal energy, we will preferabily choose Titanium alloys or Nickel super-alloys, but they are more expensive and difficult to manufacture. All polymers, such as CFRP or GFRP, must be eliminated because their deformation energy acts in a non-linear way – that's a behavior we would like to avoid in mechanical watches.

Therefore, we will choose low-carbon steel-based springs. This material is rather cheap, easy to manufacture and has a high fatigue strength limit (about 400 MPa for 10^7 cycles).

If we take into account the cost condition in addition to energy, machinability and fatigue strength conditions, we get another Ashby diagram illustrated on Fig. 3.3.

3.3 Wheels

In this section, we will discuss about the different wheels found on the watch, including the gearbox and the spring barrel.

The objectives to satisfy are multiple :

- Minimize the cost;
- Resist to shocks;

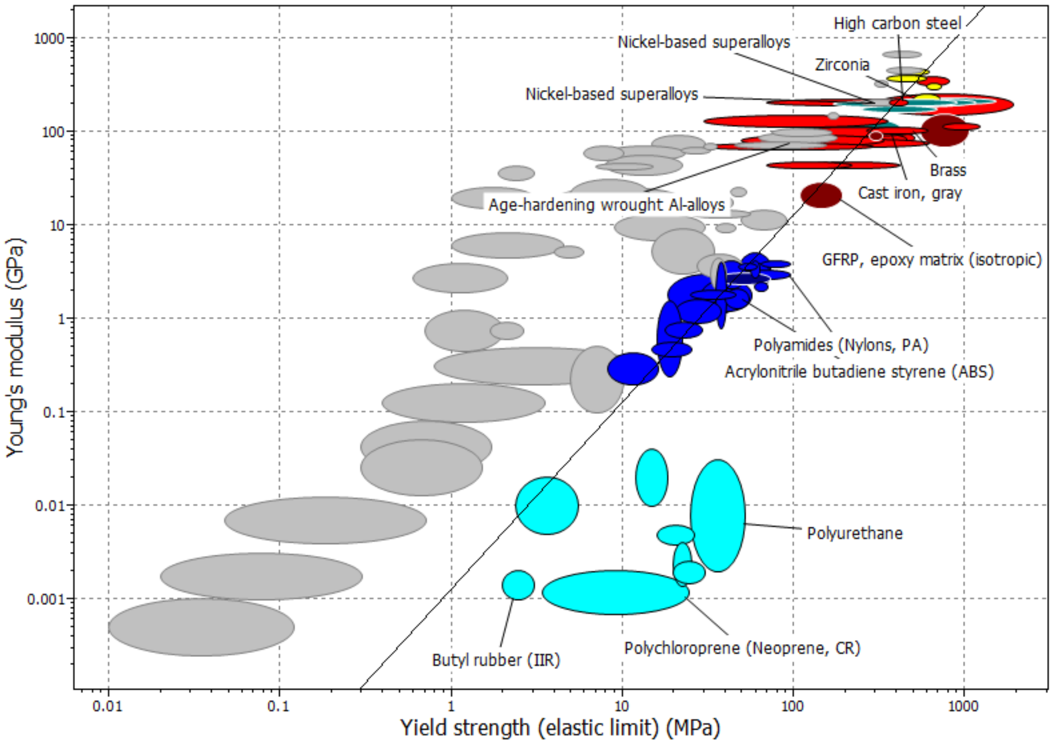

Figure 3.1: Materials maximizing the stored energy without any other constraint

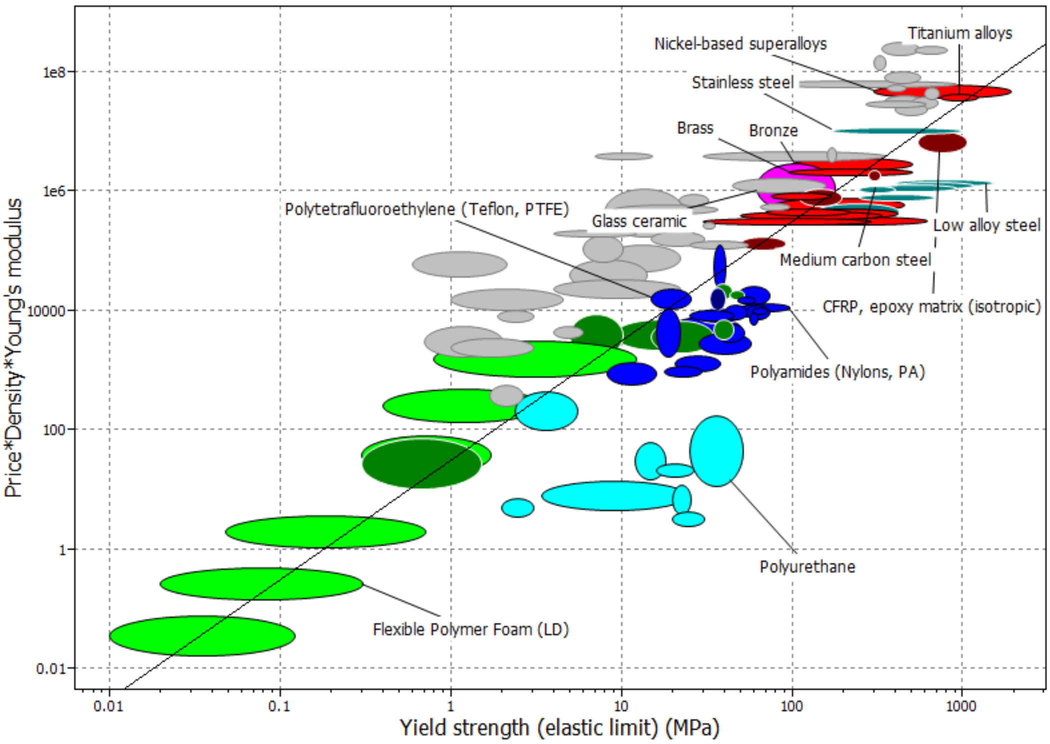

Figure 3.2: Materials minimizing the cost without any other constraint

Materials	$\rho[\frac{\mathrm{kg}}{\mathrm{m}^3}]$	E [GPa]	σ_f [GPa]	$c\ [\frac{USD}{kg}]$	$M_1 = \frac{E}{\sigma_f^2}$	$M_2 = \frac{\rho c E}{\sigma_f^2}$	M_{1a}	M_{2a}	M_{and}
Titanium alloys	4596	115	0.949	70	127.69	4.1081	0.0158	0.502	7.93110^{-3}
CFRP	1549	102	0.76	42	176.59	1.1499	0.0218	0.141	3.07410^{-3}
Aluminium-alloys	2693	70	0.093	1.66	8093.4	3.6181	1	0.442	4.4210^{-1}
High carbon-steel alloys	7850	207	0.681	0.76	446.35	0.266	0.0551	0.033	1.81810^{-3}
Low carbon-steel alloys	7850	211	0.775	0.85	351.3	0.234	0.0434	0.029	1.2610^{-3}
GFRP	1857	20	0.145	20.38	951.25	3.6001	0.1175	0.440	5.1710^{-2}
Stainless steel	7846	199	0.412	6.84	1172.4	6.29	0.1449	0.769	1.1110^{-1}
Bronze	8746	86	0.224	3.74	1714.0	5.6064	0.2118	0.685	1.4510^{-1}
Brass	8219	99	0.218	2.54	2083.2	4.3489	0.2574	0.531	1.3710^{-1}
Nickel-based alloys	8188	192	0.755	29.67	336.83	8.1828	0.0416	1	4.1610^{-2}

Table 3.1: This table sorts the ten best-suited materials for springs. M_{and} has to be minimized.

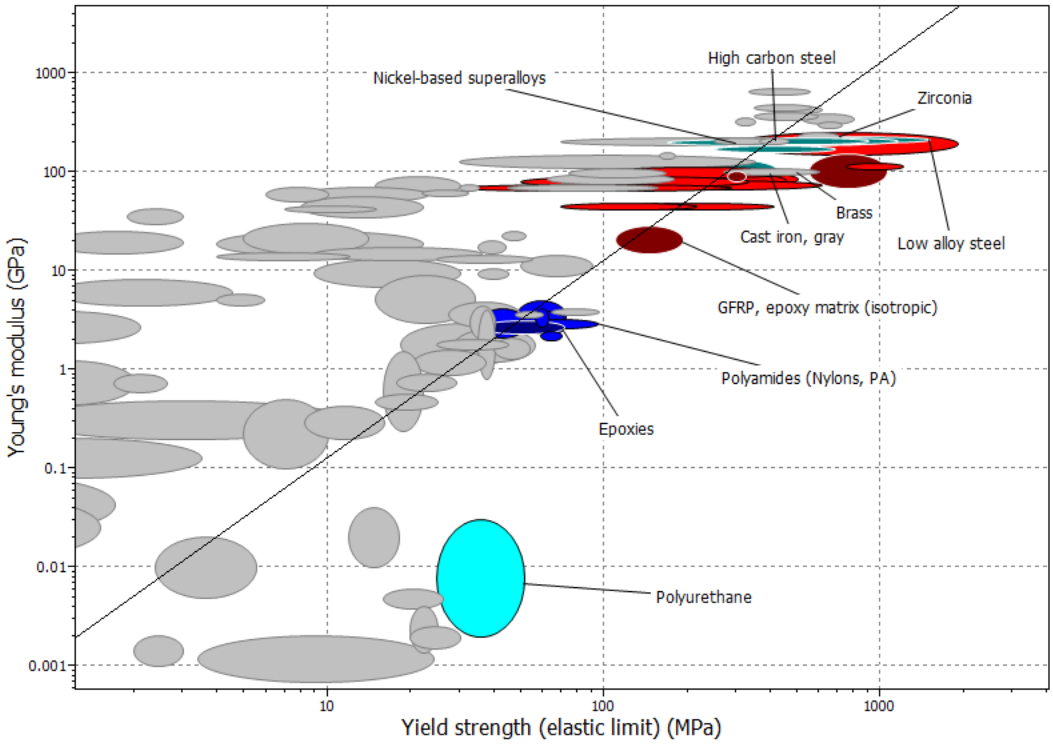

Figure 3.3: Materials minimizing cost and maximizing deformation energy, including fabrication easiness

- Easy to machine;
- Resistance to wear and tear.

The maximum stress to be applied to the wheels is given by this formula:

$$\sigma_{max} = \frac{1}{8}(3+\nu)\rho\omega^2 R^2 = \frac{m}{8V}(3+\nu)\omega^2 R^2 \leq \sigma_f \tag{3.3}$$

where ν is the Poisson's ratio, ω the pulsation, ρ the density, V the volume, m the mass and R is radius.

Since $V = 2\pi Rt$ with t the thickness, we can isolate our free variable t from the equation (3.3). So, we can minimise the cost by injecting the free variable t into :

$$C = \rho c V = 2\pi R t \rho c$$

and we find that

$$C = \underbrace{\frac{\rho(3+\nu)c}{\sigma_f}}_{\text{material}} \underbrace{\frac{mR\omega^2}{8}}_{\text{force}} \underbrace{R}_{\text{geometry}} \tag{3.4}$$

To minimize C, we also have to minimize $\frac{\rho(3+\nu)c}{\sigma_f}$. In logarithmic scales, it comes :

$$\begin{aligned} \log M &= \log(\rho(3+\nu)c) - \log \sigma_f \\ \Leftrightarrow \log(\rho(3+\nu)c) &= \log \sigma_f + \log M \\ \Leftrightarrow y &= x + \log M \end{aligned}$$

In CES, we draw a first Ashby diagaram (Fig. 3.4), without any other constraints.

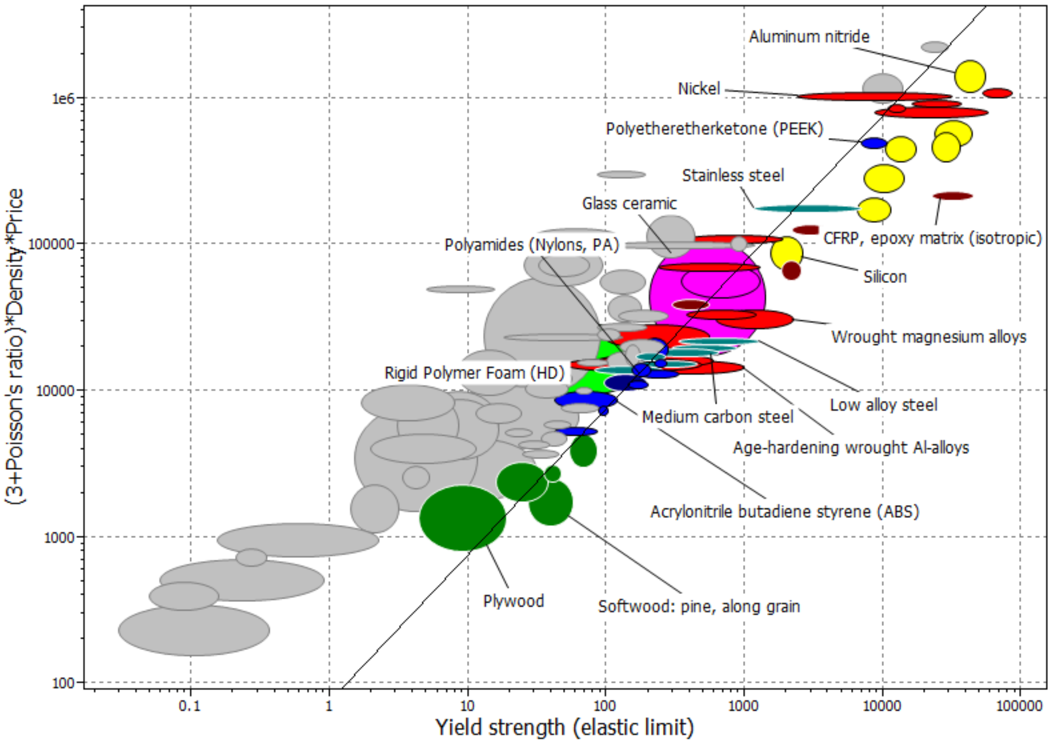

Figure 3.4: Materials minimizing cost for gears (without constraints)

We would also like to maximize the resistance to shocks :

$$W = G_c = \frac{K_c^2}{E(1+\nu)}$$

and in logarithmic scales :

$$\begin{aligned} \log W &= 2\log(K_{Ic}) - \log(E(1+\nu)) \\ \Leftrightarrow y &= 2x - \log G_{Ic} \end{aligned}$$

We get a second diagram (Fig. 3.5) in CES.

We look at the eight materials chosen by CES, and compare them in the table 3.2 using the AND-method with weight factor of 1. For this, we have to convert the maximum criterion of resistance to shoks into a minimum one. This is simply done by inverting the maximum criterion $M_2 = \frac{1}{W} = \frac{E(1+\nu)}{K_c^2}$.

We see on table 3.2 that the most convenient material is low-carbon steel. But if we consider the resistance to shocks for sole criterion, Brass is the most suitable material. We impose a minimum hardness of 150 HV (Vickers Pyramid Number) to satisfy the wear and tear tolerences. All the listed materials, excepted Aluminium alloys, satisfy these conditions.

By combining the two previous diagram, we draw the final graph 3.6 with all constraints and manufacturing limitations.

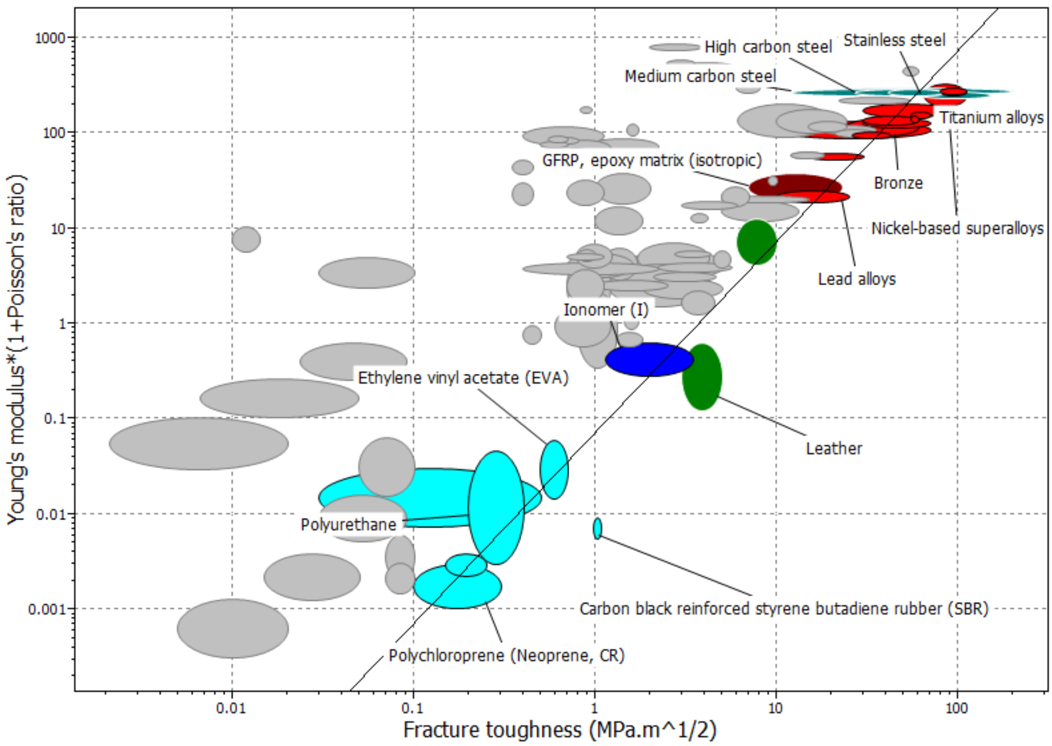

Figure 3.5: Materials maximizing the resistance to shocks for gears (without constraints)

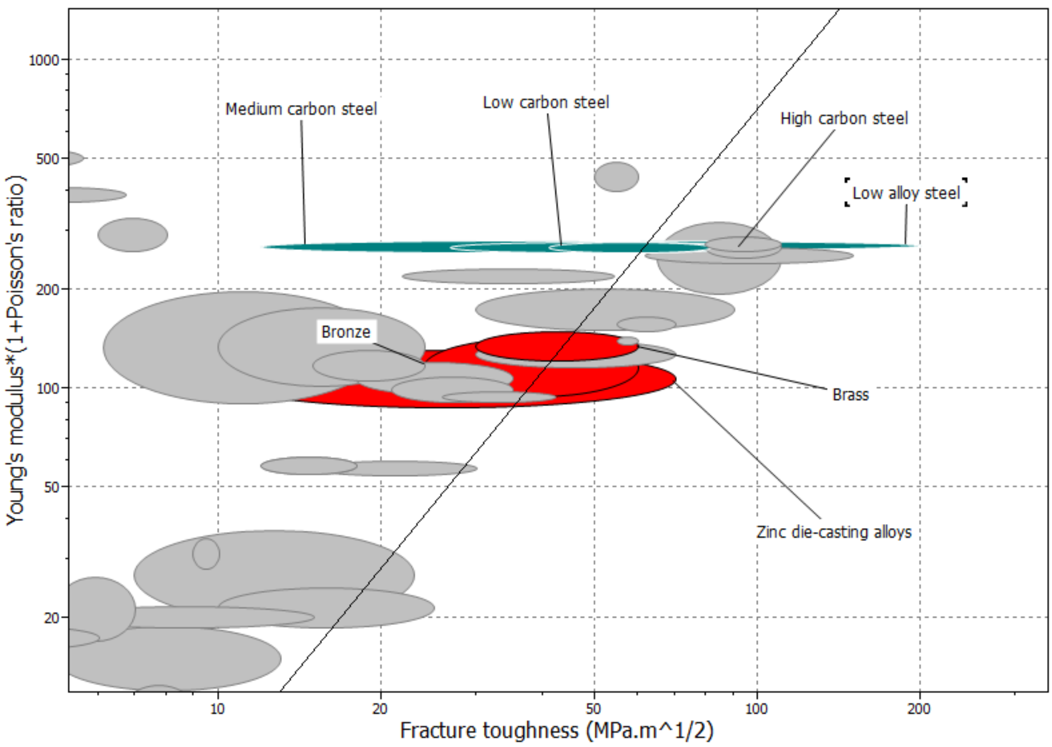

Figure 3.6: Materials minimizing cost, maximizing resistance to shocks and easily machinable

Material	$\rho[\frac{\mathrm{kg}}{\mathrm{m}^3}]$	ν [-]	$c\ [\frac{USD}{kg}]$	$\sigma_f\ [GPa]$	$E\ [GPa]$	$K_c\ [GPam^{1/2}]$	$M_1 = \frac{\rho(3+\nu)c}{\sigma_f}$	$M_2 = \frac{E(1+\nu)}{K_c^2}$	M_{1a}	M_{2a}	M_{and}
Low alloy carbon-steel	7850	0.29	0.846	0.775	211	0.0529	$2.819\ 1O^4$	$9.717\ 10^4$	$5.767\ 10^{-2}$	$4.001\ 10^{-1}$	$2.307\ 10^{-2}$
High carbon steel	7850	0.29	0.759	0.681	207	0.0498	$2.876\ 10^4$	$10.769\ 10^4$	$5.884\ 10^{-2}$	$4.434\ 10^{-1}$	$2.609\ 10^{-2}$
Medium carbon steel	7850	0.29	0.704	0.524	208	0.0332	$3.469\ 10^4$	$24.286\ 10^4$	$7.097\ 10^{-2}$	1	$7.097\ 10^{-2}$
Low carbon steel	7850	0.29	0.665	0.314	207	0.058	$5.467\ 10^4$	$7.956\ 10^4$	$1.119\ 10^{-1}$	$3.276\ 10^{-1}$	$3.666\ 10^{-2}$
Aluminium alloys	2693	0.34	1.688	0.093	70	0.033	$16.387\ 10^4$	$8.583\ 10^4$	$3.353\ 10^{-1}$	$3.534\ 10^{-1}$	$1.185\ 10^{-1}$
Zinc alloys	5886	0.32	1.214	0.190	82	0.027	$12.488\ 10^4$	$15.506\ 10^4$	$2.555\ 10^{-1}$	$6.385\ 10^{-1}$	$1.631\ 10^{-1}$
Brass	8219	0.35	2.537	0.218	99	0.042	$32.003\ 10^4$	$7.435\ 10^4$	$6.548\ 10^{-1}$	$3.061\ 10^{-1}$	$2.004\ 10^{-1}$
Bronze	8746	0.35	3.736	0.224	86	0.038	$48.877\ 10^4$	$8.007\ 10^4$	1	$3.297\ 10^{-1}$	$3.297\ 10^{-1}$

Table 3.2: This table sorts the eight best-suited materials for gears. The most suitable has to minimize M_{and}.

3.4 Pallets

The main pallet must resist to shocks and bending, while being as cheap as possible.

On one hand, maximizing the resistance to shocks and cracking implies maximizing the yield strength $W_1 = \sigma_f$ and the fracture toughness $W_2 = K_{Ic}$.

On the other hand, we have to minimize the deformation δ given by:

$$\delta = \frac{FL^3}{C_1 EI} \tag{3.5}$$

where F is the force, L the length, c_1 a tabulated constant, E the Young's modulus and I the second moment of inertia.

Since

$$\sigma_{max} = \frac{FL^2}{I} \leq \sigma_f$$

we can isolate I (our free variable) and replace it in the equation (3.5). So, we have to find the miminum for δ, with

$$\delta = \frac{\sigma_f L}{c_1 E}$$

We have $M_1 = \frac{\sigma_f}{E}$ which, in logarithmic scales, is written

$$\log E = \log \sigma_f - \log M_1$$

To minimize the cost $C = \rho c V = \rho c L \sqrt{12I}$, we replace I by the expression 3.5. We obtain:

$$C = \underbrace{\frac{\rho c}{\sqrt{\sigma_f}}}_{\text{material}} \underbrace{\sqrt{12\ F}}_{\text{force}} \underbrace{L^2}_{\text{geometry}}$$

or, in logarithmic scales:

$$\log \sigma_f = 2 \log(\rho c) - 2 \log M_2$$

where $M_2 = min(C)$.

In CES, we plot an Ashby diagram (Fig. 3.7) for all constraints, including for machinability.

To compare the materials bewteen them, we list them in table 3.3. For this purpose, we transform the minimum criteria into maximum ones: $W_3 = \frac{1}{M_1} = \frac{E}{\sigma_f}$ and $W_4 = \frac{1}{M_2} = \frac{\sqrt{\sigma_f}}{\rho c}$.

It appears that low-carbon steel is the most convenient material. Wood is eliminated because this material is hardly isotropic and doesn't resist much to cracks. Glass is also evicted because it is too brittle, while not fulfilling the everyday-use requirements. So, pallets in watches are most of the time made of metals or polymers.

3.5 Shafts

The wind-up mechanism is made of a shaft and a crown wheel. The shaft must withstand the torsional couple applied thanks to the crown wheel. Once again, minimizing the cost will be required.

Stress in torsion is written as

$$\sigma = \frac{4T_f}{\pi R^3} \leq \sigma_f$$

Material	$\rho[\frac{\text{kg}}{\text{m}^3}]$	$c\ [\frac{USD}{kg}]$	$E\ [GPa]$	$\sigma_f = W_1\ [GPa]$	$K_c = W_2\ [GPam^{1/2}]$	W_3	W_4	W_{1a}	W_{2a}	W_{3a}	W_{4a}	W_{and}
Low alloy steel	7850	0.846	211	0.775	0.0529	272.29	$1.326\ 10^{-4}$	1	0.912	0.339	0.802	0.248
High carbon steel	7850	0.759	207	0.681	0.0498	304.42	$1.386\ 10^{-4}$	0.879	0.859	0.379	0.838	0.240
Low carbon steel	7850	0.665	207	0.314	0.0580	659.88	$1.074\ 10^{-4}$	0.405	1	0.822	0.649	0.216
Aluminium alloys	2693	1.613	74	0.241	0.0271	306.39	$1.130\ 10^{-4}$	0.311	0.467	0.382	0.683	0.038
Cast iron	7149	0.654	172	0.412	0.0345	417.98	$1.373\ 10^{-4}$	0.532	0.595	0.521	0.830	0.137
Magnesium alloys	1710	5.474	44	0.217	0.0147	204.61	$0.498\ 10^{-4}$	0.280	0.253	0.255	0.301	0.0054
Bamboo	693	1.729	17	0.039	0.0059	441.37	$1.654\ 10^{-4}$	0.050	0.102	0.550	1	0.0028
Glass ceramics	2638	5.066	84	0.105	0.0016	802.54	$0.243\ 10^{-4}$	0.135	0.028	1	0.147	0.00056

Table 3.3: This table sorts the eight best-suited materials for pallets. The most suitable has to maximize W_{and}.

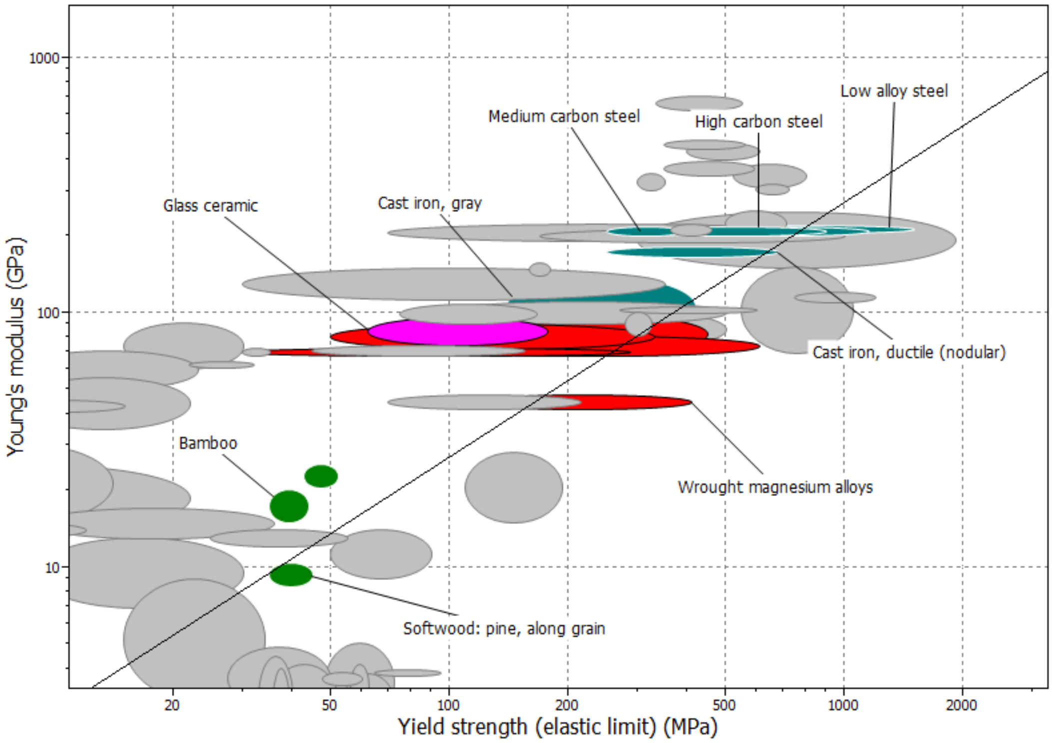

Figure 3.7: Materials which minimize the costs, maximise the shockes resistance, easily to manufacture and minimise the deformation for pallets

where T_f is the applied couple, R the radius (our free variable) and σ_f the yield strength. We thus have our first contraint on the material.

Minimizing the cost can be expressed as $C = \rho c V \approx \rho c \pi R^2 L$.

By eliminating R between the two last equations, we have:

$$C = \underbrace{\frac{\rho c}{\sqrt[3]{\sigma_f}}}_{\text{material}} \underbrace{\sqrt[3]{\frac{4T_f}{\pi}}}_{\text{force}}$$

so that we have to minimize $M = \frac{\rho c}{\sqrt[3]{\sigma_f}}$

$$\begin{aligned} \log M &= \log(\rho c) - \frac{2}{3}\log\sigma_f \\ \Leftrightarrow \log\sigma_f &= \frac{3}{2}\log(\rho c) - \frac{3}{2}\log M \\ \Leftrightarrow y &= \frac{3}{2}x - \frac{3}{2}\log M \end{aligned}$$

The Ashby diagram we represent in CES is free of constraints (Fig. 3.8). In this diagram, we see that the available materials are numerous. So, we introduce some constraint on machinability with a view to obtain a diagram where the number of materials is much more reasonable (Fig. 3.9).

We study the six materials included in the table 3.4. We see that Magnesium alloys and polymers can be used, but for aestetic reasons only metals are considered.

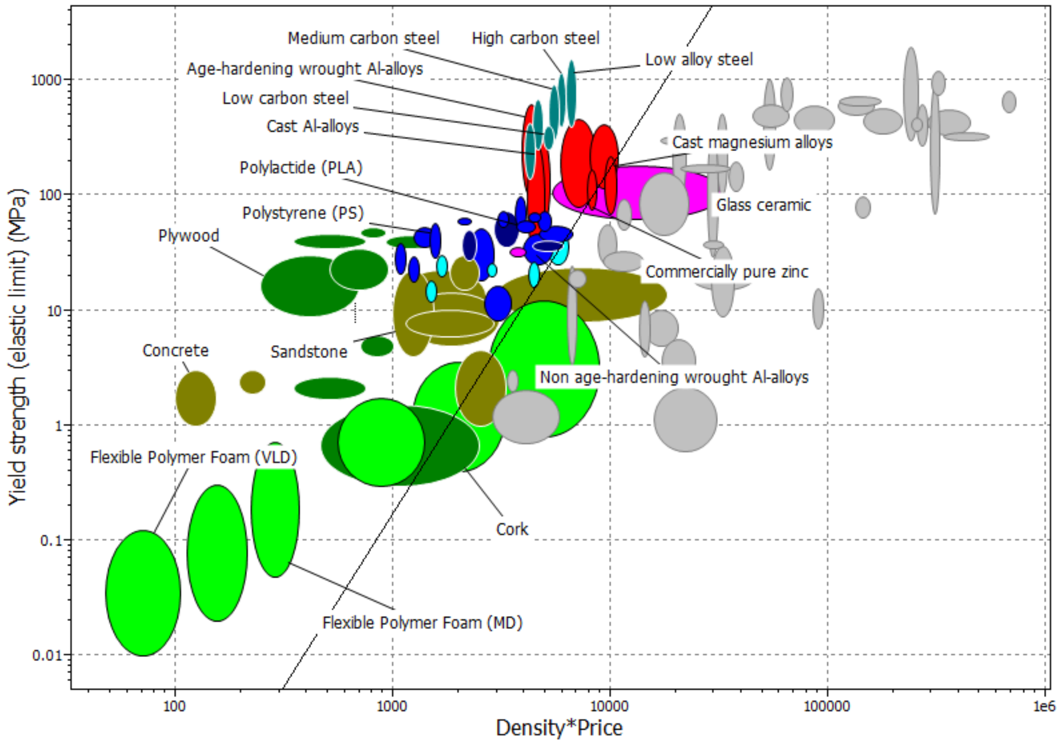

Figure 3.8: Materials which minimize the costs without other constraints for the crown wheel.

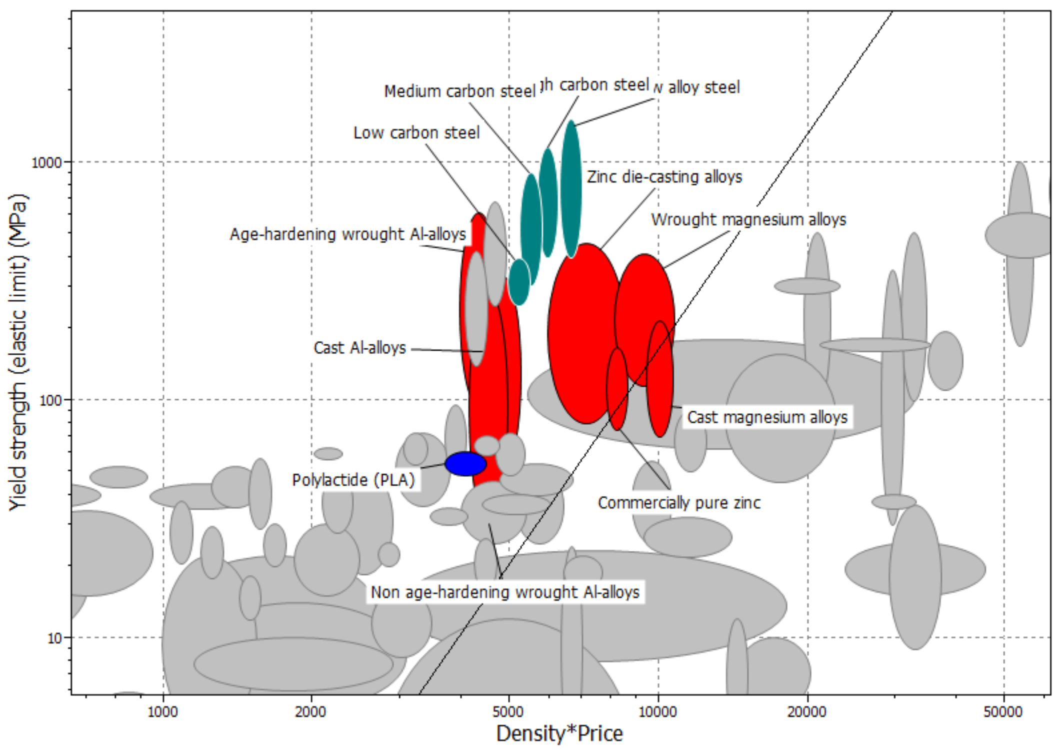

Figure 3.9: Materials which minimize the costs with some condition of the manufactoring facilities for the crown wheel.

Material	$\rho[\frac{\text{kg}}{\text{m}^3}]$	$c[\frac{\text{USD}}{\text{kg}}]$	σ_f [MPa]	M	M_a
High carbon steel	7850	0.759	681.18	76.96	0.189
Low alloy steel	7850	0.846	774.60	78.74	0.193
Aluminium alloys	2693	1.837	128.45	188.61	0.463
Zinc alloys	5886	1.214	189.74	216.40	0.531
PLA	1230	3.311	53.67	286.23	0.703
Magnesium alloys	1710	5.474	217.14	407.29	1

Table 3.4: This table sorts the six best-suited materials for shafts. The most suitable has to minimize M or M_a.

Material	E $[GPa]$	ν $[-]$	H $[VH]$	K $[GPam^{1/2}]$	W	W_a
Stainless steel	202	0.275	339	0.3015	0.1197	1
Nickel alloys	130	0.285	367	0.1342	0.0396	0.331
Gold alloys	90	0.330	248	0.1342	0.0374	0.312
HM carbon fiber	6	0.005	15	0.0217	0.0012	0.010
Fluoro elastomer	$3.1\ 10^{-3}$	0.4945	15	$9.397\ 10^{-4}$	0.0028	0.023

Table 3.5: This table sorts the five best-suited materials for watch cases. The most suitable has to maximize W or W_a.

3.6 Casings

The casing has to withstand shocks, corrosion and UV-rays.

To select a material fulfilling these conditions, we have to maximize both the hardness and the resilience :

$$W = HG_{Ic} = H\frac{K_{Ic}^2}{E(1+\nu)}$$

and, in logarithmic scales,

$$\begin{aligned} \log W &= \log(HK_{Ic}^2) - \log(E(1+\nu)) \\ \Leftrightarrow \log(E(1+\nu)) &= \log(HK_c^2) - \log W \\ \Leftrightarrow y &= x - \log W \end{aligned}$$

The corresponding Ashby diagram (Fig. 3.10) shows that metals and polymers have the best performance index. If we apply some limits, such as resistance to corrosion and UV-rays, we modify the diagram by removing undesirable materials (Fig. 3.11).

We studied five materials in the table 3.5. All of them resist to corrosion and UV-rays, and all are easily machinable.

We see that stainless steel perfectly fits the given conditions. Nevertheless, we also see on the diagram some unconventional materials like elastomer or carbon fibers, in addition to polymers, corks and precious metals (e.g. Gold, Titanium, Nickel, Silver, Tantalum).

Another approach is to deposit a non-corrosive metal on the casing, giving resistance to corrosion through a thin layer of, say, Gold, Chrome, Zinc or polymer.

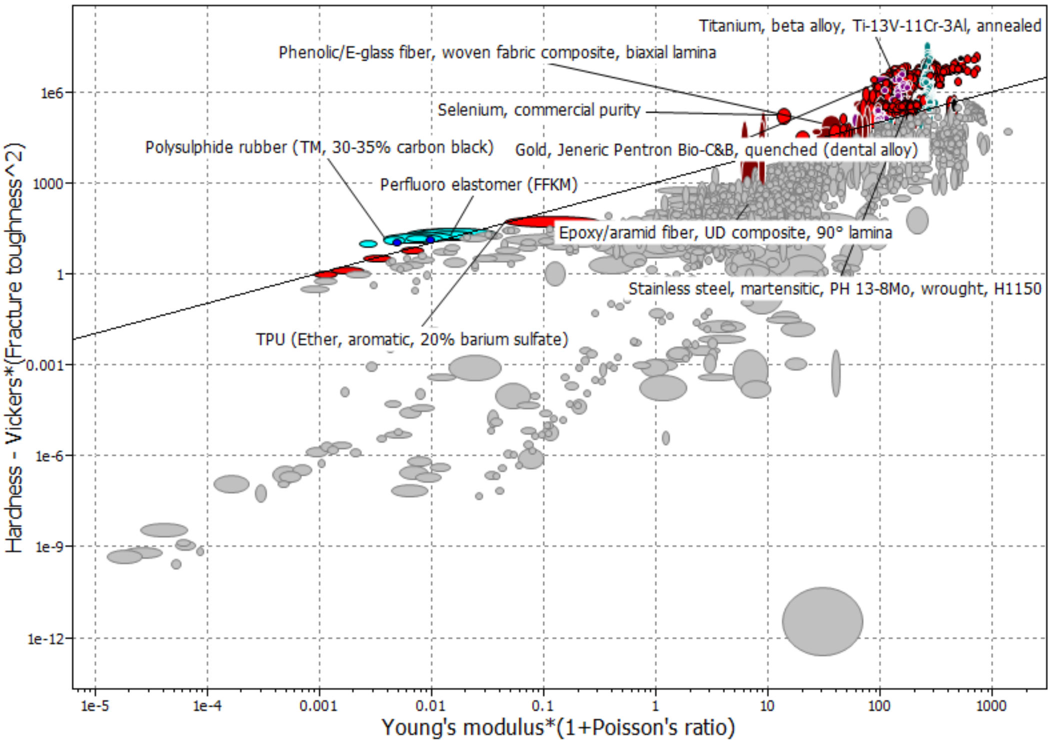

Figure 3.10: Materials maximizing resistance to shocks (without other constraints) for casings.

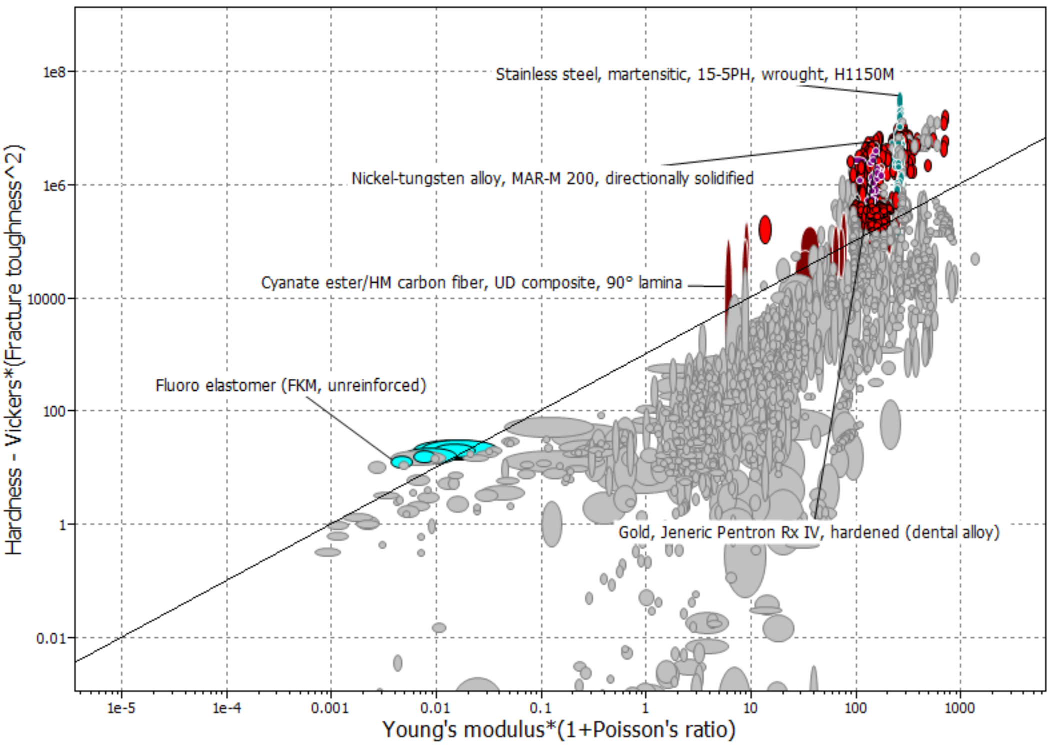

Figure 3.11: Materials maximizing resistance to shocks (with conditions on machinability, corrosion and UV resistance) for casings.

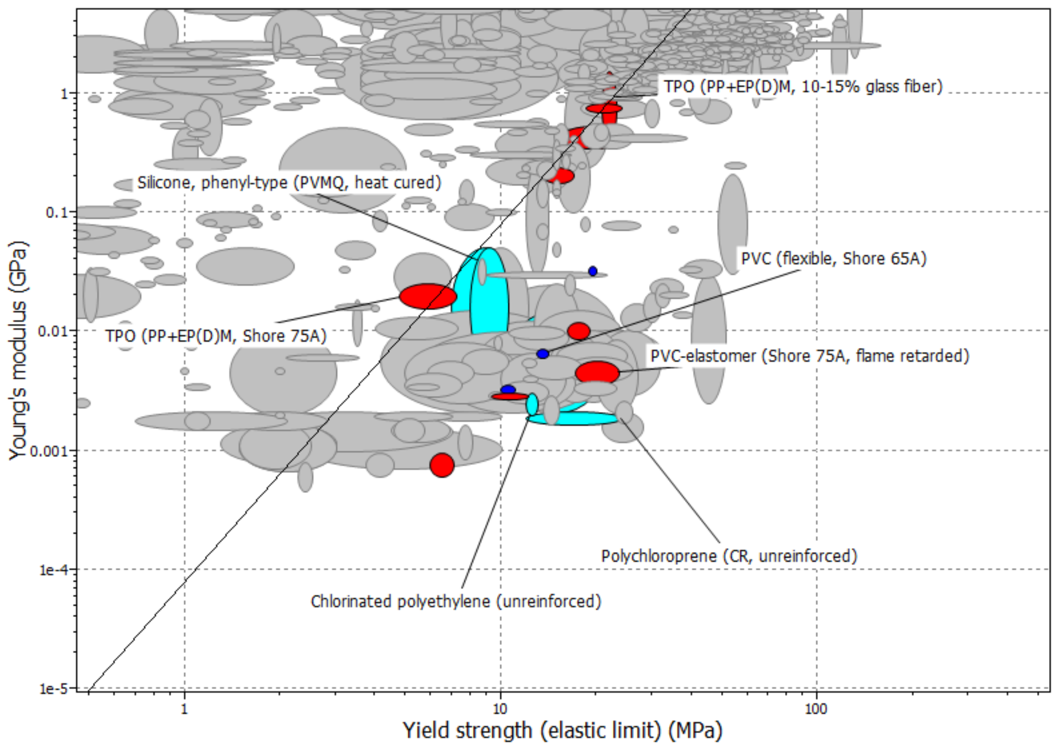

Figure 3.12: Materials which maximise the tight condition and which have some fabrication constraints and are corrosion resistance.

3.7 Gaskets

To be hermetic, the materials suited for gaskets must maximize $\frac{\sqrt{\sigma_f^3}}{E}$ and $\frac{1}{E}$, such that, in logarithmic scales,

$$\begin{aligned} \log W &= \frac{3}{2}\log\sigma_f - \log E \\ \Leftrightarrow \log E &= \frac{3}{2}\log\sigma_f - \log W \\ \Leftrightarrow y &= \frac{3}{2}x - \log W \end{aligned}$$

In CES, We represent an Ashby diagram including some fabrication conditions and resistance to corrosion (Fig. 3.12).

We list in the table 3.6 the materials suggested by CES. We see that polychloroprene is widely the best-suited one.

3.8 Hands

The hands should not bend, so we must find materials limiting the deflection δ.

Under the constraint

$$\sigma = \frac{L^2 F}{4I} \leq \sigma_f$$

Material	E $[GPa]$	σ_f $[GPa]$	$W_1 = \frac{\sigma_f^{3/2}}{E}$	$W_2^{\frac{1}{E}}$	W_{1a}	W_{2a}	W_{and}
Polychloroprene	0.0019	0.017	1.1877	537.22	1	1	1
PVC-elastomer	0.0044	0.0201	0.6415	224.77	0.540	0.418	0.226
Polyethylene	0.0024	0.0125	0.5699	408.25	0.480	0.760	0.365
PVC-flexible	0.0065	0.0135	0.2418	154.30	0.204	0.287	0.059
Silicone	0.0158	0.0092	0.0555	63.246	0.047	0.118	0.0055
TPO	0.0198	0.0059	0.0228	50.577	0.019	0.094	0.0018

Table 3.6: This table sorts the five best-suited materials for gaskets. The most suitable has to maximize W_{and}.

the deflection is written

$$\delta = \frac{FL^3}{8C_1EI}$$

so that the free variable is I.

We thus find that

$$\delta = \frac{L\sigma_f}{2C_1E} = \underbrace{\frac{\sigma_f}{E}}_{\text{material}} \underbrace{\frac{L}{2C_1}}_{\text{geometry}}$$

where L is the length of the hands, σ_f the yield strength, c_1 a tabulated constant and E the Young's modulus.

Another point to take into account is minimizing the mass of the two hands. The mass is given by $m = \rho V \approx \rho b^2 L$, and since $I = \frac{b^4}{12}$, we obtain the following equations :

$$m = \underbrace{\frac{\rho}{\sqrt{(\sigma_f)}}}_{\text{Material}} \underbrace{\sqrt{3F}}_{\text{Force}} \underbrace{L^2}_{\text{Geometry}}$$

We have to minimize the following expressions :

$$M_1 = \frac{\sigma_f}{E} \tag{3.6}$$

$$M_2 = \frac{\rho}{\sqrt{(\sigma_f)}} \tag{3.7}$$

or in logarithmic scales :

$$\log E = \log \sigma_f - \log(M_1)$$
$$\log \sigma_f = 2\log\rho - 2\log M_2$$

We plot an Ashby diagram in CES, including some machinability constraints (Fig. 3.13).

We will now draw up the performance table 3.7 for some materials selected by CES. Since M_1 is much more important than M_2, we attribute respectively a weight factor of 0.75 and 0.25. We see that Nickel is the best-suited material, but Aluminium alloys, Brass or Stainless steel can also be used to reduce the cost.

3.9 Watch glass

The glass has to withstand wear and scratch and, moreover, must resist to shocks and corrosion. The glass must obviously be transparent.

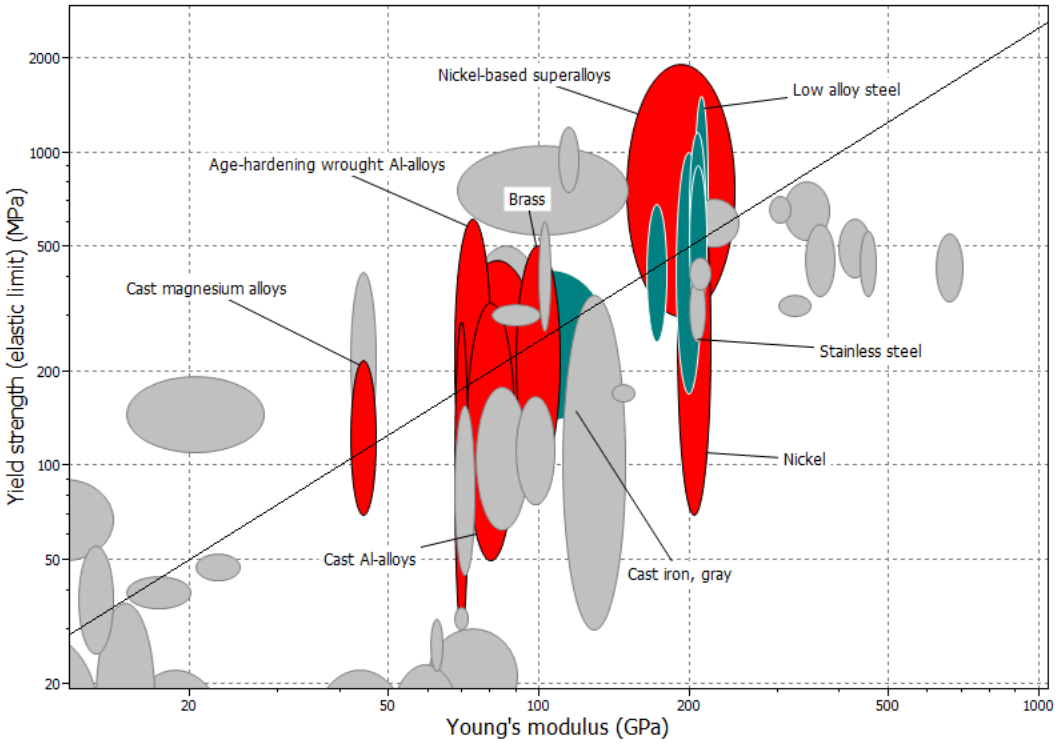

Figure 3.13: Materials minimizing mass and deflection of the hands, including machinability constraints.

Material	E $[GPa]$	ρ [kg/m^3]	σ_f $[GPa]$	$M_1 = \frac{\sigma_f}{E}$	$M_2 = \frac{\rho}{\sqrt{\sigma_f}}$	M_{1a}	M_{2a}	M_{and}
Cast Mg alloys	44	1809	0.133	2.8 10^{-3}	1.81 10^3	0.72	0.10	1.39
Nickel	204	8890	0.251	1.2 10^{-3}	17.74 10^3	0.31	1	0.42
Stainless steel	199	7846	0.412	2.1 10^{-3}	12.22 10^3	0.54	0.69	1.69
Cast Al alloys	80	2693	0.129	1.6 10^{-3}	7.51 10^3	0.41	0.42	0.64
Brass	99	8219	0.218	2.2 10^{-3}	17.60 10^3	0.56	0.99	0.65
Nickel alloys	192	8188	0.755	3.9 10^{-3}	9.42 10^3	1	0.53	1.17
Low alloy steel	211	7850	0.775	3.7 10^{-3}	8.92 10^3	0.95	0.50	1.14

Table 3.7: This table lists the best-suited materials for hands. $M_{and} = M_{1a}^{3/4} M_{2a}^{1/4}$ is minimized.

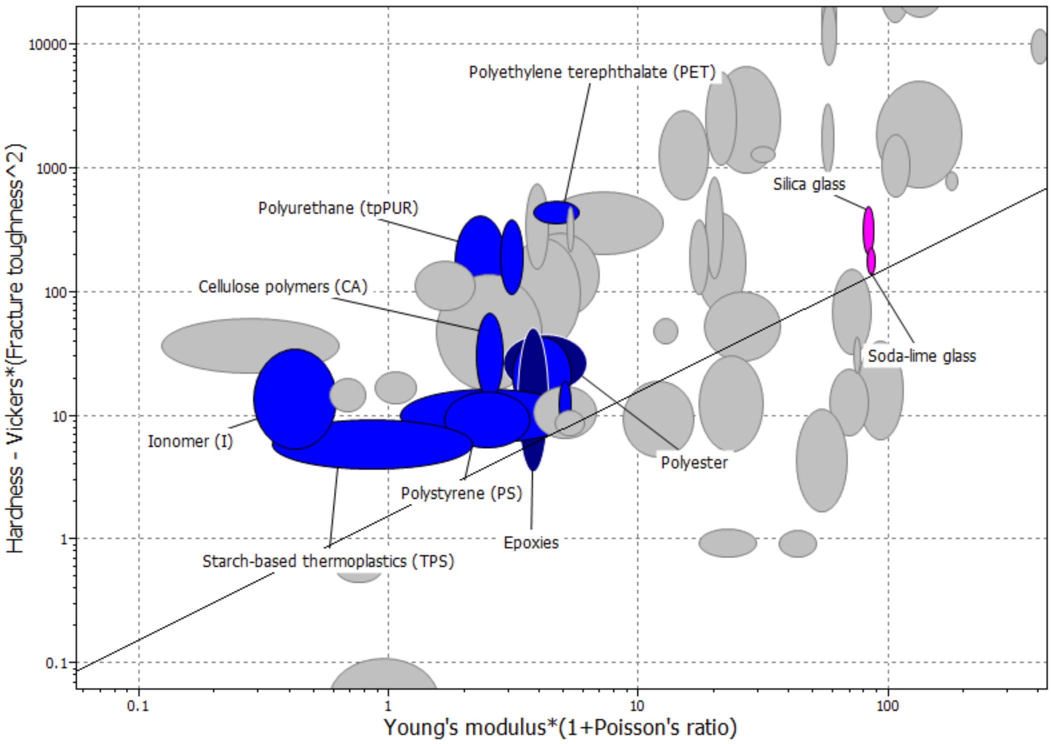

Figure 3.14: Materials maximizing resistance to shocks, including some machinability constraints for watch glasses.

We have to maximise the same function as seen in section 3.6:

$$W = \frac{HK_c^2}{E(1+\nu)}$$

Here, we introduce other constraints such as transparency or machinability. In an Ashby diagram corresponding to these conditions, we find some materials that may be appropriate (Fig. 3.14).

In the table 3.8, we list some interesting materials. It appears that P.E.T. (polyethylene triphosphate) seems to be the best-suited material; however, it is transparent only when the thickness is rather small. So, in practice [3], we use silica glasses or cellulose polymers. But the best available is a one crystal glass.

Material	$E\ [GPa]$	$\nu\ [-]$	$H\ [VH]$	$K\ [GPam^{1/2}]$	W	W_a
Silica glass	71	0.169	654	$6.928\ 10^{-4}$	$3.785\ 10^{-6}$	0.0402
Soda-lime glass	70	0.215	461	$6.205\ 10^{-4}$	$2.088\ 10^{-6}$	0.0222
Ionomer	0.29	0.444	3.46	$2\ 10^{-7}$	$32.20\ 10^{-6}$	0.3424
PET	3.38	0.388	17.83	$5\ 10^{-7}$	$94.03\ 10^{-6}$	1
Polyurethane	1.65	0.408	19.12	$3\ 10^{-7}$	$75.05\ 10^{-6}$	0.7981
Cellulose polymers	1.79	0.410	12.25	$2\ 10^{-7}$	$12.14\ 10^{-6}$	0.1291
Polystyrene	1.77	0.393	12.06	$8.775\ 10^{-4}$	$3.773\ 10^{-6}$	0.0401

Table 3.8: This table lists the seven best-suited materials for the glasses. The most suitable has to maximise W or W_a.

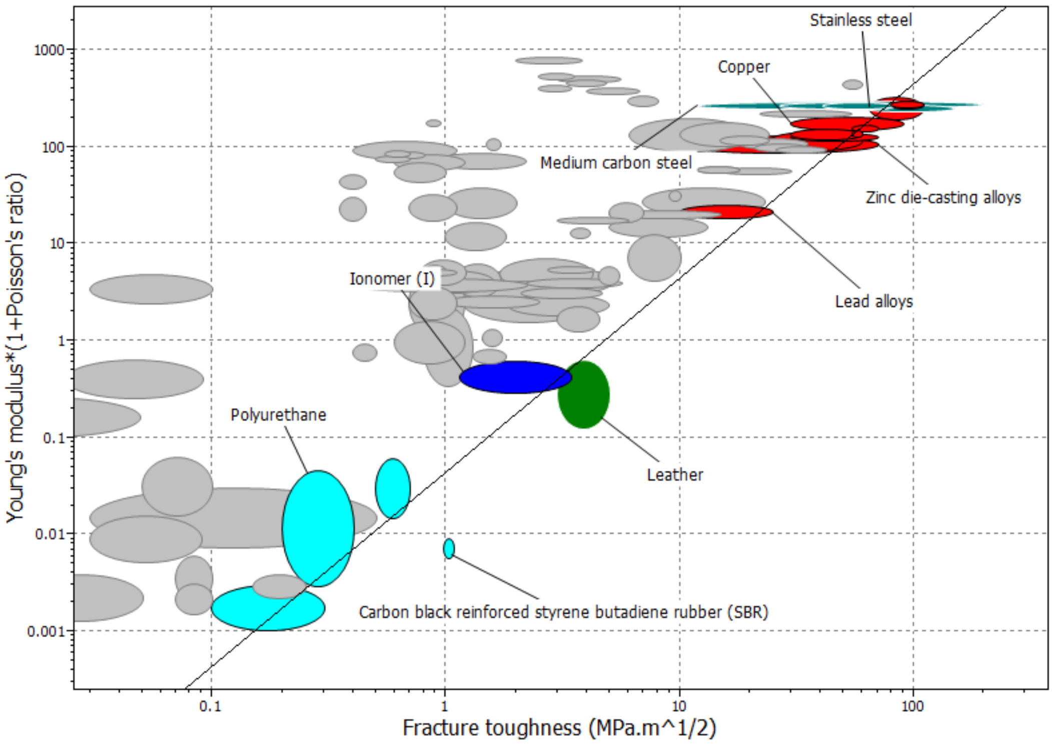

Figure 3.15: Materials maximizing resistance to shocks for wristbands.

3.10 Wristbands

Wristbands are usually made in two different ways: on one hand, they are made of a single piece of polymer or leather; on the other hand, they are an assembly of rigid materials – usually metals.

Wristbands have to withstand corrosion, shocks, UV-rays, tension forces and cracks. We thus have to maximise:

$$W_1 = \sigma_f \text{ and } W_2 = \frac{K_c^2}{E(1+\nu)}$$

We obtain the figure 3.15 in CES which regroups a multitude of materials.

We regroup some materials in table 3.9, and fix the weight factors to 1. As such, We see that stainless steel is a good material for wristbands fabricated piecewise. We can also have medium-carbon steel, on which we deposit a thin protective layer made of Gold, Chrome or plastic. For a one-piece wristband, we choose leather or polyurethane. In practise, we find Titanium, Leather, Nylon, Silver, Silicone, Rubber and some more. source:http://www.watchstyle.fr/vollmer2.htm visited the 20th November 7:43 pm.

Material	E $[GPa]$	ν $[-]$	K $[GPam^{1/2}]$	$W_1 = \sigma_f$ $[MPa]$	W_2	W_{1a}	W_{2a}	W_{and}
Leather	0.224	0.155	0.0039	7.07	$5.808\ 10^{-5}$	0.013	1	0.013
Polyurethane	0.008	0.494	0.0003	35.71	$0.691\ 10^{-5}$	0.068	0.119	0.0081
Stainless steel	199	0.270	0.0964	412.31	$3.676\ 10^{-5}$	0.787	0.633	0.498
Medium carbon steel	208	0.290	0.0332	523.93	$0.412\ 10^{-5}$	1	0.071	0.071
Lead alloys	14.866	0.440	0.0158	18	$1.168\ 10^{-5}$	0.034	0.201	0.0068
Zinc alloys	82.462	0.287	0.0265	189.74	$0.659\ 10^{-5}$	0.362	0.113	0.0409
Ionomer	0.291	0.444	0.002	11.47	$0.930\ 10^{-5}$	0.022	0.160	0.0035

Table 3.9: This table lists the seven best-suited materials for wristbands. The most suitable has to maximize W_{and}.

Chapter 4

Conclusion

During this in-depth study, we have seen that selecting materials is widely an iterative process. We first have to find what are the objectives for a piece with a given function. Than, we look after the biggest constraints and identify a free variable for each one – which can be arduous.

From all the materials fulfilling the above requirements, we have yet to found materials that meet the user expectations thanks to additional conditions, e.g. machinability, transparcency, heat-resistance.

Another difficulty are pieces manufactured in different ways, e.g. the wristband is usually made up of several metallic pieces or by a single polymer piece.

∴

To conclude in some words, we can write that finding good materials for practical applications was much more difficult than what we thought before. CES is a powerful tool to help us in this task, but selecting the best-suited material still needs to keep some critical mind. It is also interesting to have a look at what others did before for similar applications, because every material has his own properties, advantages and disadvantages.

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