mirrORCLE

DBB216 Creative Mechanical Engineering

Report on Mechanical Design and Engineering by Jelle Wories

Objective: "A report of the application of sound mechanical design and engineering principles to an Industrial Design project of the student's own choice."

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1) Introduction

‘’Exercising is fashionable. Whether you have been given exercises by a physiotherapist, to help recover from low back pain, or are improving your fitness, there comes a time where you stand in front of the mirror, and exercise. But are you doing it right?

The Mirrorcle uses a motion tracker to capture the points of your back and visualize them as a line in your reflection. It can remind you of how to do you exercise, and predict how long it will take for you to achieve your recovery, or fitness goal.” [1]

This project was done as part of a Smart Health research group at the faculty of Industrial Design, in collaboration with Prof. dr. A.A.A (Annick) Timmermans, from the University of Hasselt, faculty Geneeskunde en Levenswetenschappen

Figure 1 *Mirrorcle, a B2 project from the Industrial Design faculty*

This report focuses on the mechanical engineering of the project Mirrorcle, covering the following aspects:

A) **Original Mechanics**, showing the original construction of the project
B) **Mechanical Evaluation**, using mechanical knowledge gained in this elective to (theoretically) improve construction
C) **Material Selection**, setting up wishes and demands and selecting materials accordingly
D) **Manufacturing Techniques**, taking a look at covered manufacturing techniques to see which suits the project best.

[1] J.W.H. Wories, J. S. Faber, M. L Smith & D. A. Muller (2015), Introduction, Mirrorcle Report B2.2

2) Original Mechanics

2.1 Concept

To give some context to the mechanical evaluation, I'll give some insight into the original mechanics and manufacturing of Mirrorcle. In the original context, Mirrorcle was designed for use at home, given out by physiotherapists, so it needed to be portable. Also, the original target group for Mirrorcle was people with lower back problems, whom are not known to be great at lifting heavyweight object. Figure 2 shows a diagram of how Mirrorcle would be set up. The top part would have an LCD screen in it for displaying the visual feedback. The ''mirror'' plates consist of perspex with one-way mirror film on them, allowing for the user to see him/herself and for the TV visuals to appear through the mirror.

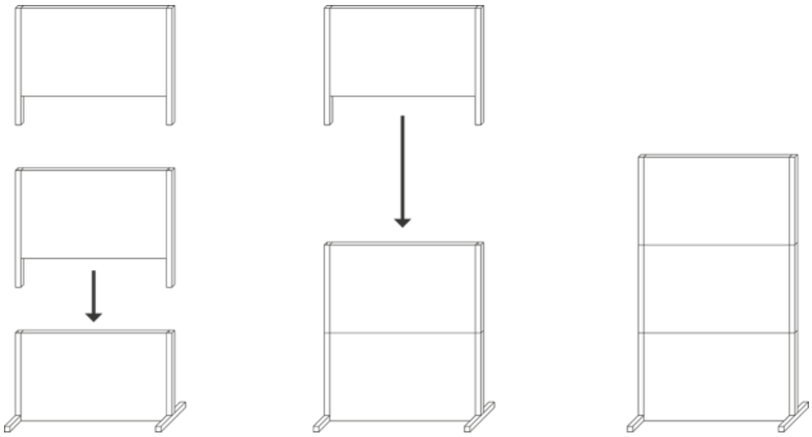

Figure 2 *How to set up Mirrorcle*

2.2 Mechanics

The 3 parts were designed to slide into each other, using different sizes of aluminium rods (figure 6). Consisting of an inner framework, which would hold the mirror plates in place, and an outer framework; bigger aluminium rods that would slide into each other and carry the inner frameworks. (figure 3)

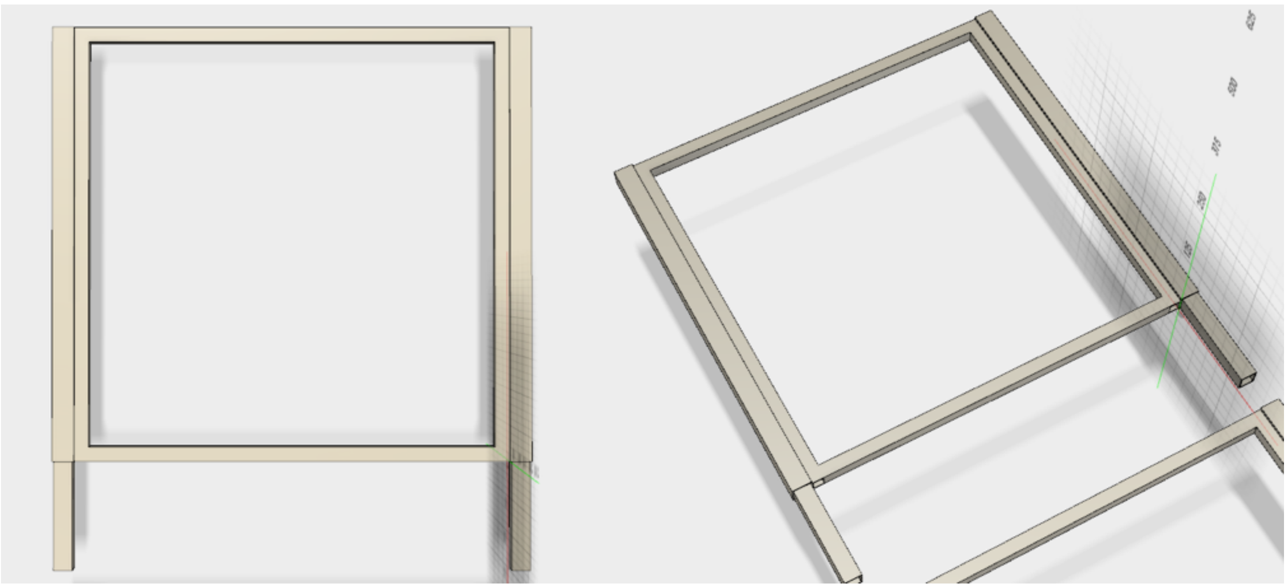

Figure 3 *3D model of framework* [2]

[2] 3D model made using Autodesk Fusion 360

2.3 Materials and Manufacturing

Materials
For material choice, there was no elaborate argumentation to base our material selection on. For the mirror plates, we needed a see-through material to put the one-way mirror film on, so we chose the cheapest available nearby, which turned out to be perspex. For the frame, we wanted a material that would look good, be somewhat lightweight and not too expensive, so we chose aluminium.

Manufacturing
The frame is made out of aluminium (prefabricated) rods, which were cut to size (figure 4+6) and assembled using screws. Screw threads were made in the aluminum using a tap and die (figure 5).

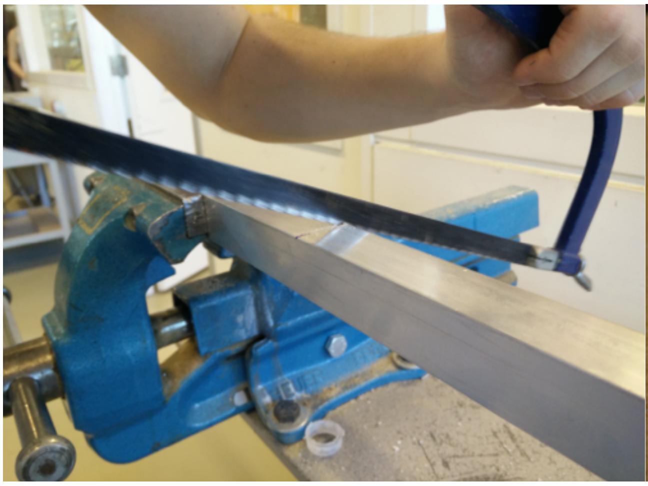

Figure 4 *Cutting the aluminium rods*

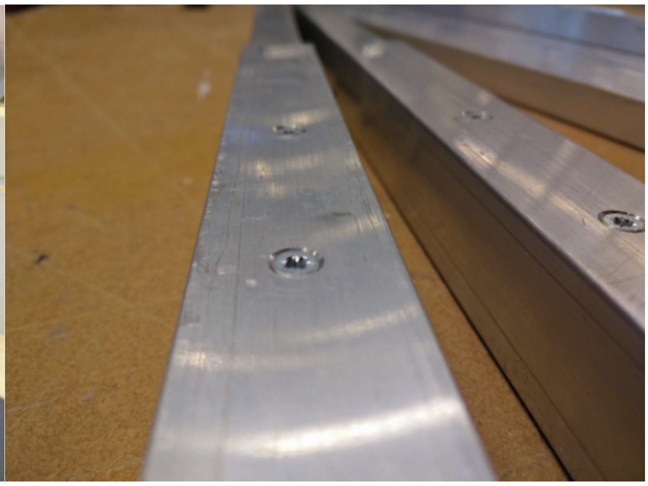

Figure 5 *Screws tapped into the aluminium*

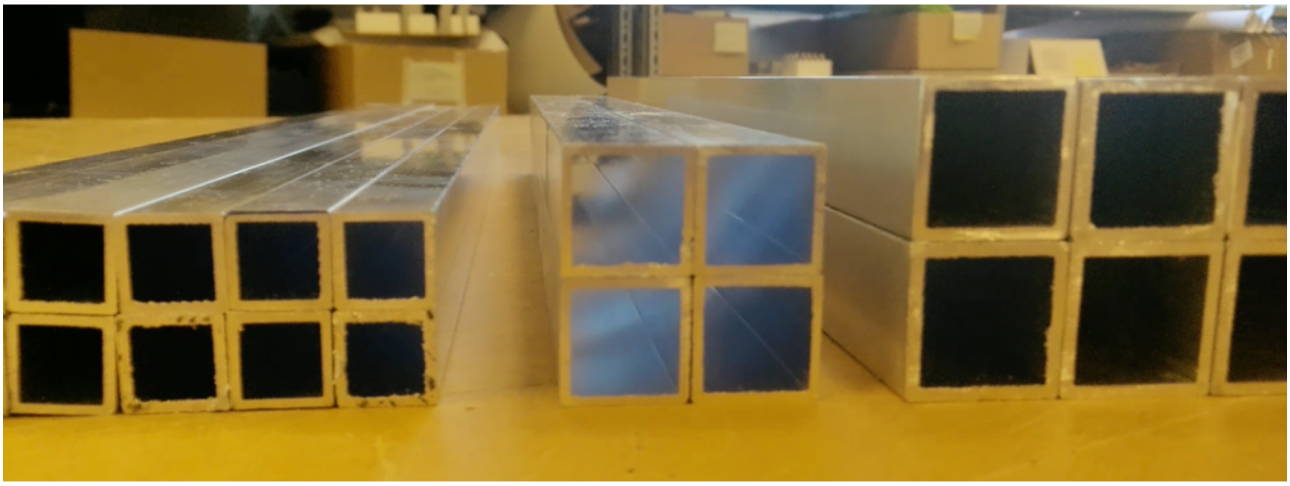

Figure 6 *3 sizes of aluminium rods*

The frame was built of 3 sizes of aluminium rods (figure 6). Out of the smallest aluminium rods, the inner frame was put together using corner brackets, fastened with screws tapped into the aluminium. The vertical rods that are connected to the outer frame were also connected using screws, tapped into the outer rods of medium and largest size. This way, the medium rods were automatically connected to the largest rods as well. Figure 7 shows the result.

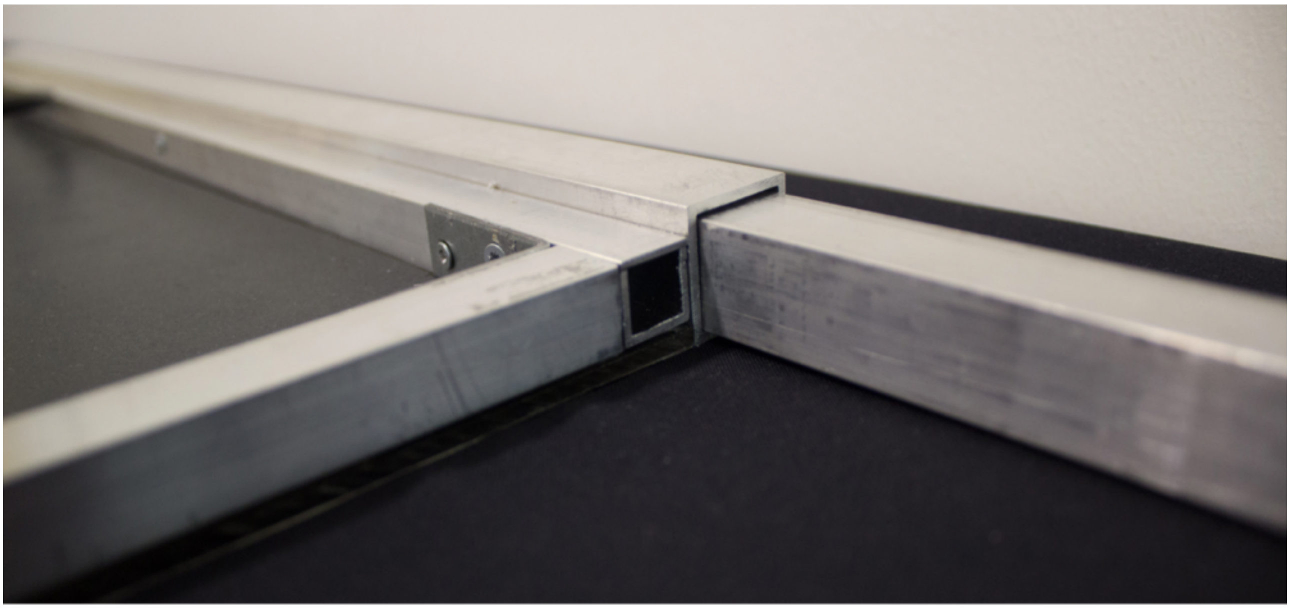

Figure 7 *Result* [3]

[3] J.W.H. Wories, J. S. Faber, M. L Smith & D. A. Muller (2015), Evaluation, Mirrorcle Report B2.2

3) Mechanical Evaluation

3.1 Instable Frame

As seen in figure 5, screws (tapped into the aluminium) were used to assemble the aluminium frame. According to J.G. Skakoon (2008)[4], objects are best held in place using force closure, not form closure. Using screws as a nesting force (figure 8) was a good choice, as it makes use of this principle.

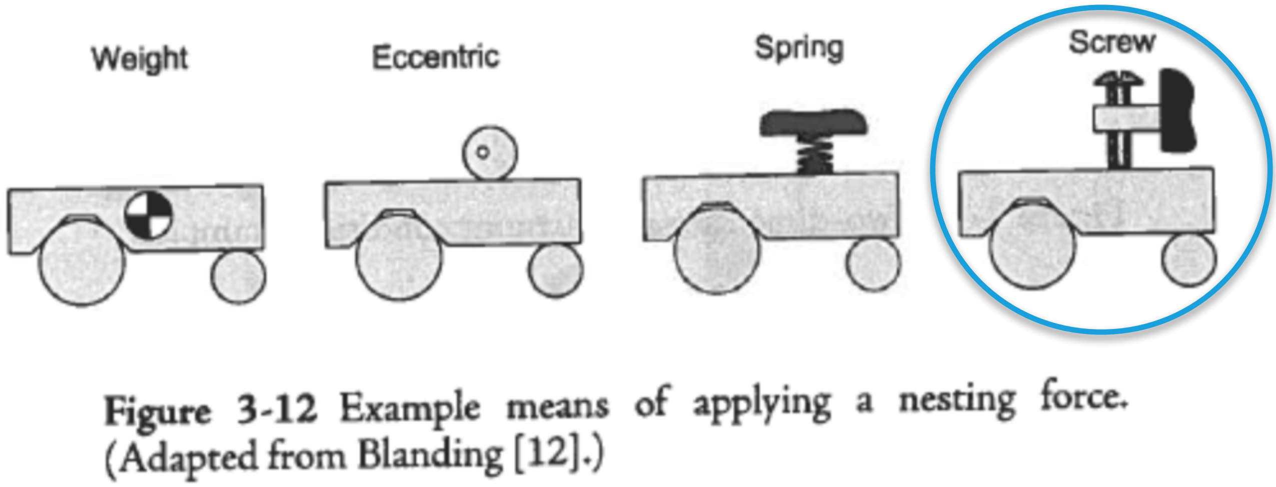

Figure 8 *Applying a nesting force* [5]

However, the screws loosened quite quickly due to wear and tear, which is relatively high for this concept, as it is meant to be assembled and disassembled on a regular basis. Loose screws made an already wobbly construction even more wobbly.

Solutions

1. *Triangulate*

    This issue could have been solved quite easily by placing some diagonals in the framework. Structures without triangulating members rely on the rigidity of connecting joints (which were a source of the wobbly problem in Mirrorcle's case) between members for stiffness.[5]

2. *Attach back panels*

    Another way of triangulation is using back panels to increase stiffness in the construction (figure 9). You see this method of creating stiffness in a lot of wardrobes, bookshelves etc.

    This would mean having to think about where to exactly attach the back panels, to ensure maximum rigidity.

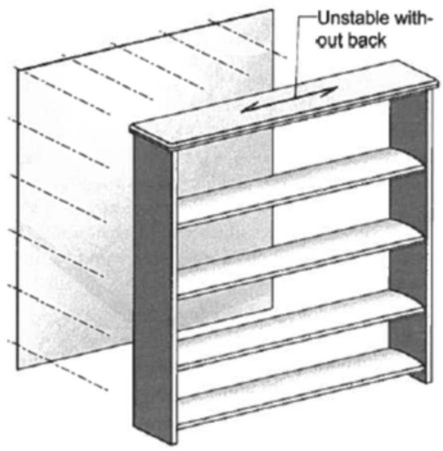

Figure 9 *Triangulation*

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[4] J.G. Skakoon (2008), The Elements of Mechanical Design, ASME Press, New York

[5] F. L. M. Delbressine (2016), Elements Of Mechanical Design Lecture Material, DBB216

3. *Product in 1 piece*

Because the mirror was for home use, it had to be modular. The placing of the LCD screen was thus limited to either in the middle segment or in the top segment, whilst the lower back often lies exactly in between. This had not been thought through. Also, because the mirror was broken up into 3 pieces, a clear visible line could be seen in between the pieces, because of different light refraction, making people lose several limbs in their reflection.

Later in the semester, a switch to the fitness market was made […], so the mirror no longer had to be carried around, in a fitness centre it would have a fixed place.[6] Making the Mirrorcle one large product eliminates wear from regular assembly and disassembly (however, it being bigger might increase wear from transportation), which would make construction easier.

3.2 Friction during Assembly

When sliding the 3 frame parts into each other, inconsistent friction takes place (either no friction at all, or a great amount). This is because the margin on the aluminium was either too big or too small, so the objects were (attempted to be) fixed in place using form closure.

Solution

What would have been better was using force closure (Skakoon, 2008)[7]. Sliding friction should be avoided at all times, and the length of linearly guided components should be maximized [8]. This means that the part that slides into frame below needs to be as long as possible, and should be guided in its way in.

One way of using force closure is to use elastic fits (figure 10). Elastic fits make use of elastic deformation properties of materials, allowing them to bend (deform) on purpose. Instead of using square parts that slide into each other, a polymer cylinder could be placed inside the square aluminium frame, into which another cylinder (polymer or aluminium) with ribbons slides. Elasticity keeps it central, gravity and weight push it down into the elastic fits.

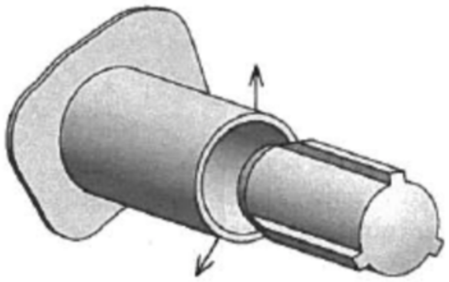


Figure 10 Elastic deformation [8]

[6] J.W.H. Wories, J. S. Faber, M. L Smith & D. A. Muller (2015), Reflection, Mirrorcle Report B2.2

[7] J.G. Skakoon (2008), The Elements of Mechanical Design, ASME Press, New York

[8] F. L. M. Delbressine (2016), Elements Of Mechanical Design Lecture Material, DBB216

3.3 Plate Attachment

The inner framework of Mirrorcle held two plates in place, one on the frontside and one on the backside. There was no real mechanical system to hold them in place, except for the aluminium on the vertical sides and a lot of glue.

Solution: Elastic Fits

Figure 11 shows how we could attach the plates to the frame using elastic fits on the vertical sides, and could be held in place on the bottom rods from the frame using pins and indentations in the plates (figure 12), using gravity to push it down. This way, all degrees of freedom are eliminated. Although this would work pretty well from a mechanical viewpoint, it bends the mirror only slightly, which might deform the image seen in the mirror. This would have to be tested wether this is a problem or not.

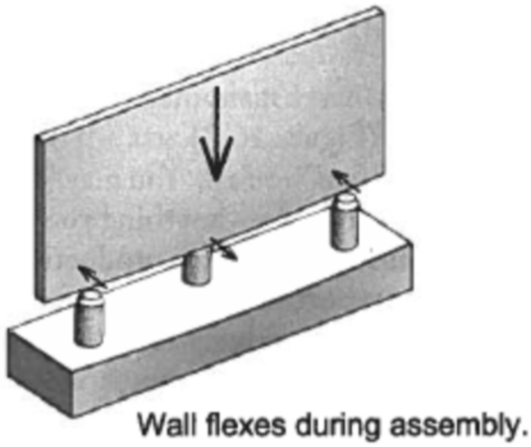


Figure 11 *Elastic fits* [9]

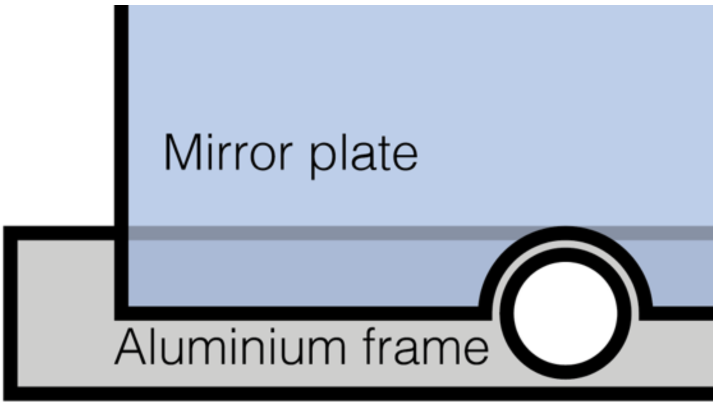


Figure 12 *Plates with indentations*

[9] F. L. M. Delbressine (2016), Elements Of Mechanical Design Lecture Material, DBB216

3.4 Footwork

In the original concept and prototype, Mirrorcle has 2 horizontal bars of aluminium as feet (figure 13). Although this is visually appealing, there is a lot of stress on these feet because of the T-shaped connections they make with the rest of the framework. Because the LCD screen is in the top part of the framework, the construction is slightly top-heavy, making it more likely to tip over. This increases stress on the horizontal bars even more.

Solutions

1. *Adapt foot*

   Some diagonal bars could be added to triangulate the foot, and thereby relieve stress of the T-shaped joint where the frame connects with the feet.

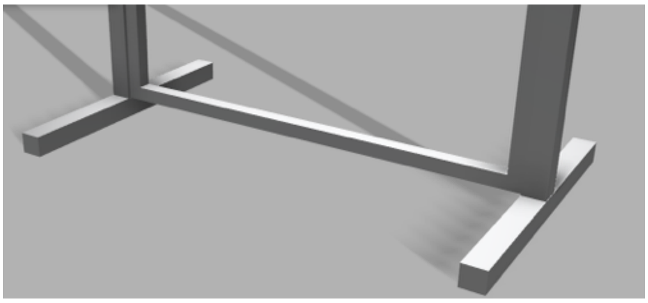


Figure 13 *Footwork of original Mirrorcle* [10]

2. *Triangulate entire structure*

   Instead of using 2 feet, the entire relation of structure with the ground could be triangulated by removing the horizontal bars and adding a third leg to the back. This way, the construction would always stand stable, and spread forces more evenly into the ground. Although this would again be the best option in from mechanical viewpoint, it would tilt the mirror backwards which is not desirable for viewing angles. On top of this, the mirrorcle is for home use, in which floors are often evenly levelled enough for the Mirrorcle to be stable.

[10] Made using Autodesk Fusion 360

4) Material Selection

Below is an argumentation for material selection. All of the material data comes from CES Edupack (M.F. Ashby), and are listed in appendix A. Firstly, a list of demands and wishes is presented, after which a databank of material properties was searched to select a material that fits these demands and wishes. The results were surprising, as both outcomes are the same as the original choice, although now scientifically supported. Nice addition: both materials are recyclable, increasing the eco-friendliness of our product.

4.1 Frame

Demands and wishes

Lightweight (low density)	Durable (Fatigue strength at 10^7 cycles)
Stiff, strong and impact resistant (E-modulus)	Processability (drilling, welding, assembly, coating)
Scratch resistant	Cheap

Material: Aluminium [11]

Aluminium has a relatively low density (2,5e3 - 2,9e3 kg/m^3) in comparison with its high E-modulus (72-89 GPa) as seen in figure 14, sufficient fatigue strength (32-157 MPa)(figure 15), is easy to drill, can be welded (although chemical fixation is probably preferable), looks nice when coated, and is relatively cheap (1,28-1,41 EUR/kg). These characteristics make aluminium the best choice, compared to other metals and alloys or other materials.

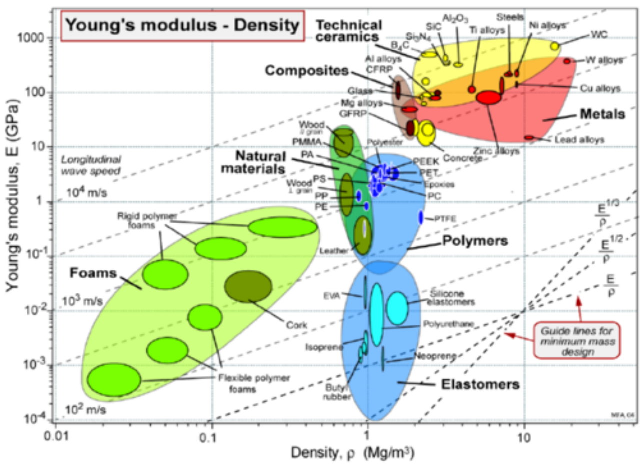


Figure 14 *Material behaviour* [12]

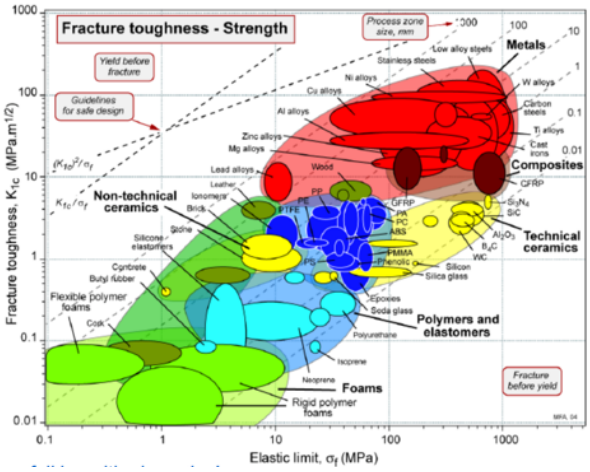


Figure 15 *Fatigue strength* [12]

Optional: polymers

Using polymers for the framework might also be possible, but to ensure the same stiffness/weight ratio as aluminium, a complicated construction design would be necessary. On top of this, aluminium has a nicer look to it, and is more easily available in prefabricated formats.

[11] Type: Cast Aluminium Alloy

[12] M. Ashby (2005), Materials Selection in Mechanical Design, Elsevier

4.2 Mirror Plates

Demands and wishes

Lightweight (low density)	Durable (Fatigue strength at 10^7 cycles)
Stiff, strong and impact resistant (E-modulus)	Processability (drilling, assembly, coating)
Scratch resistant	Cheap
Light transmission (>95%)	Colour stability

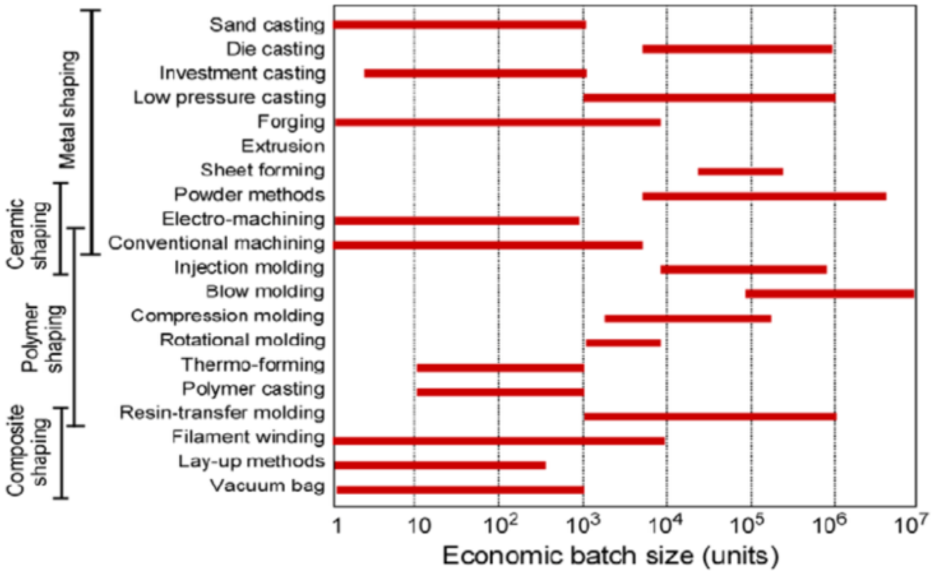
Material: Polymethyl Methacrylate (PMMA, acrylic, perspex)
Pespex has a relatively low density (1,16e3 - 1,22e3 kg/m^3), proper E-modulus (2,24-3,8 GPa) and good fatigue strength (15,2-32,7 MPa) compared to others, has optical quality transparency, is relatively cheap (1,91-2,10 EUR/kg), and has good colour stability.

Perspex seems like the best choice for material. It resembles glass the most, but glass is too heavy, too brittle and too expensive. Polycarbonates are possible as well, as perspex and polycarbonate share a majority of material properties, although it is more expensive (2,58 - 2,84 EUR/kg), lower E-modulus (2 - 2,44 GPa). It does have a higher fatigue strength (22,1-30,8 MPa).

5) Manufacturing Techniques

5.1 Processing Operations

Shaping
Casting the aluminium into the right shapes would be a viable option, but the main challenge with aluminium casting is coping with the shrinkage (of 3.5 to 8.5%)[13] that happens during solidification; this requires mold design to get the right final dimensions and to avoid hot tearing, cracking or porosity. Despite this constraint, aluminium castings of great complexity are practical, especially because (sand-, & investment-)casting is great for batch sizes of 1 to 1000 (figure 16), which is probably the amount of products we would want to make, at least for now.



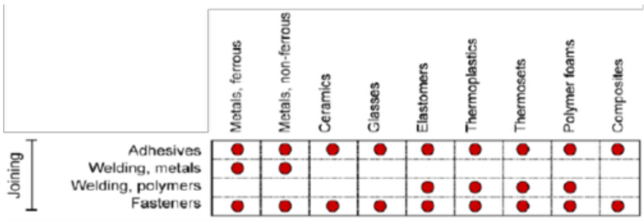
The mirror plates, made from PMMA, can be cut to size very easily. To obtain stiffness of these plates, we might try to incorporate some form of flanging, although the plates will be attached to the frame, which will probably give them enough stiffness.

Figure 16 [14]

Surface Processing
The aluminium frame could be brushed, polished and coated to make it more scratch resistant and give it a more sophisticated look. The mirror plates could also be coated to increase adhesion of the one-way mirror film with the perspex, or another coating to decrease flare, improve reflection, etc.

5.2 Assembly Operations

The reason that the screws, tapped into the aluminium, came loose is probably because aluminium is somewhat of a soft material (though stiff and strong), allowing for the screws to deform the aluminium. This is not desirable, although this property does make the material easy to process. This probably makes casting the aluminium is the best option, because it also eliminates the need for (weak and thus problematic) mechanical joints.



For construction, all parts could be joined using adhesives (figure 17). Fasteners could be used as well, but because aluminium is a soft materials, adhesives are preferred.

Figure 17 Joining methods [14]

[13] See appendix A for material properties

[14] M. Ashby

Appendix A: Material Properties

Cast Al-alloys

Description

The material

Almost all aluminum alloys for casting contain 5 - 22% silicon (Si) -- the silicon makes the alloys more fluid so that they fill the mold and take up fine detail, even in thin sections. Further additions of copper (Cu) or magnesium (Mg) give age-hardening alloys. The plain Al-Si alloys are used for marine components and hardware and for cooking utensils because of their good resistance to corrosion in salt water; and they are used for pistons and cylinder liners because of their good thermal conductivity and low expansion. As a general rule the casting alloys have lower ductility and strength than the wrought age-hardening alloys -- few have tensile strengths above 350 MPa.

Composition (summary)

Al + 5 - 22% Si, sometimes with some Cu, Mg or Zn to allow age-hardening.

Image

Caption

Aluminum casting alloys almost all contain silicon to make them fluid, allowing castings with good finish and detail.

General properties

Density	2.5e3	-	2.9e3	kg/m^3
Price	* 1.28	-	1.41	EUR/kg

Mechanical properties

Young's modulus	72	-	89	GPa
Shear modulus	25	-	34	GPa
Bulk modulus	66	-	72	GPa
Poisson's ratio	0.32	-	0.36	
Yield strength (elastic limit)	50	-	330	MPa
Tensile strength	65	-	386	MPa
Compressive strength	50	-	330	MPa
Elongation	0.4	-	10	% strain
Hardness - Vickers	60	-	150	HV
Fatigue strength at 10^7 cycles	32	-	157	MPa
Fracture toughness	18	-	35	MPa.m^0.5
Mechanical loss coefficient (tan delta)	1e-4	-	0.002	

Thermal properties

Melting point	475	-	677	°C
Maximum service temperature	130	-	220	°C
Minimum service temperature	-273			°C
Thermal conductor or insulator?	Good conductor			
Thermal conductivity	80	-	160	W/m.°C
Specific heat capacity	900	-	995	J/kg.°C
Thermal expansion coefficient	16.5	-	24	µstrain/°C

Electrical properties

Electrical conductor or insulator?	Good conductor			
Electrical resistivity	2.5	-	8	µohm.cm

Optical properties

Transparency	Opaque			

Processability

Castability	4	-	5	
Formability	3	-	4	
Machinability	4	-	5	
Weldability	3	-	4	
Solder/brazability	2	-	3	

Eco properties

Embodied energy, primary production	203	-	238	MJ/kg
CO2 footprint, primary production	12	-	13.1	kg/kg
Recycle	True			

Supporting information

Design guidelines

Aluminum casting alloys are designed to be fluid so that they fill the mold and take up details well -- alloying with silicon is the most effective way to do this. Some of the alloys are designed for die-casting, some for permanent mold casting and some for sand casting. The main challenge with aluminum casting is coping with the shrinkage of 3.5 to 8.5 % that happens during solidification; this requires mold design to get the right final dimensions and to avoid hot tearing, cracking or porosity. Despite this constraint, aluminum castings of great complexity are practical. Recent developments in rheo-casting and squeeze casting overcome some of the problems of dimensional accuracy. The mechanical properties of the cast alloys are less good and more variable than those of the wrought series.

Technical notes

No classification system for cast aluminum alloys has international acceptance. In the most widely used (the AAUS system), the first digit indicates the alloy group. In the 1xx.x group, the second two digits indicate the minimum percentage of aluminum; thus 150.x indicates a composition containing a minimum of 99.5% aluminum. The digit to the right of the decimal point indicates the product form: 0 means 'castings' and 1 means 'ingot'. In the 2xx.x to 9xx.x groups, the second two digits are simply serial numbers. The digit to the right of the decimal point again indicates product form. Age-hardening alloys carry the suffix T and a number between 0 and 8 to indicated the state of heat treatment. More information on designations and equivalent grades can be found in the Users section of the Granta Design website, www.grantadesign.com

Phase diagram

Polymethyl methacrylate (Acrylic, PMMA)

Description

The material

When you think of PMMA, think transparency. Acrylic, or PMMA, is the thermoplastic that most closely resembles glass in transparency and resistance to weathering. The material has a long history: discovered in 1872, first commercialized in 1933, its first major application was as cockpit canopies for fighter aircraft during the second World War.

Composition (summary)

(CH3-CH2-C-CO-OCH3)n

Image

General properties

Density	1.16e3	-	1.22e3	kg/m^3
Price	1.91	-	2.1	EUR/kg

Mechanical properties

Young's modulus	2.24	-	3.8	GPa
Shear modulus	0.803	-	1.37	GPa
Bulk modulus	4.2	-	4.4	GPa
Poisson's ratio	0.384	-	0.403	
Yield strength (elastic limit)	53.8	-	72.4	MPa
Tensile strength	48.3	-	79.6	MPa
Compressive strength	72.4	-	131	MPa
Elongation	2	-	10	% strain
Hardness - Vickers	16.1	-	21.9	HV
Fatigue strength at 10^7 cycles	* 15.2	-	32.7	MPa
Fracture toughness	0.7	-	1.6	MPa.m^0.5
Mechanical loss coefficient (tan delta)	* 0.0105	-	0.0179	

Thermal properties

Glass temperature	84.9	-	165	°C
Maximum service temperature	41.9	-	56.9	°C
Minimum service temperature	-123	-	-73.2	°C
Thermal conductor or insulator?	Good insulator			
Thermal conductivity	0.0837	-	0.251	W/m.°C
Specific heat capacity	1.49e3	-	1.61e3	J/kg.°C
Thermal expansion coefficient	72	-	162	µstrain/°C

Electrical properties

Electrical conductor or insulator?	Good insulator			
Electrical resistivity	3.3e23	-	3e24	µohm.cm
Dielectric constant (relative permittivity)	3.2	-	3.4	
Dissipation factor (dielectric loss tangent)	0.05	-	0.06	
Dielectric strength (dielectric breakdown)	15.7	-	21.7	1000000 V/m

Optical properties

Transparency	Optical Quality			
Refractive index	1.49	-	1.56	

Processability

Castability	3	-	5	
Moldability	4	-	5	
Machinability	3	-	4	
Weldability	5			

Eco properties

Embodied energy, primary production	* 93.8	-	110	MJ/kg
CO2 footprint, primary production	* 3.4	-	3.8	kg/kg
Recycle	True			

Recycle mark

7 Other

Supporting information

Design guidelines

Acrylic, PMMA, is hard and stiff as polymers go, easy to polish but sensitive to stress concentrations. It shares with glass a certain fragility, something that can be overcome by blending with acrylic rubber to give a high-impact alloy (HIPMMA). PVC can be blended with PMMA to give tough, durable sheets. Acrylic is available as a sheet, rod or tube and can be shaped by casting or extrusion. Cell casting uses plates of glass and gasketing for a mold; it allows clear and colored panels up to 4 inches thick to be cast. Extrusion pushes melted polymer pellets through a die to give a wide variety of shapes, up to 0.25 inches thick for sheet. Clear and colored PMMA sheet lends itself to thermoforming, allowing inexpensive processing. A hybrid sheet manufacturing process, continuous casting, combines the physical benefits of cell casting and the cost efficiency of extrusion. Extruded and continuous cast sheet have better thickness tolerance than cell-cast sheet. PMMA can be joined with epoxy, alpha-cyanoacrylate, polyester or nitrile-phenolic adhesives. It scratches much more easily than glass, but this can be partially overcome with coatings.

Technical notes

Polymers are truly transparent only if they are completely amorphous - that is, non-crystalline. The lumpy shape of the PMMA molecule ensures an amorphous structure, and its stability gives good weathering resistance. PMMA is attacked by esters, ketones, acids and hydrocarbons, and has poor resistance to strong acids or bases, solvents and acetone.

Typical uses

Lenses of all types; cockpit canopies and aircraft windows; signs; domestic baths; packaging; containers; electrical components; drafting equipment; tool handles; safety spectacles; lighting, automotive tail lights, chairs, contact lenses, windows, advertising signs, static dissipation products; compact disks.

Tradenames

Acrive, Acrylite, Acryrex, Altuglas, Cyrolite, Diakon, Glasflex, Goldrex, Lucite, Lucryl, Optix, Oroglas, Perspex, Plexiglas, Plexit, Sumiplex