# Investigation of a Manufactured Article
## Cigarette Lighter

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## This is part of a set of resources on the topic.

- Powerpoint summary
- Supervisor Guide
    - For teaching assistants or instructors giving a background and answers to likely student questions.
- For Students
    - MiniProject - Investigation of a manufactured article
        - Explaining the project
    - Instructions for Dismantling
        - How to do this safely
    - Data Booklet
        - With lab test data for reference
    - Materials Selection for a Lighter
        - Instructions on materials selection methodology and how to use CES EduPack.

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**Selecting materials for the lighter tank using CES**

## 1. Introduction

A summary of how to use CES (Cambridge Engineering Selector) software is provided in separate notes and, as stated there, factors that need to be considered when designing a product and optimising materials to be used include:

- functionality: to ensure the product does what is wanted;
- fabrication: easier manufacturing might mean a more expensive material is cheaper to use;
- aesthetics: attractiveness will promote sales but also an aesthetic appearance is often indicative of improved functionality;
- economics: cost of the item itself, service costs (if applicable), planned lifetime;
- environment - sustainability: includes energy expended, "greenhouse" emissions, recycling.

With regard to functionality, it is necessary to consider the properties need to be specified and constrained when choosing suitable materials for the lighter tank. For this exercise, the following four properties only will be included, although in practice there clearly will be a far greater number of properties and considerations that will be used:

yield strength:   the stress above which a material changes its shape in a permanent manner;

toughness:       the ability of a material to absorb energy without breaking;

density:          the lighter should not be unduly heavy;

price:            need to find the cheapest material that can be used.

[Note that the first two properties, yield strength and toughness, will be covered in greater detail in Course D on mechanical properties later this term.]

## 2. Ranges of acceptable values for the two mechanical properties

Approximate values for the ranges of acceptable values for the two mechanical properties may be estimated as follows.

### 2a. Yield strength

The pressure in the wall of a spherical container was analysed in Course A (see pages AH21 -22). It was shown that the stress $\sigma$ in a spherical vessel of radius $r$, with a wall thickness $t$, and containing a fluid exerting a pressure $P$ is given by the following equation:

$$\sigma = \frac{Pr}{2t}$$

A similar equation can be derived for a cylindrical pressure vessel and has the form

$$\sigma = \frac{Pr}{t}$$

It is specified (expected) that the fuel will exert a pressure of 19 bar in the lighter fuel tank; this is equivalent to a stress of 1.9 MPa. Clearly, the tank itself must not deform or fail under this stress and so this is the minimum value for the yield strength of the material to be used. In practice, a safety factor is always used and a higher value for the yield strength must be specified; a figure of 20 MPa might be a suitable as the maximum value as higher values represent over design and are likely to be more expensive.

**Hence the range of values for the yield strength $\sigma$ can be taken as  2 < $\sigma$ < 20 MPa.**

## 2b.  Fracture toughness

The toughness of a material is its ability when stressed to absorb energy without breaking; brittle is the opposite of tough.  In practice, the effect of flaws or defects can reduce substantially the toughness of a given material since they tend to locally magnify the magnitude of any applied stress.  The flaws ordefects may be internal or external; the latter often being surface scratches. The effect of surface cracks is clearly demonstrated by considering the cutting of glass, e.g. to replace a window pane.  It is relatively easy to cut the glass to precisely the correct shape if the surface of a sheet is first scored using a diamond wheel; on stressing the glass sheet by bending, it then breaks cleanly along the scratch introduced and at a much lower load (stress) than otherwise would have been the case.

There are several ways by which toughness of materials can be measured and the effects of flaws or defects assessed.  Given the importance of surface cracks, one way is to measure the growth of sharp surface cracks into the material and then record the length of the cracks that result in failure. This results in a measure of the fracture toughness $K_{IC}$ for a given material.  An equation (derived in Course D) relating the fracture toughness to the applied stress $\sigma$ and the length of a surface crack $a$ is:

$$K_{IC} \approx \sigma\,(\pi\,a)^{\frac{1}{2}}$$

An estimate of the required toughness of the lighter's fuel tank may be obtained by assuming that the greatest load on the lighter might occur when it is thrown at a hard surface, and allowing for the stress concentration that occurs at any defect or crack, as is now briefly shown.

Assume the lighter takes 0.1 s when thrown against the hard surface starting with an initial velocity $u$ of zero and reaching a velocity $v$ of 10 m/s on impact.  Note that a professional tennis serve may be greater than 100 km/hr or ~ 30 m/s.

The acceleration $a$ is estimated from $v - u = at$ where $t$ is the time, and so $a = \sim 100$ m s$^{-2}$.  If the mass of the lighter is 25 g, then the force $F$ on impact (using $F = ma$) will be ~ 2.5 N.

Now, to estimate stress, consider the area on which this force acts.  The lighter can be considered to be a large object.  However, the actual contact area on impact with the wall is relatively small, assume 2 mm$^2$.  Hence the stress $\sigma$ (given by $\sigma = F/A$) will be 1.25 N mm$^{-2}$, or 1.25 MPa.

When considering fracture toughness, any singularity in the geometry of a body will lead to a stress concentration.  Hence it is the local stress at the end of a surface crack which will be significant. For a crack, this local stress concentration, $\sigma_{max}$, is given[1] by equations of the form:

$$\sigma_{max} = \sigma\left(1 + 2\frac{a}{b}\right) = \sigma\left(1 + 2\sqrt{\frac{a}{\rho}}\right)$$

where   $\sigma$ is the applied stress          $a$ is the surface crack length,
           $b$ is the crack width, and          $\rho$ is the radius of curvature at the crack tip.

Assume a surface crack has length $a = 0.5$ mm and is only 0.1 mm wide, $b$.  Using the first of the above expressions, the stress concentration factor $(1 + 2a/b)$ will be approximately 11.  Hence the stress at the crack tip will be of the order of 1.25 x 11 MPa or ~15 MPa.

Using $\sigma = 15$ MPa and a = 0.5 mm in the equation for fracture toughness gives $K_{Ic} \sim 0.6$ MPa m$^{-\frac{1}{2}}$.

**Hence, allowing for a safety factor in a similar manner to the yield stress, the range of values for the fracture toughness $K_{IC}$ might be taken as  $1 < K_{IC} < 4$ MPa m$^{\frac{1}{2}}$.**

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[1] http://en.wikipedia.org/wiki/Stress_concentration#Concentration_factor

### 3. Selection of suitable materials for the lighter tank

It is now possible to use CES to examine which materials might be suitable for the lighter tank given the ranges of acceptable values for the two mechanical properties plus the additional requirement that the lighter be as light and cheap as possible.

3a.  Use CES to plot a graph of density (x–axis) versus yield strength (y-axis).  This would allow materials with appropriate yield strengths and light weight to be identified – see Figure 1.  However, since both density and price need to be optimised simultaneously, the x-axis can be modified to show density multiplied by price; in this way, materials with the lowest products of both parameters will be shown on the left-hand side of the axis – see Figure 2.  This is obtained by modifying the x-axis using the advanced button and selecting both density and then price as the two attributes, as described in section 5b of the notes on using CES.

3b.  As a new graph stage, a graph of density x price (x–axis) versus fracture toughness (y-axis) now needs to be plotted and will look like that shown in Figure 3.  At this point, no constraints have been considered and hence all 97 materials are still shown in the Results pane on the left-hand side.

3c.  The constraint on the values of yield strength now can be introduced using the addition of a selection box as is described in section 4 b of the notes on the use of CES.  Click on the Selection box symbol ⬜ when showing the graph of density x price versus yield strength, and then move the mouse to draw a box on the graph with the yield strength between 2 and 20 MPa.  The result should be as in Figure 4.   Given that the object being considered is the lighter fuel tank, It is evident that some of the materials shown as still possible will be unsuitable, i.e. the olive green (ceramics-stones) and the dark green (woods).  Hence it is sensible to further restrict the possible materials by making the selection box narrower to eliminate both the unsuitable materials just described as well as those which have high values of density x price.  The result is shown in Figure 5, and now only 16 materials from the original 97 meet the constraint specified.  Moreover, it is clear that some still in the list (e.g. the remaining ceramics-stones and woods) would not be suitable.  The materials identified using only the constraint on yield strengths are shown below.

| | |
|---|---|
| Acrylonitrile butadiene styrene (ABS) | Natural Rubber (NR) |
| Brick | Paper and cardboard |
| Butyl Rubber | Plaster of Paris |
| EVA | Polyethylene (PE) |
| Granite | Polyisoprene Rubber (IIR) |
| Hardwood: oak, across grain | Rigid Polymer Foam (HD) |
| Ionomer (I) | Rigid Polymer Foam (MD |
| Marble | Slate |

3d.  In a similar fashion, the constraint on the values of fracture toughness now can be introduced, again using the addition of a selection box as is described in section 4 b of the notes on the use of CES.  The fracture toughness is limited to between 1 and 4 MPa m$^{\frac{1}{2}}$, and the resulting graphs are shown in Figures 6 and 7.  The materials identified using only the constraint on fracture toughness number some 24, with only some of the above materials included.

3e.  It now is possible to see which materials can be identified if both constraints (on yield strength and fracture toughness) are applied together by changing the Show criterion in the Results screen on the left-hand side to "Pass all stages".  Now the only 8 materials are identified and these are:

| | |
|---|---|
| Acrylonitrile butadiene styrene (ABS) | Ionomer (I) |
| Brick | Marble |
| Granite | Polyethylene (PE) |
| Hardwood: oak, across grain | Slate |

3f.  There clearly are only three materials that might be considered for the lighter tank at this stage given the additional constraints of fabrication.  The three polymers that might be considered are

Acrylonitrile butadiene styrene (ABS)          Ionomer (I)        Polyethylene (PE)

The properties of these can be seen by double clicking on their names to obtain a fact sheet.   In reality, the fuel tank is made from a variant of ABS since this family of polymers is easily fabricated but has superior mechanical properties than, say, polyethylene (see the relative positions of these two polymers on Figures 5 and 7), without a great penalty in price x density. The two variants (ASA, acrylic-styrene-acrylonitrile, and SAN, styrene-acrylonitrile) are described in the Supporting Information.  Guidelines which appear on the ABS fact sheet after the list of properties.   It is clear that this family of material meets the various criteria for the lighter tank, including ease of fabrication and the variant chosen, SAN, also is transparent, an additional requirement.
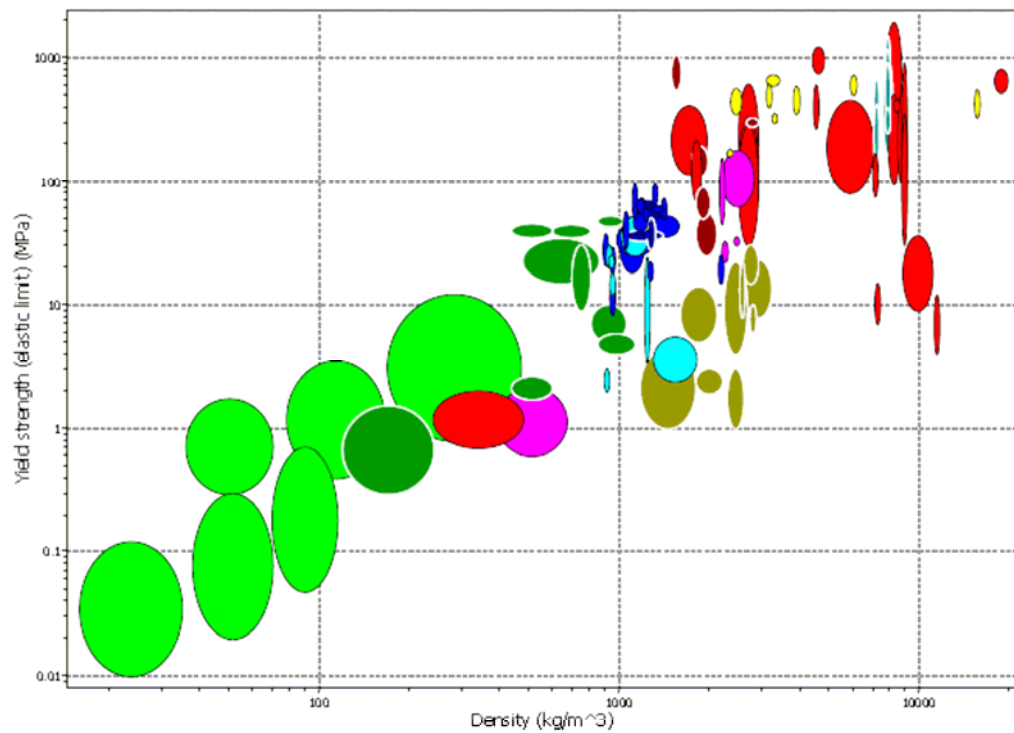
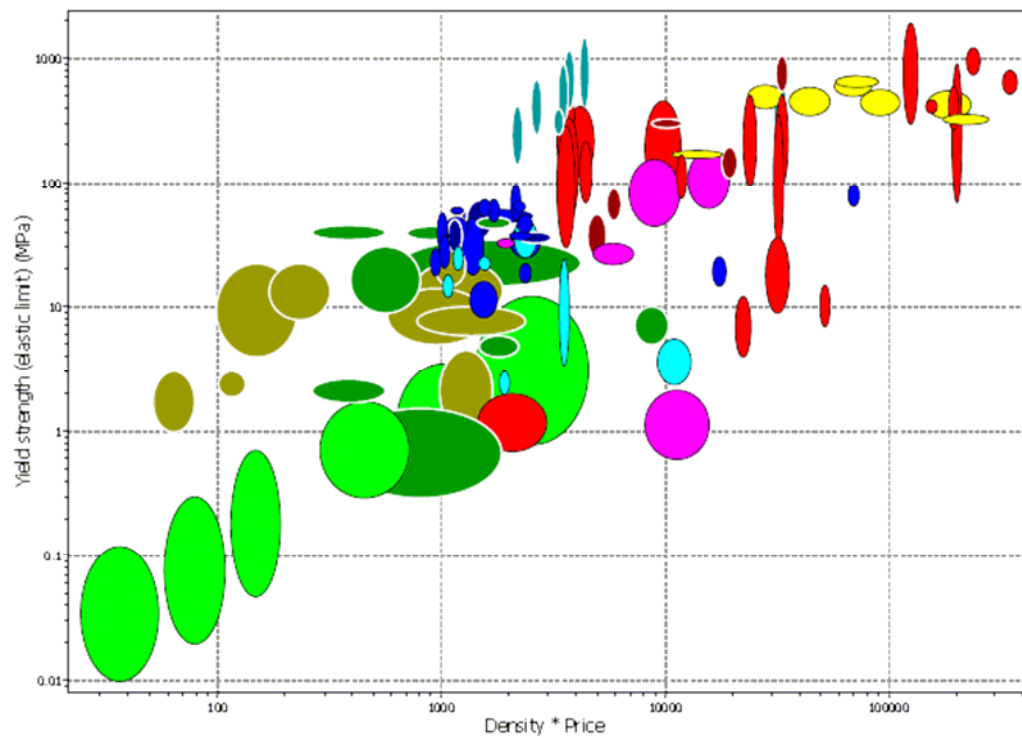Figure 1.  Yield strength versus density [all 97 materials in Level 2].



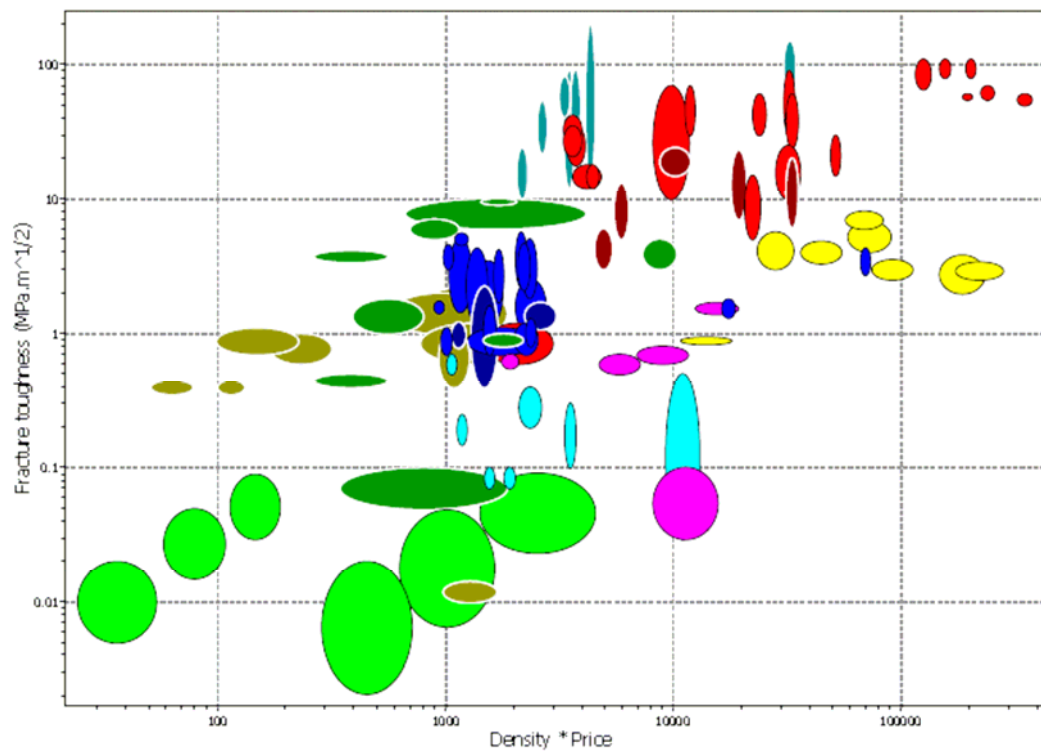Figure 2.  Yield strength versus density * price [all 97 materials in Level 2].

Figure 3.  Fracture toughness versus density * price [all 97 materials in Level 2].
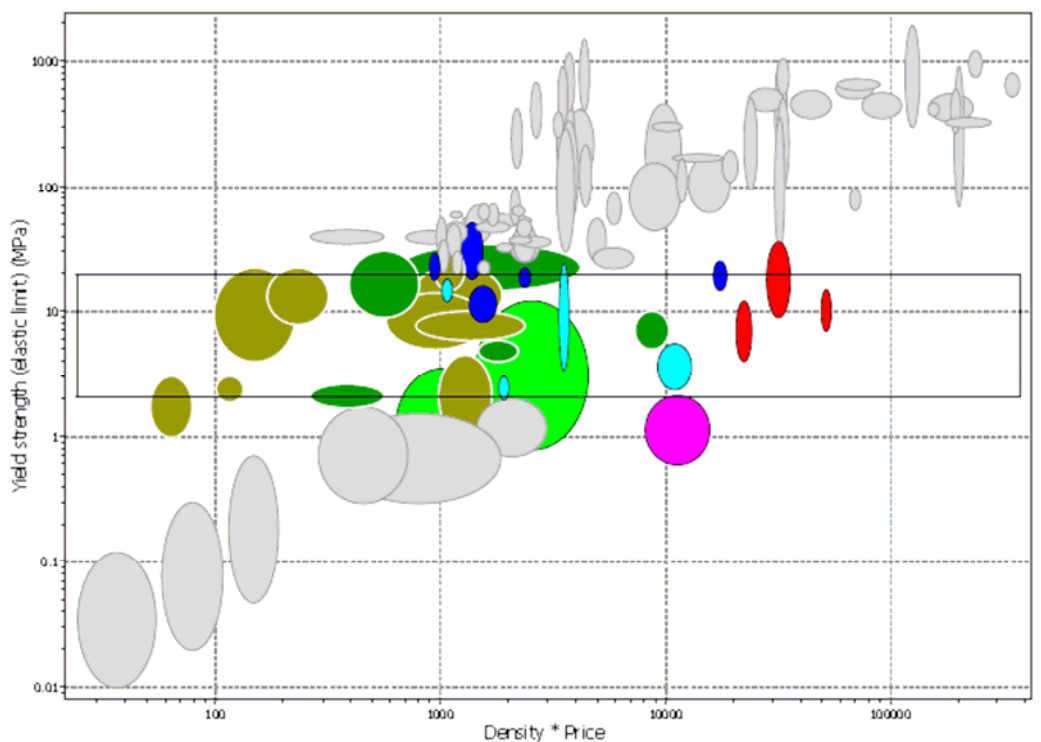


Figure 4.  Yield strength $\sigma$ versus density * price.

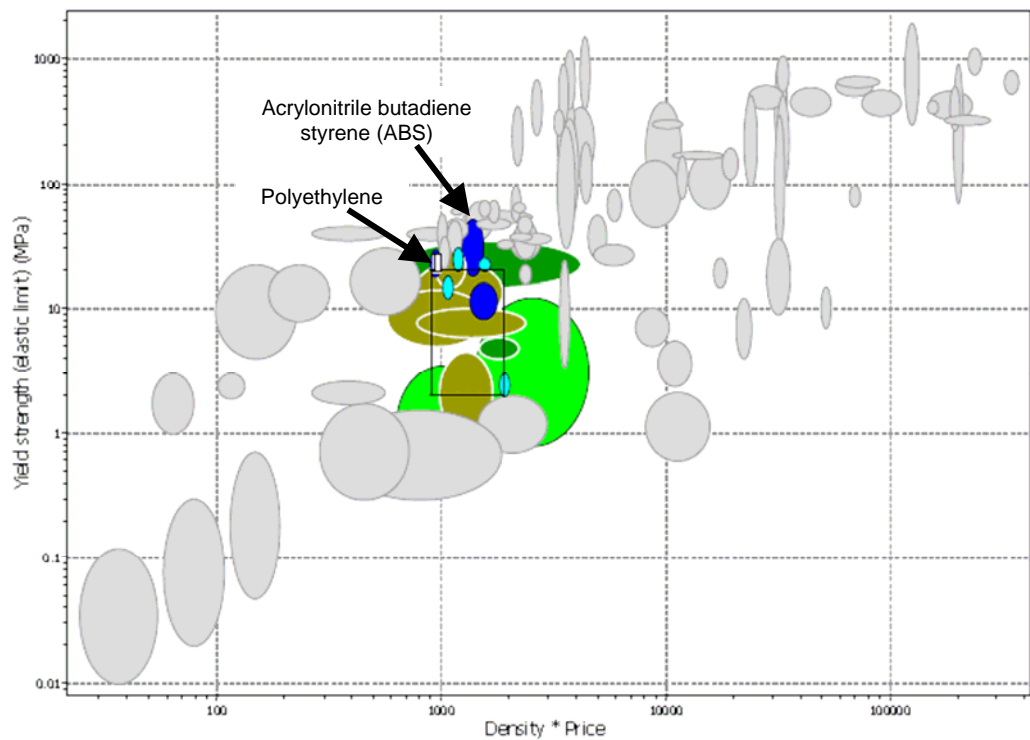Constraint on yield strength of **2 < $\sigma$ < 20 MPa**  [subset of 29 materials still possible.]

Figure 5.  Yield strength versus density x price.

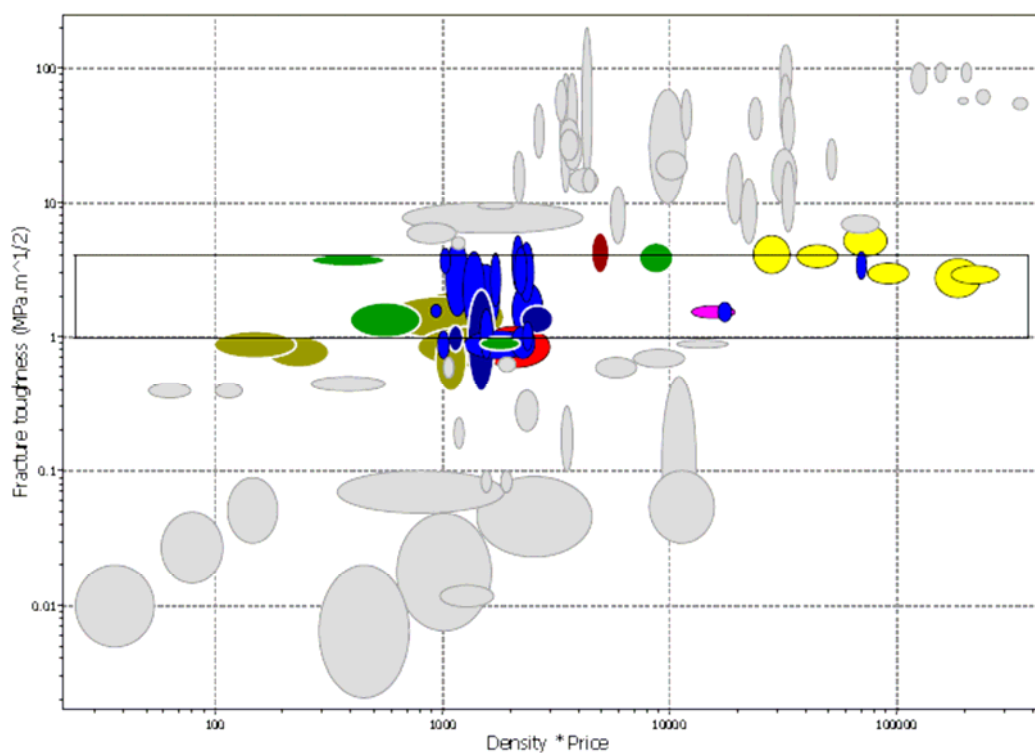Reduced subset [16 out of 97] of materials with yield strengths between 2 and 20 MPa



Figure 6.  Fracture toughness versus density x price.

Constraint on fracture toughness of 1 to 4 MPa m$^{\frac{1}{2}}$ [39 materials still possible.]
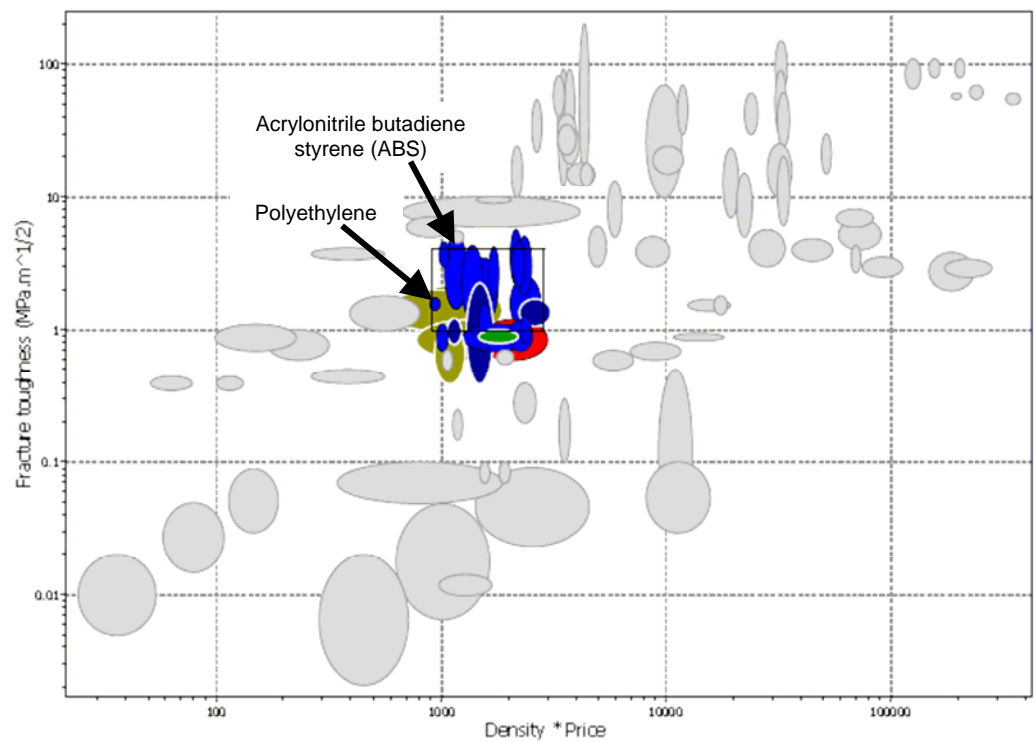
Figure 7.  Fracture toughness versus density x price.

Reduced subset [24 out of 97] of materials with fracture toughness 1 to 4 MPa m$^{1/2}$

## Author

We would like to thank Dr. Rob Wallach of the Materials Science and Metallurgy Department of the University of Cambridge for contributing this resource. You can contact him via the website www.msm.cam.ac.uk.

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