

Question 3

I. Introduction

In the next pages the following statement is going to be considered:

“When considering ceramics, metals of polymers, it is convenient to group ceramics and metals together whereas polymers have to be considered separately”

To properly discuss this statement a parallel is going to be drawn between the three different materials, by describing and explaining clearly their similarities and their differences. First of all, we are going to focus on the general information we can find about metals, ceramics and polymers and then we will get deeper in the subject by analysing their structures, their mechanical properties and the way they are produced. This will lead to a final conclusion in which we would be able to finally criticise the statement.

II. General Information

All the three different kind of materials that are being considered are spread all over the world and have been used for several decades. They can all be found in nature but also manufactured by humans in order to be used in everyday life.

Concerning their basic properties, metals and ceramics can be compared. Indeed, depending on the carbon concentration in iron-based metals for example, they can be used as constructional materials, machinery parts, cutting tools, anti-corrosion protections and as electrical components as well. Even if ceramics are on several points different – they are not as tough, they are brittle and can be used as insulators – they still have some common properties with metals and usually can do better than them. Indeed they can for instance replace metals in high performances structures, in building foundations, in cuttings tool or in wear resistant surfaces.

On the contrary, polymers are often used in very different ways. Because they are not strong materials – their stiffness is much less than that of metals and ceramics – and also because their properties can vary drastically with a small change of temperature they usually cannot be used as structural materials. Furthermore, polymers can be used for very special applications like packaging or as textiles (nylon) which make them, for general use at least, considered separately.

III. Structures

III.1. Atomic scale

First of all, the smallest scale is going to be looked at. As far as pure metals are considered, they usually have a basic crystal structure, such as b.c.c., f.c.c., c.p.h. etc. Also, metals can be turned into alloys, usually to give them improved mechanical properties. Alloying elements dissolve in pure metals to give solid solution. As we can see in figure 3.1 this solubility in metals can be interstitial or substitutional.

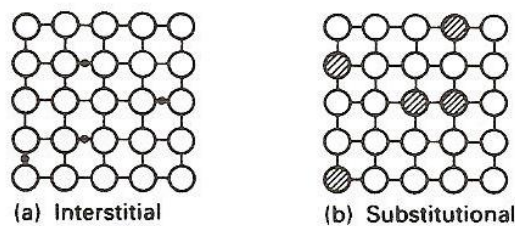


Figure 3.1: Solid solution structures for metals

Polymers have a completely different structure. Indeed, they are no longer ordered, regular nor symmetrical. Most of them are amorphous and made of long chains of molecules. They are also divided in categories depending on their degree of polymerisation and on the organisation of their molecules (linear, branched, or networked). None of this exists for metals. The only similarity that can be found between metals and polymers is that sometimes some of them have a crystalline network and a unit cell can be defined. But even the most crystalline of polymer is 80% crystal.¹ The structure would look something like figure 3.2.²

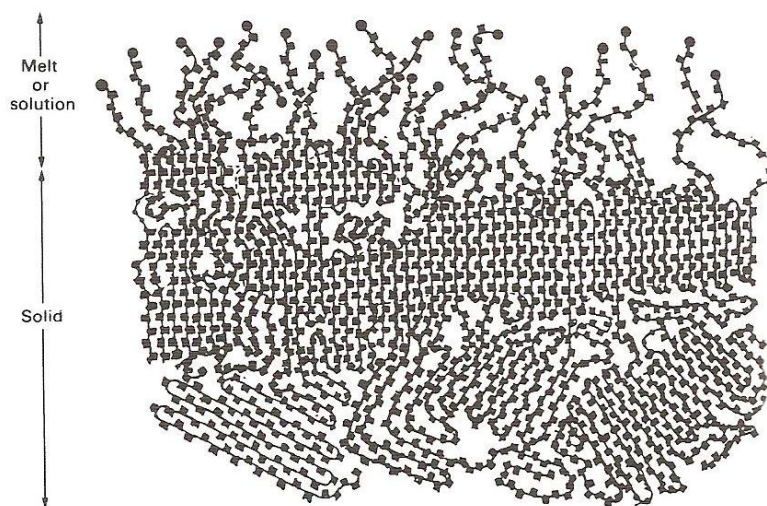


Figure 3.2: Schematic drawing of a largely crystalline polymer.

¹ Ashby, M. F., Jones D. R., (2005), *Engineering Materials 2*, Butterworth Heinemann, p. 257

² Ashby, M. F., Jones D. R., (2005), *Engineering Materials 2*, Butterworth Heinemann, p. 258

As for metals, ionic and covalent ceramics usually have a simple crystal structure. Zirconia (cubic), magnesia (rocksalt structure), or diamond (cubic), are good examples. Considering this, metals and ceramics can be grouped together. On the contrary, silica and silicates are based on a SiO_4 monomer which can be chained and give a three dimensional network like in polymers. Same thing happen for commercial glasses which are made of the identical SiO_4 monomer but organized in an amorphous way. This is once again is very similar to polymers which are never 100% crystallized. As a consequence it is important to keep in mind here that ceramics can sometime be very close to polymers.

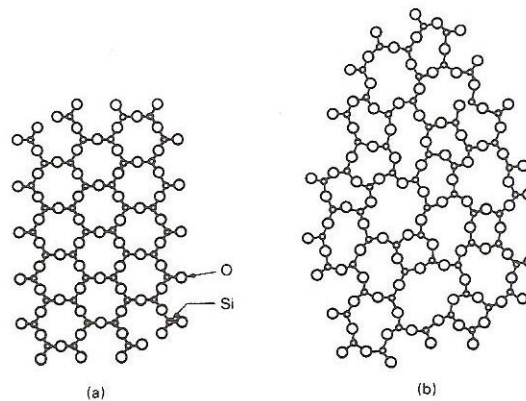


Figure 3.3: Silicate crystalline network (a). Silicate glassy network (b).³

Finally, ceramics can also be tuned into alloys to modify their properties. As for metals, octahedral and tetrahedral holes are filled by alloying atoms and the structures end up being very similar.

As a conclusion on the atomic scale, it has been proved that as a general rule there are more similarities between ceramics and metals than between polymers and the two others materials. But it would be a mistake to fully associate metals in polymers in every case.

III.2. Microstructures

In this section, we are now zooming out a little bit to look at the different microstructures.

The microstructures of random metallic alloys can be seen figure 3.4.⁴ As it can be seen, metals are organised in grains linked together by boundaries. Theses boundaries are the result of the typical solidification mechanism of metals. As the cooling begins, small solid crystals appear and start growing. The purpose of this section is not to detail the whole mechanism (which is quite complicated), but in the end, grains are formed from initial crystals and end up meeting each other. This is why we see those typical microstructures with boundaries for metals

³ Ashby, M. F., Jones D. R., (2005), *Engineering Materials 2*, Butterworth Heinemann, p. 189

⁴ http://www.copper.org/resources/properties/129_6/consolidation.html, viewed 6 Nov 2008

http://www.copper.org/resources/properties/microstructure/cu_nickel.html, viewed 6 Nov 2008

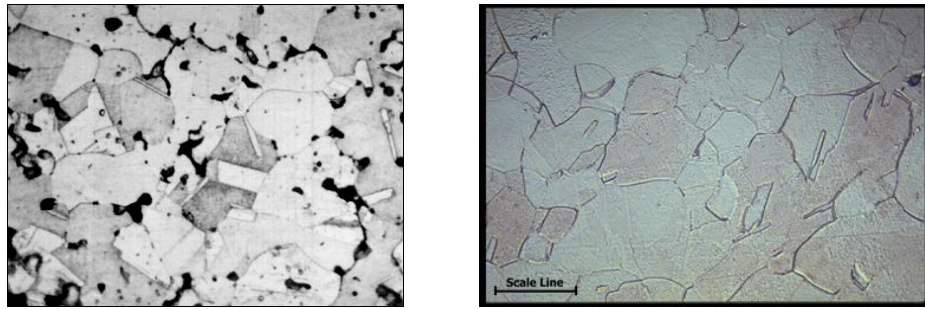


Figure 3.4: Left: Microstructure of Sintered Bronze (Magnification: 200X).
Right: Microstructure of a Copper-nickel alloy (Scale Line Length: 25 microns).

Ceramics microstructures look a lot like metals ones. Indeed they are also made of grains (which are usually perfect crystals), separated by boundaries. As in metals, some cracks on the microstructure can be seen as well as defects and impurities. But there are also some differences. The biggest one is that ceramics are usually not fully dense: porosities in 20% of the whole microstructure can be seen very often.⁵

So once again here, ceramics and metals can be compared but not completely related.

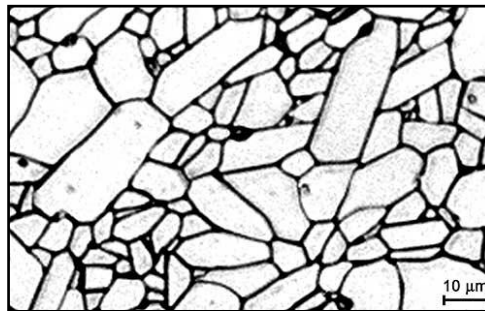


Figure 3.5: Microstructure of an aluminium oxide ceramic (99.7 %)⁶

Concerning polymers they do not have a well defined microstructure that could be compared with metals and ceramics ones. As we said before they are just a mix of molecules tangled around each other.

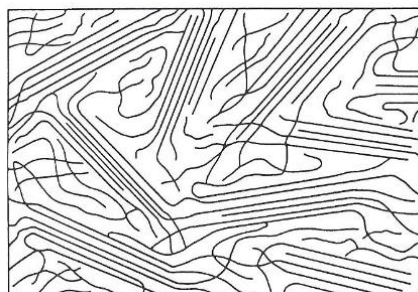


Figure 3.6: Organisation model of a polymer.

⁵ Ashby, M. F., Jones D. R., (2005), *Engineering Materials 2*, Butterworth Heinemann, p. 190

⁶ http://www.keramverband.de/brevier_engl/3/4/2/3_4_2.htm, viewed 6 Nov 2008

So as a conclusion on the microstructure section, it is clear that it makes sense to consider polymers apart of metals and ceramics.

IV. Mechanical Properties and behaviour

IV.1. Basic Properties

The main idea here is a lot like the previous section II. Indeed, Talking about how these three materials are used in everyday life by humans is indirectly referring to basic mechanical properties and behaviour. It has already been explained that even though differences exist (hardness, wear resistance, brittle behaviour...), metals and ceramics can easily be compared regarding basic properties.

First of all metals and ceramics usually have a quite similar young modulus: around 210 GPa for steels, 70 for aluminium alloys, and 69 for silica or 390 for alumina.⁷ On the contrary, this is absolutely not true the E modulus of polymers which is not constant at room temperature (the next section will get back to that).

Ceramics and metals also do not have the very particular rubbery state in which elastomers can be at certain temperatures. Some polymers are capable of elastic extensions of 300%⁸ or more and recover completely. That kind of behaviour is obviously impossible for a metal or a ceramic.

IV.2. Temperature and time

Like it has already been said in the general information section, a small variation of temperature can change radically the mechanical properties of polymers. As a consequence, when metals and ceramics have a constant stiffness and strength near room temperature, polymers have not, and can sometime go through all the mechanical states between -20°C and +200°C.⁹

Their response to temperature is very different to the other materials. Melting point is no longer the key temperature and sometimes does not even exist (when a thermoplastic is not crystallised). Instead, a new temperature called Glass Temperature, T_g , is defined to fully describe and understand their behaviour. The following figure shows this importance of T_g and the dependence of the Young's modulus on temperature.

⁷ Ashby, M. F., Jones D. R., (2005), *Engineering Materials 2*, Butterworth Heinemann, p. 325

⁸ Ashby, M. F., Jones D. R., (2005), *Engineering Materials 2*, Butterworth Heinemann, p. 269

⁹ Ashby, M. F., Jones D. R., (2005), *Engineering Materials 2*, Butterworth Heinemann, p. 362

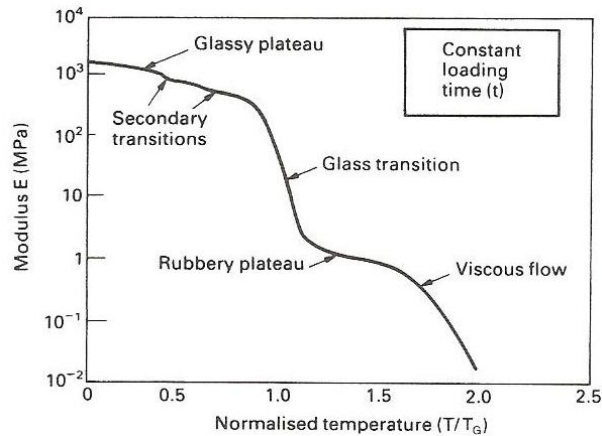


Figure 4.1: Young modulus values for a polymer

Last point about temperature is the thermal shock resistance. Like ceramics, some polymers are brittle below $0.75T_g^{10}$ and small cracks can also be seen on their surface. It is not the point here to fully describe the behaviour of polymers regarding temperature but the important thing to remember is that all of these properties and particularities are usually very specific to polymers and as the statement is suggesting, they have to be considered separately here.

Finally, there are also some similarities between the three materials because they can, under particular circumstances be time dependent. Indeed, metals ceramics and polymers all creep when they are hot, and as shown figure 4.2, the creep curves are exactly the same.

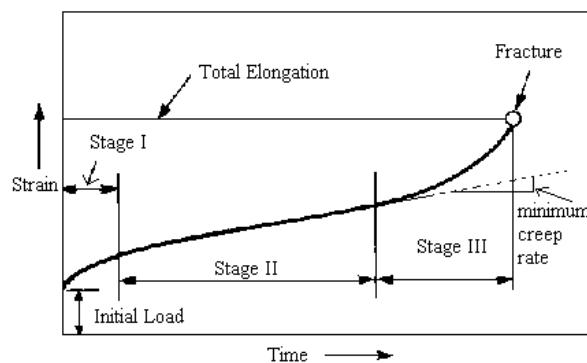


Figure 4.2: A typical creep curve for metals ceramics and polymers

Concerning time dependence again, polymers can be compared to metals and ceramics. Indeed, if a polymer is put under a constant load and as the loading time goes up, values of the Young modulus change but an equivalent for these new values could be find at another temperature. This is the equivalence between time and temperature, a behaviour that can also be observed with metals and ceramics.

¹⁰ Ashby, M. F., Jones D. R., (2005), *Engineering Materials 1*, Butterworth Heinemann, p. 273

As a conclusion, polymers are once again different from ceramics and metals but not on every aspects. As a consequence, it would be wrong to separate them completely from the other two materials

IV.3. Stress and Failure

In this last section of the mechanical properties, behaviour under stress is going to be analysed. The following figure shows the schematic stress curve for a random metal. Three steps can be separated to describe a typical metal behaviour: First of all the elastic deformation occurs, then the plastic deformation goes on and finally rupture happens.

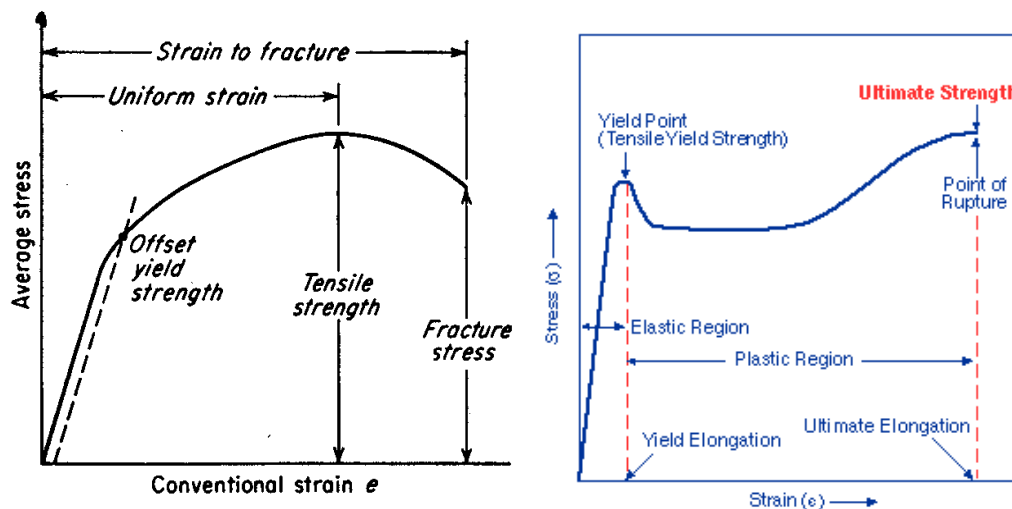


figure4.3: Schematic Stress/Strain behaviour curve for a metal (left) and a thermoplastic (right)¹¹

Polymers, especially thermoplastics at low temperature, have a very similar behaviour, as it is also shown figure 4.3. They also go through an elastic regime before entering the plastic regime which leads to rupture as the strain increase.

On the contrary, ceramics usually fail within the elastic regime and that is why they are called brittle materials. As it has already been said in IV.2, thermosets are usually brittle below $0.75T_g$ and also fail within the elastic regime. Therefore some polymers can be compared to ceramics regarding their behaviour under stress.

At last, crack propagation can be described with the same equation for all the materials, as soon as they are brittle. Every of them have small surface cracks (depth a) and the material will fail if:

$$\sigma = \frac{K_c}{\sqrt{\pi a}}$$

As a conclusion it has been show here that it is not really possible to group any of the materials together.

¹¹ http://www.scudc.scu.edu/cmdoc/dg_doc/develop/material/property/a2200002.htm, viewed 9 Nov 2008

V. Production and joining

Last thing that is going to be discussed is the way to produce any of these materials and the possibility to join them.

V.1. Production

Main route for processing metals is quite common. Usually the basic metal is melted and then cast into a mould. But there are also different possibilities like precision forming or powder forming. Machining on metals is very easy via cutting, turning, drilling processes for instance. Finally, surface finishing like polishing, grinding, plating or painting are also possible.

On the contrary the range of processing routes for ceramics is not as large. Because of their very high melting point, it is usually not convenient to cast ceramics like metals. Also, the main processing route for ceramics is sintering. As for metals, the raw material used is a powder which is then heated and pressed. The energy drives sintering.

Furthermore, because of their lack of plastic regime (like it has been explained in IV.3), it is usually not possible to form ceramics by deformation.

Concerning polymers, because of their special properties, processing routes are way different. The raw materials can very often be extracted from nature and then modified or transformed. Polymers are synthesized by chemical reactions and this cannot be compared to the way metals and ceramics are produced.

Finally, as for metals but unlike ceramics, polymers can easily be formed. Thermoplastics for instance soften with a small variation of temperature and can be extruded, injected and moulded.

As a conclusion no obvious association can be done here.

V.2. Joining

As it is easily noticeable in everyday life, ceramics metals and polymers are very often associated within a same product. Concerning joining it is indeed not really possible to establish a distinction between these three materials.

The only little problem is with ceramics. Because of their brittle behaviour, they cannot be riveted or bolted. As a consequence, in order to join ceramics to other materials processing route which avoid stress concentration have to be used. Ceramics are for example joined to metals by coating and by using adhesives.

VI. Summary and conclusion

To be able to have a clear view on everything that have been said, the following table sums up all the information by categories and associates which material is closer to the other considering these categories.

Table 6.1: Summary and comparisons

Section	Subsection	Likely to group
General information	None	Metals and Ceramics
Structure	Atomic Scale	Metals and Ceramics / Possibly Ceramics and Polymers
	Microstructures	Metals and Ceramics
Mechanical properties	Basic Properties	Metals and ceramics
	Temperature an time	Metals and Ceramics / Ceramics Metals and Polymers
	Stress and failure	Metals and Polymers / Possibly Metals, Ceramics and Polymers
Production and joining	Production	Some similarities but all different overall
	Joining	Metals ceramics and polymers

As a conclusion, everything that has been said before and summed-up in table 6.1 show that, like the statement was saying, it is indeed convenient to group metals and ceramics and to consider polymers separately. But it has to be kept in mind that it is only true for most of the situations and some particularities exist. If for instance, response to stress behaviour, time dependence, or joining is considered, polymers can also be compared to metals and ceramics.