Metallographic Phenomena As Observed in Cheeses

22.033 - Nuclear Systems Design Project

November 20, 2011

Cabot Clothbound Cheddar (cow) - Peacham/Greensboro, Vermont, USA

Hard cheese, aged 10-14 months

Cabot Clothbound is a handsome natural-rinded traditional cheddar. Bandaged with muslin and skillfully aged a minimum of 10 months at the Cellars at Jasper Hill. Cabot Clothbound has all the characteristic texture of an English-style cheddar with the sweet caramel and milky flavors that sets it apart from other bandaged cheddars. The flavor profile is at once sweet, savory, nutty, and tangy.

Maps removed due to copyright restrictions.

Willis Wood's Pure Apple Cider Jelly - Springfield, Vermont, USA

The Wood family has been making Cider Jelly since 1882. They use the same apple press they started out with to grind and press fresh apples to make sweet cider. The cider is then evaporated in a wood-fired stainless steel evaporator until the cider is reduced to 1/9 of its original volume and becomes this sweet and intensely appley concentrated jelly. It couldn't be any simpler: just concentrated cider with nothing added, no preservatives or sweeteners. The cider from about 30 to 50 apples is concentrated in every pound of Cider Jelly.

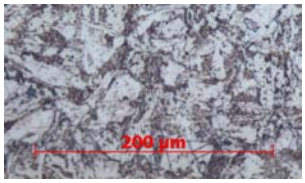
Courtesy of Formaggio Kitchen. Used with permission.

The Granular Structure of Metals, Intergranular Fracture

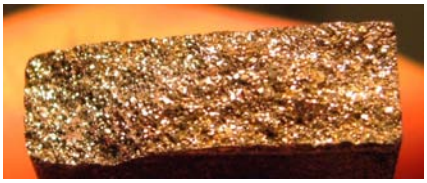
Most metals are composed of grains, or small regions of continuous crystallinity. The boundaries between these grains are called *grain boundaries*. A quick cut, polish and etch of most metal surfaces will reveal the crystalline nature of the metal. An everyday example can easily be seen in aluminum alloy traffic poles, where the grains can be as large as one centimeter in diameter.

Intergranular (IG) fracture is a failure mode of metals, where they break along grain boundaries instead of through the metal, known as *transgranular (TG) fracture*. IG fracture usually indicates some sort of significant weakness at the grain boundaries of a metal. High doses of radiation, as well as corrosion phenomena (such as stress corrosion cracking, or liquid metal embrittlement in LFRs) can lead metals to IG fracture.

Cheddar cheese breaks with an IG fracture pattern due to the *cheddaring process*. Curds of cheddar cheese are pressed together in large molds, draining the whey from the curd. These curds then posses grain boundaries that are much weaker than the curds themselves.



A469 Rotor Steel from Alcator C-Mod



W-1 tool steel, IG fracture after quenching

Comte Le Fort (cow) - Jura, France

Hard cheese, aged 16-24 months

After WWII, Marcel Petite bought an unused munitions fort from the French Government because he felt that it would be an ideal environment for aging his 70lb wheels of French Gruyère known as Comté. This cheese is from the high altitude Jura region in southeastern France. The Montbéliard cows graze on meadows teaming with pissenlit, or wild dandelion.

The crystals of lactic acid present inside the cheese are a by-product of the lactose fermentation process. They add a tartness and a crunch to this cheese.

Maps removed due to copyright restrictions.

Artisinal French Bread - Cambridge, MA, USA

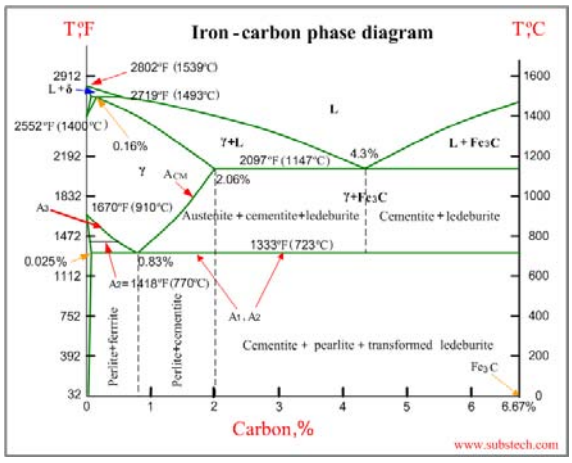
Gruyère cheeses go very well with starches, like bread, or pair superbly melted over potatoes. A good French bread is an excellent vector for balancing the medium flavors of Comté, as well as cleansing the palate between cheese tastings.

Supersaturation, Formation of Secondary Particle Precipitates (SPPs)

Elements often have limited solubilities in each other, and as they cool, phases of one composition will form with an *interdendritic liquid* forming around them. This interdendritic liquid can become supersaturated in one element as it cools, leading to precipitation of certain phases. In Comté cheese, lactic acid produced by bacteria supersaturates and precipitates out as crunchy crystals. In Zircaloys, found as fuel cladding in LWRs, these SPPs precipitate out, leading to enhanced strength and corrosion properties.

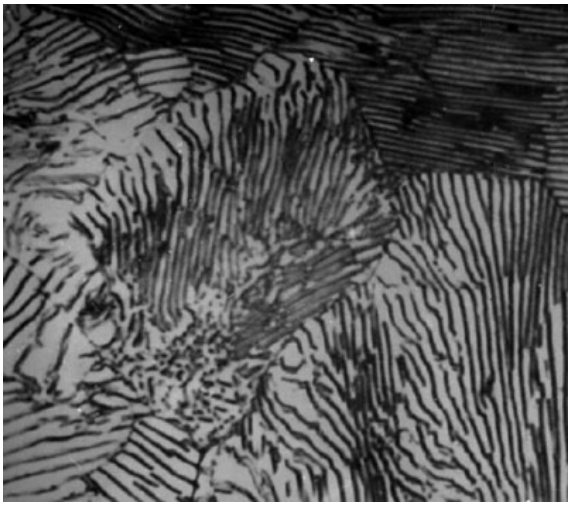
A more familiar example of supersaturation and precipitation of a secondary phase can be found in carbon steel. Steel with more carbon than is soluble in ferrite alone will precipitate out as *pearlite*, a lamellar mixture of *ferrite* (with little carbon) and *cementite* (Fe_3C). The line at the lower left of the Fe-C phase diagram shows just how little carbon is soluble in ferrite alone.

The lactic acid crystals in this cheese are a result of supersaturation in the interdendritic liquid as the cheese formed.



Courtesy of Dimitri Kopeliovich. Source: Kopeliovich, D. "Iron-carbon phase diagram." SubsTech.

Iron-Carbon Phase Diagram [1]



Microstructure of pearlite, showing light bands of ferrite and dark bands of cementite [2]

Brebis Abbaye de Belloc (sheep) - Aquitaine, France

Hard cheese, aged 6 months

Abbaye de Belloc is made from sheep's milk by the Benedictine monks at the monastery of Notre Dame. Developed in 1960, the recipe is based on that of Ossau-Iraty. The milk comes exclusively from the Manech breed of sheep, courtesy of surrounding farms. The resulting cheese is mild, rich, and smooth. The texture is somewhat firm, with flavors of brown butter, nuts, caramel.

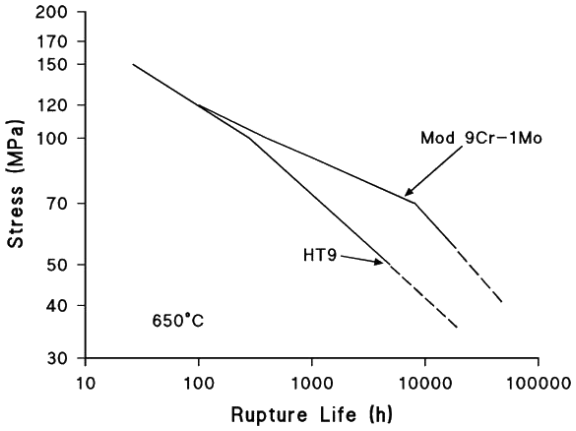
Cerise Noire, Confiture de l'Ardèche - St. Sylvestre, France

These are organic small-batch handmade preserves made by Sylvie and Pascal Raunicher at La Ferme de Mazairas in the small town of St. Sylvestre in the region of Ardèche. Their tiny farm specializes in organic fruit, using unusual varieties with tons of fresh flavor. Handpicked organic black cherries are lovingly cooked, on a low heat until this rich preserve has a striking dark purple color and flavor that has a warm sweetness and a mellow tartness. Best when paired with sheep's milk cheeses.

Creep: Deformation Under Constant Load

Metals, especially those at high temperature, can undergo *creep failure* even at loads far below their rated strength. This is because constant loads, such as pressure or gravity, do cause dislocations present in the metal to move. These effects increase in speed with higher temperature. Creep lifetimes for metals in fast reactor environments range from months to years, and can be the limiting factor in high temperature materials performance or fuel cycle length.

This cheese undergoes a creep-like phenomenon due to gravity, where it will deform irreversibly under the constant load of gravity. T91, a creep resistant steel, still possesses a finite creep lifetime. A high pressure gradient across a pipe wall can cause the diameter of the pipe to gradually thin, eventually resulting in a *creep rupture* once the wall thickness is reduced enough. Creep lifetime can be greatly reduced with an improper heat treatment (see below), such as overtempering T91 to make it too soft.



Creep rupture lifetimes for HT-9 and T91 [3]

Creep rupture failure of T91 pipe [4]

Sottocenere al Tartufo (cow) - Lombardy, Italy

Blended / Flavored Cheese (black truffles), aged 3 months

This unusual cheese is coasted with a fine, pressed layer of ash. Made from whole cow's milk, it has a rich, creamy texture and is laced with black truffles. The truffle aroma delicately flavors each bite.

Courtesy of Formaggio Kitchen. Used with permission.

Maps removed due to copyright restrictions.

Solmielato Miele de Melata (spruce honeydew) - Sicilia, Italy

Miele di Melata, or 'honeydew honey,' is honey from uncultivated and forested zones. It is distinctive from other honeys for the fact that it comes not from flowers, but from the sugary secretions of the leaves of some arboreal essence and shrubs, in this case, spruce trees. These secretions are caused by specific types of aphids (metcalfa pruinosa, or planthoppers) biting the leaves, allowing the sap to leak out and be collected by bees.

Stress Concentrators and Reduction in Tensile Strength

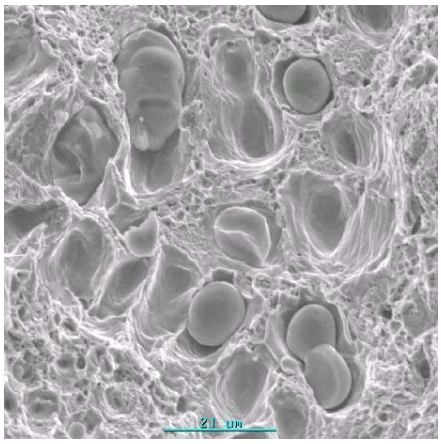
Defects in metals can produce regions of *stress concentration*. These defects can include foreign bodies (*inclusions)*, secondary precipitated phases, voids (due to casting or due to irradiation), cracks, and mechanical defects such as scratches or welding errors.

The *stress concentration factor* is a function of the *geometry* of the flaw, or the ratio of the major and minor axes of the flaw and its radius of curvature, NOT its overall size. The stress at the major axes of an elliptical flaw (such as a crack, void, or scratch) is given by:

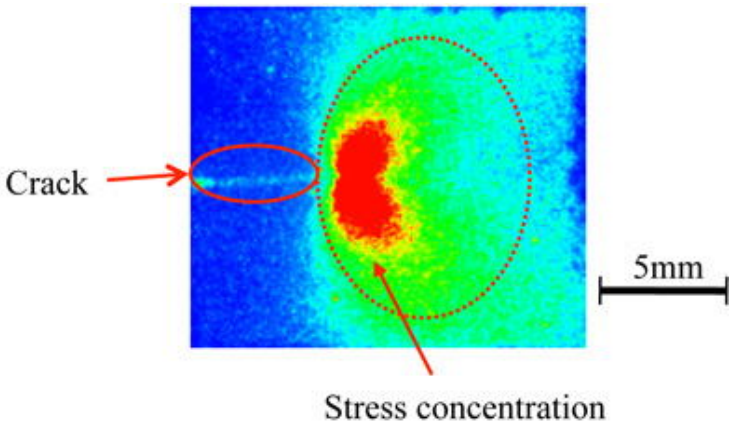
$$\sigma_{max} = \sigma_{applied}\left(1 + 2\sqrt{\frac{a}{r}}\right) \tag{1}$$

where a is the length of the crack or flaw and r is its radius of curvature at the tip. As r approaches zero, the stress approaches infinity. This σ_{max} is therefore the streess actually applied to a section of material near a crack, which explains why materials with flaws can fail well below their rated strength for intact material.

Materials therefore tend to fracture at the sites of these flaws. In this cheese, inclusions are simulated by the truffle flakes. Pulling on the tensile specimen (made out of the cheese) will invariably result in failure at one of the truffle flakes, if they are present in the narrow section of the sample. SEM micrographs of metals with cracks and inclusions will reveal their flaws on the fracture surfaces.



MnS inclusions on the fracture surface of A469 rotor steel from Alcator C-Mod



Stress concentrations of a crack as visualized by an elastico-luminescnet coating [5]

Queso Azul de Valdeon (cow & goat) - Valdeon, Spain

Blue cheese, aged 3 months, wrapped in sycamore leaves

This not too spicy blue is a blend of cow and goat's milk. Before aging, it is wrapped in sycamore leaves, giving it an earthy flavor with offsets the tangy blue making a fantastically well-balanced taste. The experience when eating Valdeon occurs in almost three separate stages. It sends a shock to the senses at first, surprising and unusual, but by mid-palate, it subsides and the spicy fruit in this cheese is present. The finish leaves an electricity on the tip of your tongue.

Maps removed due to copyright restrictions.

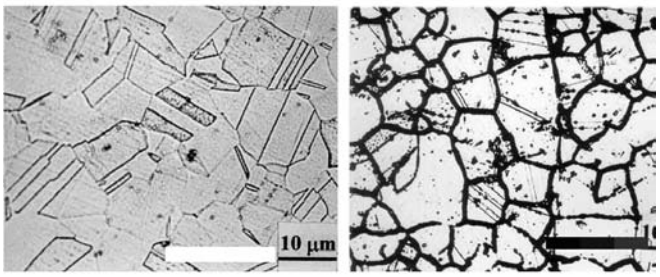
Solmielato Miele de Bergamotto (Bergamot blossom) - Sicilia, Italy

Bergamot, best known for lending its distinctive fragrance to Earl Grey tea, provides the pollen for this exceedingly rare honey. Tiny amounts are produced at a time, owing to the finickiness of the bergamot blossom. It does not grow on Sicily, but rather in nearby Calabria. The Solmielato honey producers must therefore transport their beehives by ferry to the bergamot groves in Calabria by ferry, where they release their bees to gather this rare pollen.

Grain Boundary Sensitization, Segregation, and IG Attack

Under certain conditions, metals can undergo *sensitization*, where they become more susceptible to failure by corrosion or stress than before. This can occur in a number of scenarios. One, shown in the figure below, shows what happens when 304 stainless steel is heated between 400-850 Celsius for a prolonged period of time. The carbon in the steel combines with chromium on the grain boundaries, forming chromium carbides. This locally depletes the surrounding metal, resulting in easier IG attack of the steel.

Blue cheese is quite similar to the after effects of a sensitized steel. Upon inoculation with the mold required to make blue cheese and exposure to oxygen, the mold attacks the weaker curd boundaries of the cheese faster than the curd itself. This results in the veined structure of blue cheese.



Unsensitized structure for 304 stainless steel Sensitized structure of 304 stainless steel [6]

Cheese descriptions adapted from http://www.formaggiokitchen.com/, http://ohioauthority.com/articles/food-and-drink/the-cultured-palate-strong-attractions, http://fr.wikipedia.org/wiki/Abbaye_de_Belloc, and http://www.solmielato.it/

Maps provided by Google Maps (http://maps.google.com/)

[1] Image source: http://www.substech.com/

[2] Image source: http://hsc.csu.edu.au/engineering_studies/transport/2522/heat_treat_answers.html

[3] R.L. Klueh and A.T. Nelson. Ferritic/martensitic steels for next-generation reactors. Journal of Nuclear Materials, 371(1-3):37–52, September 2007.

[4] R. Swanekamp. "Handling Nine-Chrome Steel in HRSGs." Power Engineering, Vol 100:2, 2006.

[5] AIST. "Diagnosing damages in structures and their danger level at the same time using elastico-luminescent materials." Accessed at http://www.ndt.net/search/docs.php3?id=7506&content=1, Tsukuba, Japan, 2008.

[6] Image source: http://www.solidmetals.net/2011/05/02/sensitization-of-stainless-steel/

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