AC 2008-2887: MATERIAL SELECTION FOR A PRESSURE VESSEL

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Material Selection for a Pressure Vessel

ABSTRACT

Pressure vessels are designed to contain pressure and withstand the operating mechanical and thermal transients for a specified design life. In addition they are designed to safety to leak before break (LBB). LBB describes the situation in which a leak occurs before a complete double-ended break of a component. Ductile and tough materials are widely used in nuclear pressure vessels, because of their high resistance to catastrophic rupture. The design process involves fatigue analysis to demonstrate that there is insignificant crack growth a postulated surface crack during the entire design life. However in terms of LBB the significant parameter is the elastic-plastic fracture toughness, and the material strength. However based on assessment based on linear elastic fracture mechanics, the candidate materials are carbon steels, low alloy steels and stainless steels, which interestingly are the materials that are used for pressure vessels. In terms of the fatigue crack initiation, the appropriate parameters are the threshold stress intensity factor range and the endurance limit and the material selection is based on these parameters.

INTRODUCTION

Selection of materials and manufacturing processes are important activities that are essential for structural design. Ashby (2005) was the first to demonstrate that a wide range of material properties could be collected and plotted on the same curve, where two individual material variables appear on the abscissa and the ordinate. Using this concept Granta Design (2007) has developed a software package CES EduPack which includes a wide range of data on materials, manufacturing processes and shapes for over 3000 engineering materials. The objective of the present study is explore the use of the software CES EduPack in the selection of material for a pressure vessel where competing requirements of strength and resistance to crack extension have to be met.

Traditional treatment of pressure vessels in undergraduate engineering and engineering technology curricula appears typically in the course on strength of materials where only the strength design is emphasized. The elastic analyses are invoked and deformations beyond the elastic limit are not considered. In addition there is very limited reference to fracture mechanics. There have been incidences of failure of pressure vessels that could not be attributed to strength but to brittle and ductile fracture. In addition a large number of vessels fail in fatigue for which design codes exist.

In what follows we will primarily focus on Leak before Break (LBB) which is considered a significant design feature for pressure vessels. We will discuss the issue of fatigue crack initiation for which some modifications to the software CES EduPack is needed.

LEAK BEFORE BREAK METHODOLOGY

One of the earliest methods to address LBB in pressure vessels was due to Irwin (1963) where the LBB was postulated to occur due to an axial flaw in a pressure vessel, if the flaw length was less than twice the shell thickness. This implies that the crack driving force in the radial direction would exceed that in the axial location under these conditions. Subsequently this criterion was modified by other researchers by including free surface effects, bulging effects and toughness differences in through-wall crack versus surface growth directions. As noted by Wilkowski (2006) LBB procedures and analyses vary from one industry to another depending on the level of risk and the nature of loading experienced during operation. In the natural gas pipeline industry, where pipelines stay buried in remote areas, the axial flaws tend to be problematic because of the existence of large compressive longitudinal stresses. In the nuclear industry the concepts of LBB has been applied to piping systems for the purpose of eliminating equipment used for restraining pipe whipping from a postulated pipe rupture event. The concern in this application is with the above ground plant piping systems where circumferential flaws are historically more prevalent than the axial flaws. In the LBB approach it is desirable to detect small amounts of leakage at normal operating conditions so that the leakage size flaw will be stable at transient stresses. It is also essential that there not be any sub-critical crack growth mechanism that could cause long surface flaws to occur. Such long surface flaws could lead to failure under the transient loads without any leakage warning. Application of the LBB concept thus requires reliable leak detection systems and verified leak rate estimation techniques. An important issue is to determine the condition under which piping would leak sufficiently prior to break so that an operator action could be taken before a catastrophic failure occurs.

ANALYSIS BASED ON LBB

Hoop stress σ in a cylindrical pressure vessel of radius R and thickness t, due to an applied internal pressure p is given by,

$$\sigma = \frac{pR}{t} \qquad (1)$$

If the limiting stress σ is the yield strength σ_f of the pressure vessel material, then the thickness t of the vessel to preclude yielding will be,

$$t \geq \frac{pR}{\sigma_f} \qquad (2)$$

If a through wall crack (i.e. a crack length $2a_c = t$) is detected from which a leak is taking place, then the crack will be stable if and only if,

$$\sigma \leq \frac{K_{Ic}}{\sqrt{\pi t / 2}} \qquad (3)$$

Where, K_{Ic} is the plane strain fracture toughness of the pressure vessel material. In equation (3) inserting the limiting value of σ as the yield strength σ_f of the pressure vessel material, and substituting in (2) we obtain,

$$p \leq \frac{2}{\pi R}\left(\frac{K_{Ic}^{\ 2}}{\sigma_f}\right) \qquad (4)$$

The maximum pressure is carried most safely by the material having greatest value of (K_{Ic}^2 / σ_f) – This sets the selection criterion for the LBB. Figure 1 indicates the method used to select pressure vessel material for LBB

The line with the largest (K_{Ic}^2 / σ_f) in the plot for K_{Ic} vs σ_f and the intersection with a large value of σ_y yields the steels and nickel alloys as the choice for the design based on LBB and also high strength. These procedures are indicated in Ashby (2005) and Ashby et al (2007) and are shown in Figures 2 and 3.

This activity was introduced in the sophomore strength of materials course, after material properties were discussed and the concept of fracture toughness was introduced. The software proved to be quite effective, although there was an element of confusion, because the data on Figures 1, 2 and 3 represented both ductile and brittle materials. If the data included only ductile materials the selection process would have been more representative. The students were also made aware of some of the limitations in the software in terms of absence of data on elastic-plastic fracture toughness.

ANALYSIS BASED ON FATIGUE CRACK INITIATION

This activity was introduced in the sophomore mechanical design course. The students were introduced to the subject of fatigue. The discussion centered on fatigue life. The fatigue life is divided in two phases that of initiation and propagation. The fatigue limit was described as threshold crack propagation (Suresh (2004). This is based on nucleation and growth of small cracks. Small cracks are assumed to nucleate instantly and could become propagating only when the small crack threshold is exceeded and this is assumed to grow through the process zone which is characterized by a distance parameter which is dependent on the small crack threshold stress intensity factor range, ΔK_{th} and the endurance limit $\Delta\sigma_e$ of the material. On the basis of short crack growth rate obtained for a wide variety of materials, Kitagawa and Takahashi (1976) have demonstrated that there exists a critical crack size d below which ΔK_{th} decreases with decreasing crack lengths. This parameter d was also defined by Taylor (2007) as a distance parameter given by,

$$d = \frac{1}{\pi}\left(\frac{\Delta K_{th}}{\Delta \sigma}\right)^2 \qquad (5)$$

The distance parameter is related to grain size and smaller grain size indicates stronger resistance to crack initiation. Therefore for selection of pressure vessel material for long initiation life should be based on the least value of $\Delta K_{th} / \Delta\sigma_e$. This activity could not be successfully done with CES EduPack. Although a discussion of the process zone is mentioned in Ashby (2005) and indicated in Figure 2, the application of distance parameter needs to be incorporated effectively in the software. Furthermore, CES EduPack software needs to be updated with the information on small crack threshold stress intensity factor ranges, ΔK_{th} and the endurance limits $\Delta\sigma_e$ of various structural materials.

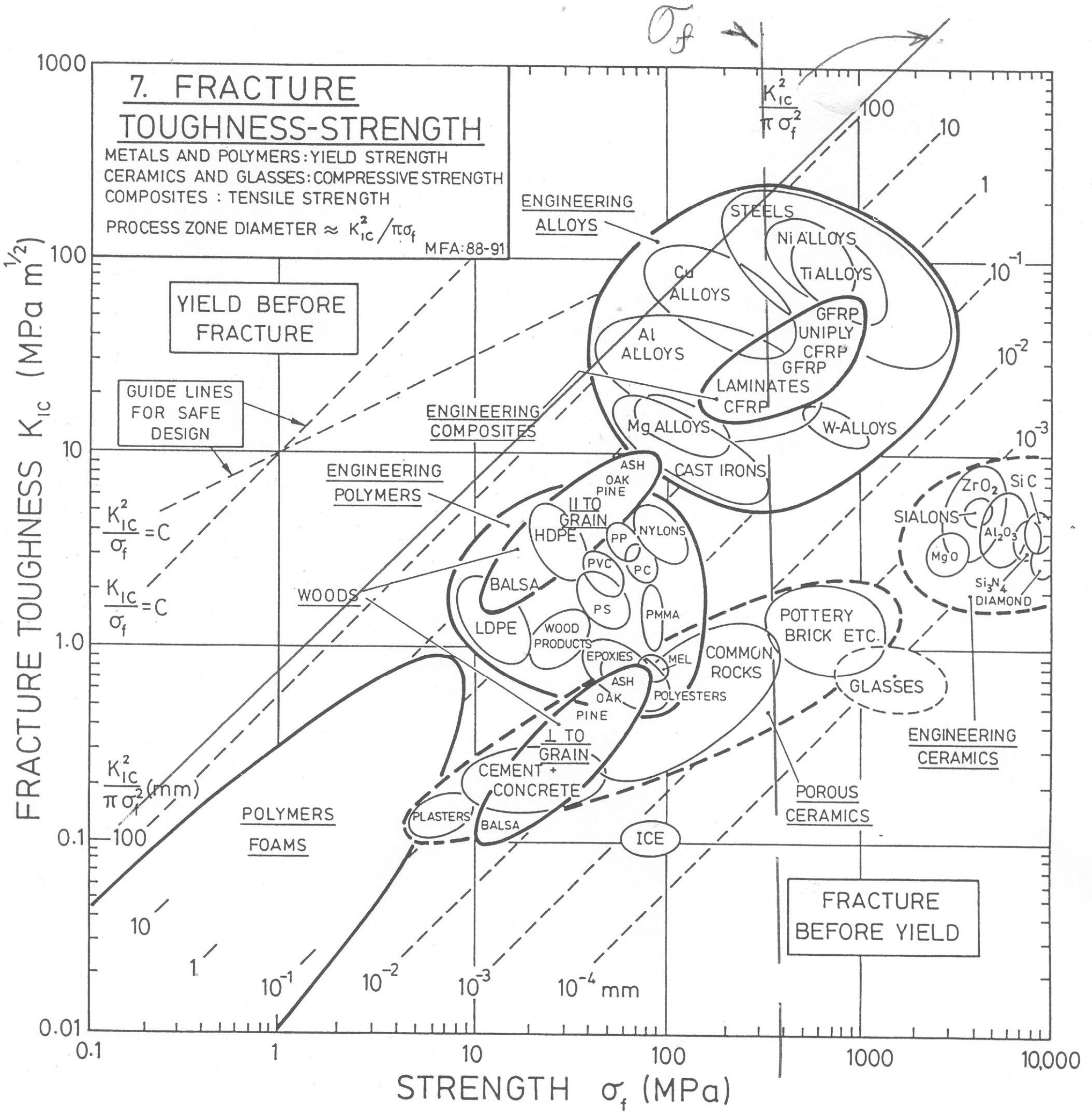

Figure 1 CES EduPack Fracture Toughness vs Strength Plot

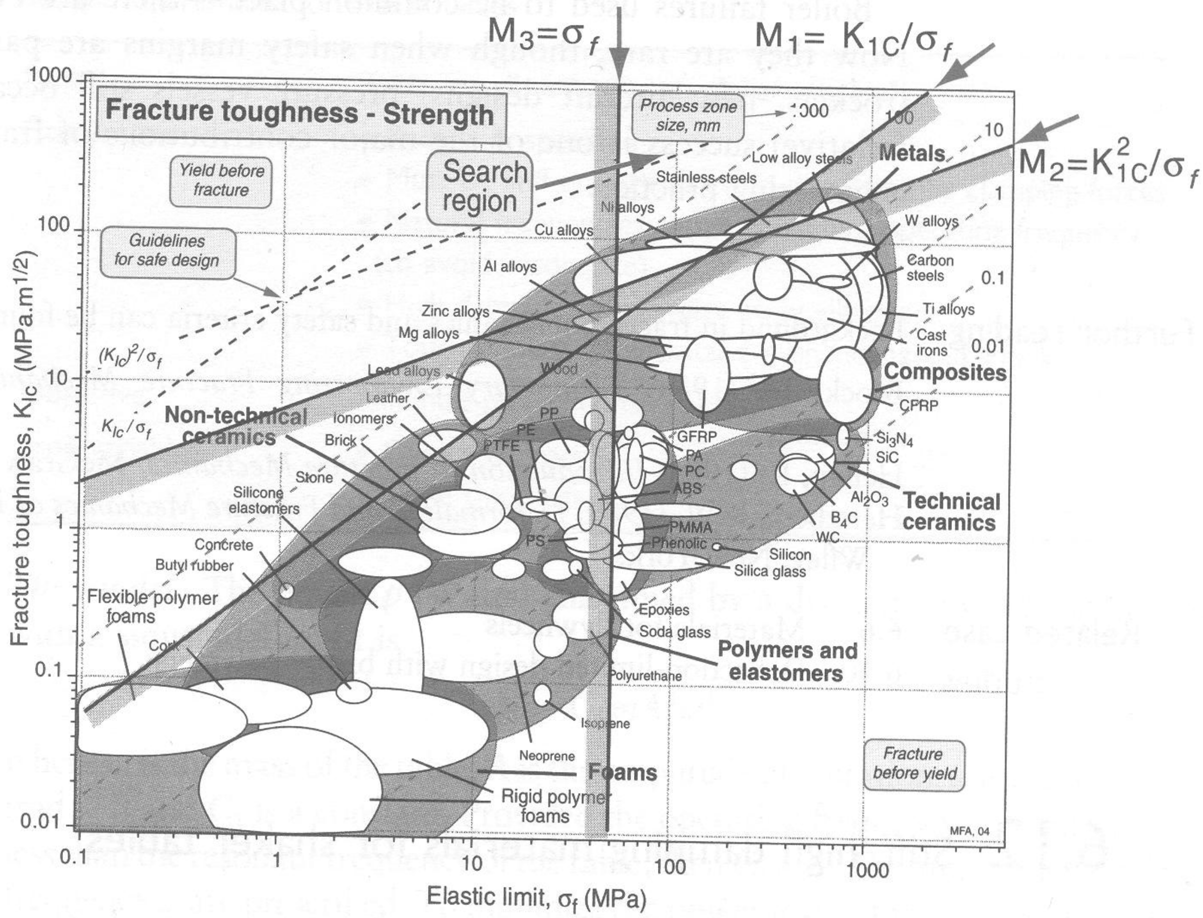

Figure 2: Fracture Toughness Vs Strength Plot from Ashby (2005)

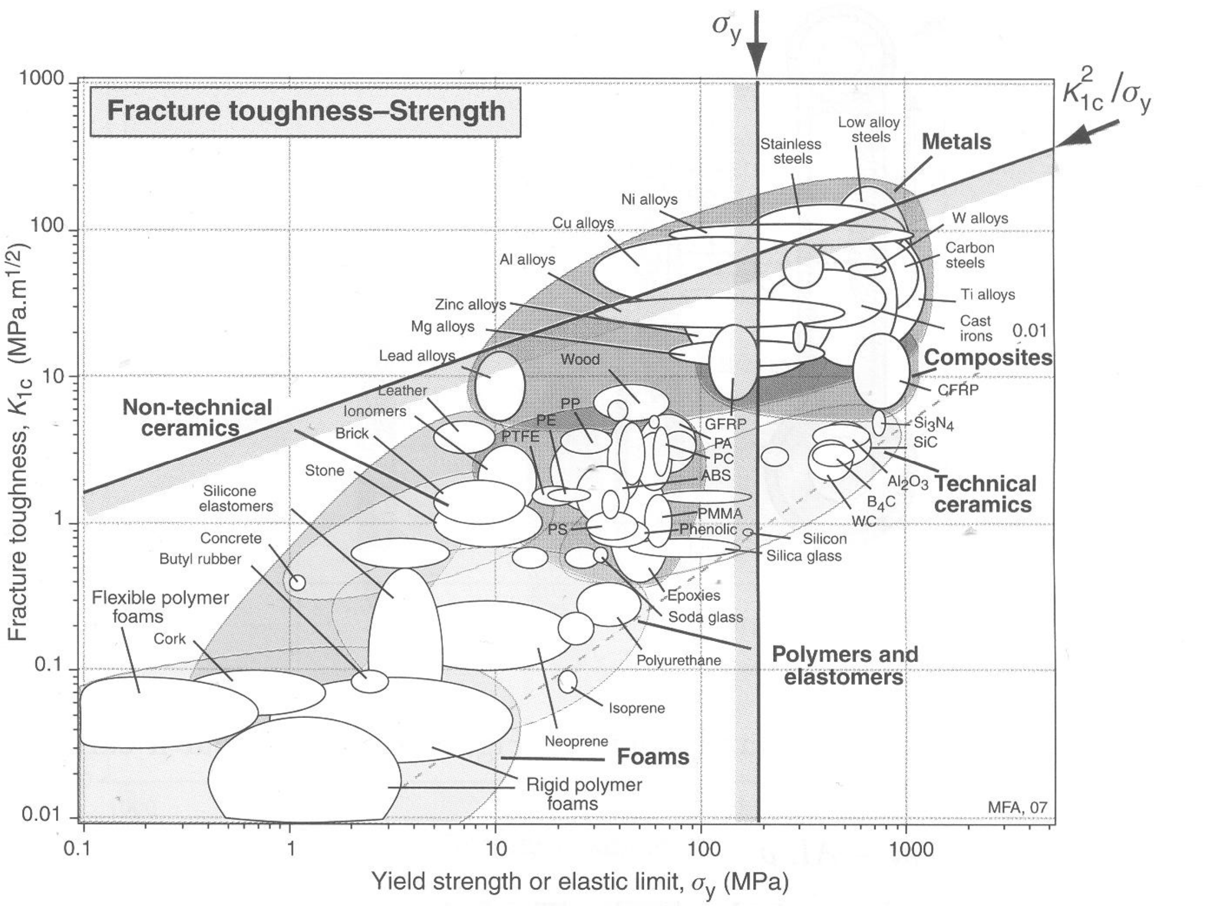

Figure 2: Fracture Toughness Vs Strength Plot from Ashby et al (2007)

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