Structural Integrity: Materials Testing
Plane Strain

This is the sort of sample that's used to measure plane strain fracture toughness. There's a notch that's been pre-machined into the sample, and a fatigue crack, a sharper T crack would be grown from the bottom of the notch, and then, using pins located into these holes, the sample would be pulled apart, it would be fractured. Now, you can see that the sample is relatively thick, and the reason that it's thick is to ensure that the crack is in a condition of plane strain.

If we look at one that's previously been fractured; so this is half of one of the samples you've just seen. And what you can see here is, that's the inside of the pre-machine notch. This region here is the fatigue crack that was grown from the base of that notch and then here, we have the final fractured region. You can see that it's very flat showing that it's a brittle fracture, there's no evidence of any shear lips at the edges of the sample which would be associated with a ductile failure.

If the material were very ductile then you would not see such a flat fracture and it may not be possible with a sample of this thickness to obtain a plain strain fracture toughness result. In that case, you would either have to use a thicker sample or to use a measurement such as CTOD instead.

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Have a look at what happens within a test specimen when a crack is loaded.
If we start by applying a small load to the crack, then it will begin to open and a small plastic zone forms at the tip of the crack. Increasing the load, increases the size of the plastic zone.

Eventually the load will reach a critical value and the crack will extend forward, into the plastic zone. This happens when the stress intensity at the crack tip reaches a critical value, which is the plane strain fracture toughness of the material. As the crack tip moves, it's preceded by a plastic zone; behind, it leaves a wake of previously deformed plastic material.

Every material has its own characteristic value of Plane Strain Fracture Toughness, or K-one-C. But what exactly does the term Plane Strain mean? To show this, first let's imagine a purely brittle material, with a crack in it.
By definition this material would deform only elastically, even right up to the crack tip. Let's consider a point near the centre of the specimen, a very small distance ahead of the crack tip. This point is close to the crack tip, but a long way, comparatively, from the edge of the specimen if the sample is reasonably thick. This point will then be in plane strain, as the distance along the crack front between the specimen edges is much greater than our distance from the crack tip.

In plane strain there is no strain parallel to the crack tip. Although near the crack tip there are large tensile strains, and these would normally cause contractions parallel to the crack because of the Poisson effect, the contractions are constrained by the large amount of surrounding material. This applies in the interior, a long way from the edge but not at the surface.
To prevent this contraction, a tensile stress is set up parallel to the crack border, which, together with the other tensile stresses, gives a state of triaxial tension at the crack tip.

Let's now move along the crack border closer to the free surface. In order for the surface to be comparatively far away compared to the distance from the crack tip, we have to move in closer to the crack tip as well. So in principle we can always find a position where the surface appears to be far from the crack tip and plane strain exists. Hence brittle materials will always exhibit a plane strain fracture.

The situation changes if we introduce the effect of plasticity at the crack tip. Near the centre of the specimen we can still identify points that are relatively far from the free surface compared to the distance from the crack tip, where a state of plane strain exists. If the plastic zone lies within this region of plane strain, any fracture will still feel the constraints of plane strain. However consider what happens as we move nearer to the free surface; as before, we must move closer to the crack border, to stay in a state of plane strain. Eventually we will have to move inside the plastic zone, and eventually we will be so far inside the plastic zone that virtually the whole plastic zone is outside the region of plane strain.
So in the middle of the specimen, the fracture will occur within the constraints of plane strain, whereas near the surface it won't.

Let's consider the type of fractures that will occur near the surface and in the centre in this case.

First, the fracture in the centre of a thick specimen. For simplicity, we'll omit the plastic zone. The maximum stress runs in this direction- this is the applied stress. The minimum stress acts within the same plane, perpendicular to the crack border; the maximum shear stress will occur at 45 degrees to both the maximum and minimum stresses; when slip occurs, it's roughly along these lines.
But as we're subject to plane strain, the development of slip will be restricted. Instead, when the failure occurs, it will be in the same plane as the original crack. It will be a flat fracture. This changes when we move towards the edge of the specimen. The fracture is no longer flat, but shows these 'shear lips'.
To understand why, it's easiest to consider first a thin specimen where the plastic zone is big compared with the specimen thickness. Virtually the whole of the plastic zone is outside the plane strain region.
The maximum stress is the same as for the thick specimen - in the direction of the applied stress; but now, the minimum stress is zero, and perpendicular to the surface; the direction of maximum shear is therefore at 45 degrees to the surface. How will this affect the fracture? Well, almost immediately the crack starts to move, it will move into material that has already suffered extensive shear at 45 degrees to the surface; the crack, being free of plane strain, turns through 45 degrees, into one or other of the planes of maximum shear.
In a very thin specimen, this is referred to as plane stress and the fracture face will be at 45 degrees to the surface. In thicker specimens this effect only operates near the free surfaces. Consequently, near the surface, we see the fracture face turn through 45 degrees, to form shear lips. This phenomenon is important because the shear lips absorb more energy than the central flat part of the fracture.
In a very thick specimen, a large proportion of the fracture will be flat. But in a thinner specimen, although the size of the shear lips won't change, the proportion of the fracture occurring under conditions of plane strain will be less. Consequently a greater proportion of the fracture will be plane stress. In this case, a measurement of plane strain fracture toughness can't be made, as the value obtained would be too large.

Fracture toughness tests therefore, sometimes need to be carried out on extremely thick specimens.