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The fracture topography of metallic glasses

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This paper discusses the way in which the features found on some tensile fracture surfaces of amorphous metals are formed. The relevance of the strongly inhomogeneous plastic flow present in these solids to the formation of the particular fracture topography discussed is pointed out, as well as features common to the well-known fracture micro-mechanisms, cleavage and dimpled rupture.

1. Introduction

The fracture topography of crystalline metals has been the subject of extensive study for many years. Generally, at a microscopic level, fracture surfaces display features which relate to some extent to the plastic behaviour of the solid just before the creation of the new free surfaces.

The microscopic fracture features at the two ends of the ductility spectrum are those of cleavage and dimpled rupture. Cleavage [1], a microscopic brittle fracture mode, shows the so-called "river patterns" on an otherwise perfectly smooth, low index, crystallographic

Figure 1 Crack nucleated dislocations (etchpits) and associated cleavage steps in LiF (× 500). After Gilman [3].

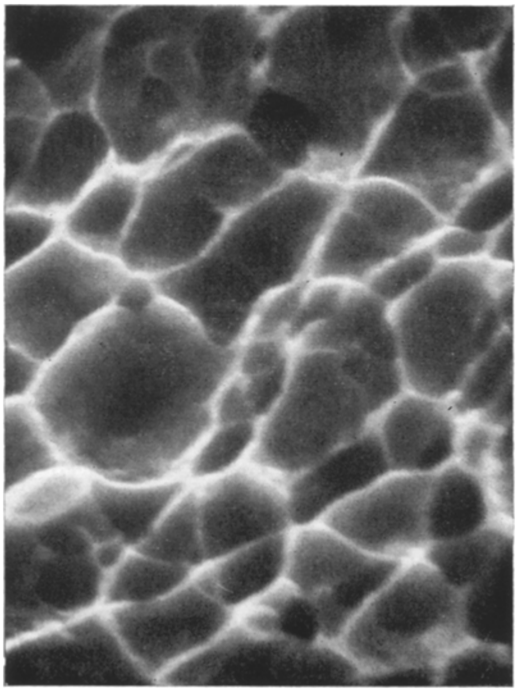

Figure 2 Dimpled rupture in Cu (× 10000).

*Now at: ALUAR Aluminio Argentino S.A.I.C., Cangallo 525, Buenos Aires, Argentina.

surface. These rivers are steps formed by the subdivision of the main crack into segments running on parallel planes. This subdivision occurs by the interaction of the crack front with the dislocation structure (screw dislocations) produced in the plastic zone at the crack tip [2] as shown in Fig. 1 [3], or with sub-boundaries [3] or general grain boundaries [1]. As the crack advances, the steps formed converge and add their height or annihilate each other depending on their sense. The local direction of crack propagation can be traced by observing the direction in which "tributaries" meet to form a main river [1]. Dimpled rupture, a microscopic ductile fracture mode [4], is the result of the nucleation, growth and coalescence of voids. These voids are nucleated during deformation prior to fracture at hard impurity or precipitate particles and in cases at grain or sub-boundaries. These voids grow in three dimensions by internal necking [5] or by ductile cutting [6]; their coalescence leads eventually to total failure of the specimen leaving the fracture surface features shown in Fig. 2.

Amorphous metals may be classified as ductile glasses. Contrary to oxide glasses, extensive shear deformation may occur before fracture. The macroscopic strain which obtain in tension before failure is rather small ($\sim 0.5\%$), but extensive localized shear deformation precedes fracture [7, 8]. This fact introduces factors which lead to a particular fracture micro-mechanism found in amorphous metals. This fracture micro-mechanism is the subject of the present paper.

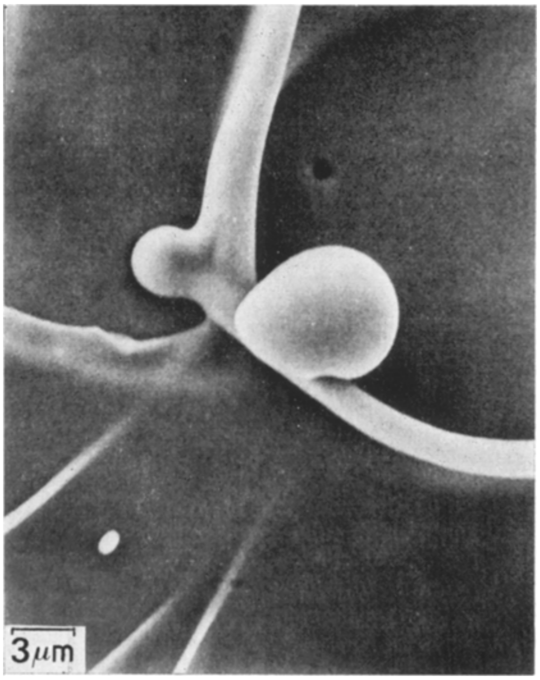

Figure 4 Magnified area of Fig. 3.

Figure 3 Vein pattern in a $Pd_{0.775}Cu_{0.06}Si_{0.165}$ amorphous alloy.

2. The ductile fracture topography in metallic glasses

Fig. 3 shows a scanning electron micrograph of a typical tensile fracture surface of a metallic glass ($Pd_{77}Cu_{16.5}Si_{6.5}$). Depending on temperature, the same topography is found on the fracture surfaces of other metallic glasses such as some based on Ni or Fe [8]. Other fracture topographies, also found in metallic glasses [8], will not be discussed here. They are generally found within temperature regions where the glass behaves in a less ductile manner.

The salient features found on fracture surfaces as that in Fig. 3 are: ridges forming a "vein pattern"* on a flat, very smooth and otherwise featureless surface at 45° to the tensile axis. Fig. 4 is a higher magnification micrograph

*This term was coined by Leamy *et al* [7], who first reported this type of fracture topography.

showing the smoothness of the main fracture surface. It also shows that the veins are not steps joining cracks at different levels as in the river patterns of cleaved surfaces, but ridges.

When one observes the two matching fracture surfaces of a tensile specimen, one generally finds that the location of the matching features, with respect to the sides of the specimen, are displaced one with respect to the other [7]. This is shown in Fig. 5 and schematically in Fig. 6 [7]. The meaning of this is simple. Shear, between the two sides, has occurred before failure. It is also found that the final fracture runs along the plane defined by the previous shear displacement, i.e. at 45° to the tensile axis. The rather featureless areas corresponding to the slip step formed just before failure are shown in Fig. 5 between the sides of the specimen and the dotted line. It is interesting to point out here that the final fracture does not occur along a surface with the highest normal stress as on a in Fig. 6, but rather along the previously sheared plane b. The normal stress on this plane b, is $\frac{1}{2}$ that on a plane such as a (Fig. 6). We can conclude from this that the sheared plane becomes weaker than any other arbitrary plane through the solid.

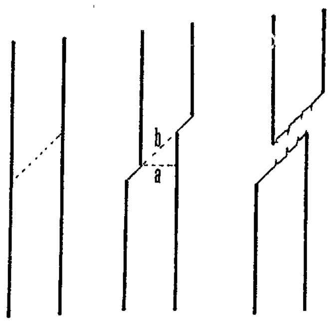

Figure 6 Schematically showing the shearing before failure and failure along the sheared surface.

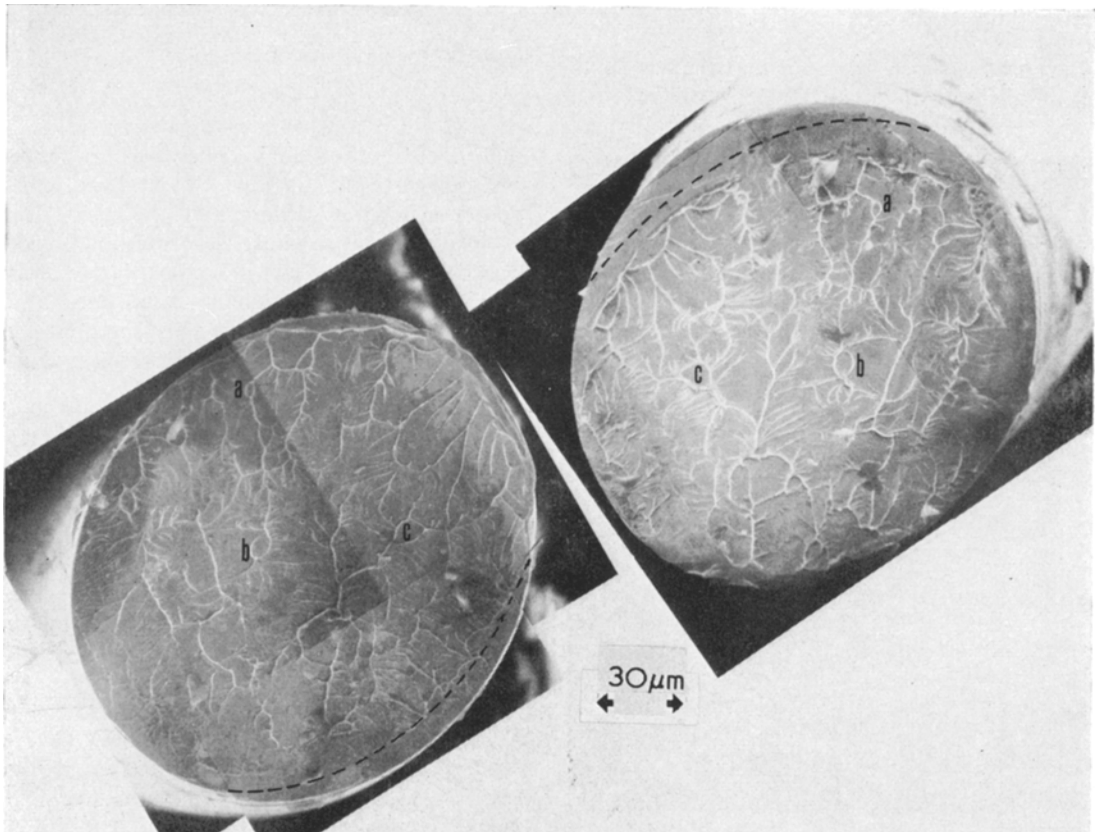

Figure 5 Matching fracture surfaces in amorphous $Pd_{0.775}Cu_{0.06}Si_{0.165}$ showing shear displacement between edge and dotted line and matching surface features. Same letters refer to same areas.

3. The model

The first important fact of the plastic behaviour of glassy metals to be recalled is its extremely inhomogeneous shear flow [7, 8]. Fig. 7 shows an example of shear bands on a $Pd_{0.775}Cu_{0.06}Si_{0.165}$ glass deformed in compression. It has been shown by Pampillo [9] that these shear bands are susceptible to preferential etching. The same etching effect was later on confirmed on bent samples of $Fe_{0.75}P_{0.16}C_{0.09}$, $Ni_{0.75}P_{0.15}B_{0.10}$ and $Pd_{0.775}Ni_{0.06}Si_{0.165}$ glasses [10]. It has been further argued [9] that this is evidence of a destruction of the short range order existent in the glass, along the sheared planes. The interchanging across these planes of many strong metal-metalloid bonds by metal-metal or metalloid-metalloid bonds leads to a weakening of the solid across these planes. Besides this, as suggested by Gilman [11], the dilatance which is probably associated with the plastic shear strain will also contribute to the weakening across sheared planes.

Figure 8 Showing at arrow a crack nucleation site. Note veins radiating from site.

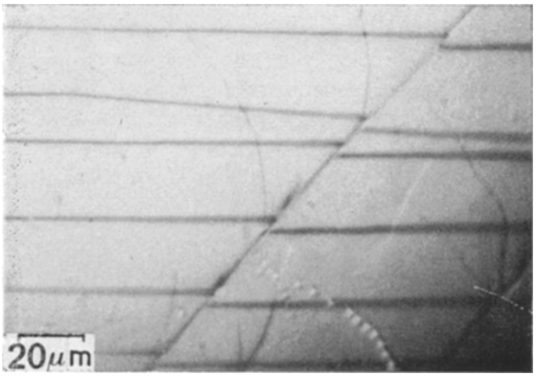

Figure 7 Intersecting shear bands in a $Pd_{0.775}Cu_{0.06}Si_{0.165}$ glass deformed in uniaxial compression.

The shear deformation prior to failure defines, therefore, a pseudo "cleavage"* plane on which the formation and propagation of cracks will occur, later on, at normal stresses lower than on any other plane. At some point, after a certain amount of shear displacement has occurred on a plane at 45° to the tensile axis, the stress normal to this plane becomes high enough to nucleate cracks at several locations inside the specimen or from the sides of it. Nucleation may occur at inhomogeneities or hard impurity particles within the solid. Such nucleation sites are sometimes recognizable on the fracture surfaces as shown by an arrow in Fig. 8. Nucleation sites may also be provided along the intersection of the strong shear bands (see Fig. 7). The cracks nucleated at several places will grow on the previously defined plane. Along the lines where these cracks meet a necked ridge is left which forms the "vein pattern".

Whether the surface on which the cracks run is as well defined as a true crystallographic cleavage surface, depends on the actual thickness of a slip band or sheared plane. To investigate this, we have made observations of the difference in level between the two sides of a ridge, by utilizing the *Y* modulation mode of the scanning electron microscope [12]. In this mode, also known as scan modulation, the output of the detector of the SEM is used as a signal to vertically displace the line scan of the cathode ray tube instead of being used to modulate the brightness of the beam as in normal usage. Fig. 9b, obtained by utilizing *Y* modulation, shows the same area as Fig. 9a with greatly enhanced details. If one interrupts briefly the line scan to facilitate following an individual line across the surface, as in Fig. 9c, one can ascertain whether

*We add the qualification "pseudo" to distinguish it from a truly crystallographic cleavage plane.

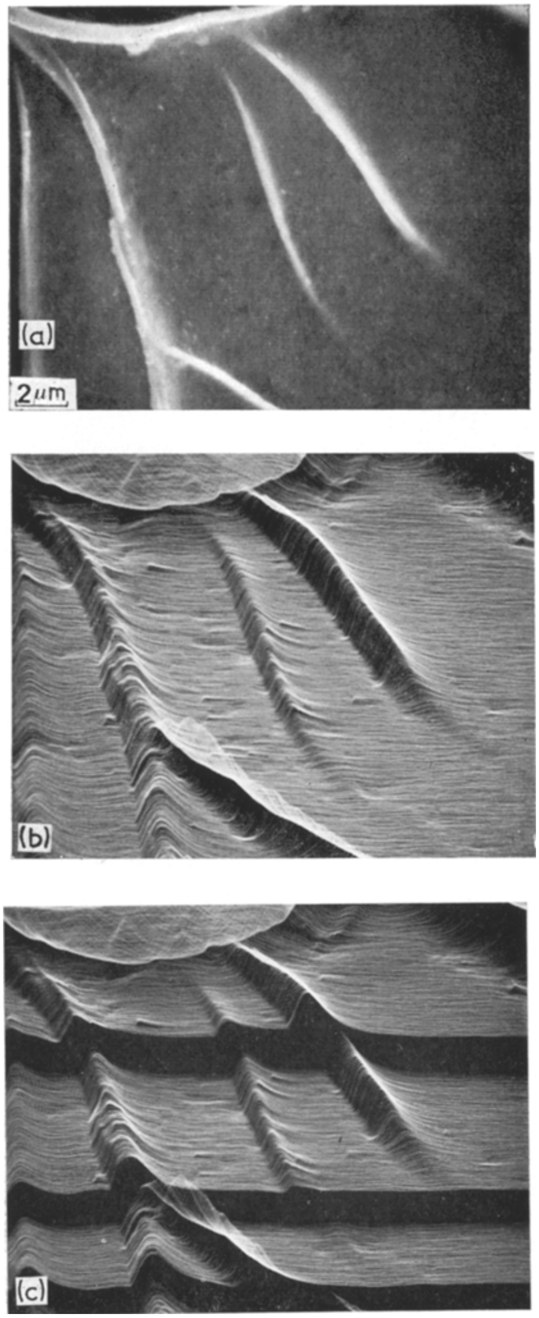

Figure 9 (a) Showing a few veins. (b) Same area taken with Y modulation. (c) Same as (b) but interrupting the scan to show that the level of the surface at the sides of a vein is the same.

the levels of the planes at the two sides of a ridge are the same. In general, no significant differences in the levels were found, indicating that the crack plane is rather well defined and therefore, the prior shear deformation occurred in a highly localized manner. The Y modulation mode also allows to see the ridges in great detail (Fig. 9b).

We can see then that this microscopic fracture mode has a characteristic which is similar to cleavage, i.e. the propagation of the main crack on a rather well defined plane. It also displays features similar to those found in dimple rupture, namely necking of the portion left between two advancing cracks. Probably the formation of the vein pattern accounts for a large fraction of the energy spent on fracture.

There are two reasons why the portion of material between two colliding pseudo "cleavage" cracks will rather neck down and leave a ridge than cut through, joining the cracks with no features left on the fracture surface. One is that when the distance between the two crack fronts becomes small enough, the stress intensity factor due to the sharp cracks will be substantially reduced and the region between the cracks will behave more as a smooth thin tensile specimen. Secondly, the heat produced within the small plastic zone ahead of the crack tip will have to be extracted through the narrow strip left between the two cracks when they become close to each other. The narrow strip between the two approaching cracks will become heated and this leads to easy plastic flow. When the cracks are far from each other, however, the heat produced at the crack tip is extracted through a semi-infinite medium and will lead only to a small temperature rise. These two factors acting together are sufficient to change drastically the microscopic fracture mode from

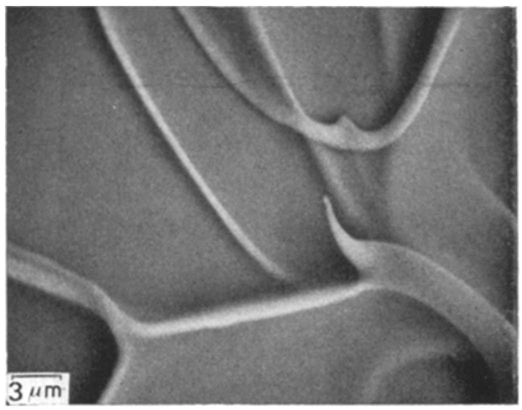

Figure 10 Whisker formed at triple ridge point; probably by high temperature viscous flow.

that of pseudo cleavage to necking by plastic flow. The temperature rise at the necking portion may be high enough to produce viscous flow if the glass transition temperature is approached. That this may be the case, is suggested by the elongated whiskers formed at triple ridge points as reported by Leamy *et al* [7] and shown in Fig. 10 (see also Fig. 4).

So far we have explained how the main "veins" can be formed by the collision of two cracks. It still remains to understand the formation of "tributaries" or "fingers" which merge into a main vein and point towards the crack nucleation site as shown in Fig. 8. A possible way to explain how these tributaries or fingers are formed is the following. If a small portion of the front of a running crack, slows down for any reason, the rest of the crack front will bow out around this portion. This causes a decrease in the stress intensity factor and increase in temperature at that point for the same reasons discussed before. Because of this, the portion of the crack front under consideration slows down even more, allowing the rest of the crack front at its sides to engulf a portion of material which eventually develops into a "finger" or "tributary vein".

It is possible to illustrate this situation with a simple experiment which, because of the strong analogy it shows, suggests a second possible explanation for the formation of "fingers" or "tributary veins". In Fig. 11 we show, from (a) to (f) the separation (area in black) of two glass slides held together by a viscous medium such as grease. The separation starts at the edges of the glass slides and propagates in an unstable way: the separation front (the equivalent to a crack front), develops "fingers" which move into the viscous medium rather than moving as a stable straight front. The final result, as we can see, is very similar to the fingers or tributary veins referred to before. The dark "fingers" in Fig. 11 are equivalent to the areas between tributary veins in, for instance, Fig. 8.

The interesting point is that the instability which leads to the formation of these fingers (dark areas) into the viscous medium is the Taylor instability [13]*. This instability occurs when a viscous fluid (in the experiment of Fig. 11, grease) is driven forward by another fluid (in Fig. 11, air) of smaller viscosity. The interface between the fluids becomes unstable and "fingers" from the *less viscous* fluid penetrate into the more viscous one.

The analogy poses the intriguing question of whether the instability which leads to the formation of the tributary veins or fingers in Fig. 8, is a result of a Taylor instability or as suggested before, because of the heating effect and loss of stress intensity factor following a disturbance

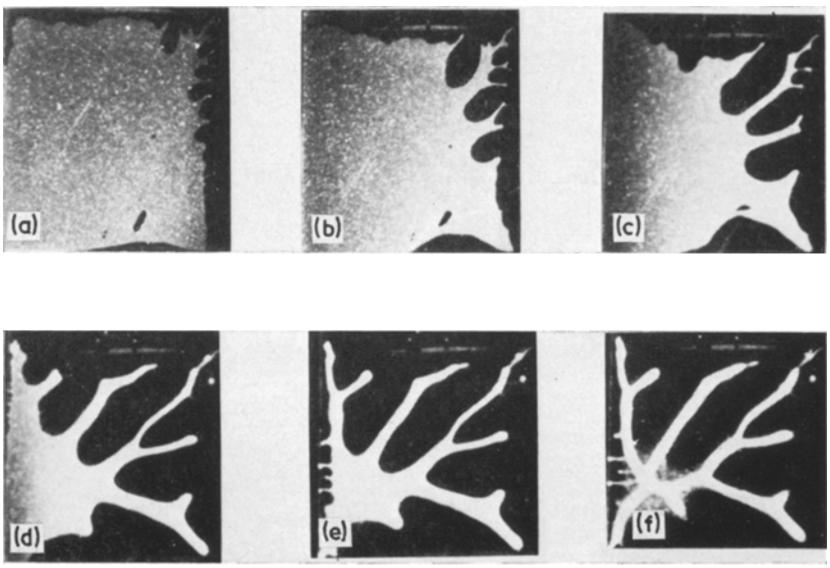

Figure 11 Simulated "crack" propagation by opening up two glass slides held together by grease. It illustrates the formation of tributary veins. In this case, the instability is due to the well-known Taylor instability.

*We thank J. J. Gilman for pointing this out to us.

which causes a bowing of the crack front. In any case, it is interesting to note that the same instability does not occur in true crystallographic cleavage.

4. Conclusions

Amorphous metals generally show a peculiar tensile fracture surface topography which may be described as a vein pattern on a flat and otherwise featureless surface at an angle of 45° to the tensile axis. We have proposed here that this topography is a result of the extremely inhomogeneous shear deformation which occurs prior to failure and prepares or defines a plane on which cracks nucleate and propagate. The vein pattern is produced by the collision of cracks nucleated at different spots due to the reduction in stress concentration produced when two cracks approach each other and to local heating of the thin slab of material left in between. This fracture micro-mechanism is similar to that of dimpled rupture, Fig. 2, except that cracks are allowed to grow only on a somewhat well defined surface rather than in three dimensions.

The formation of tributary veins or fingers, which point to the site where the crack has been nucleated, is thought to be due to an instability of the crack front created by the same heating effect and loss of stress intensity factor which makes two colliding cracks coalesce by necking with the formation of a vein or ridge. However, an intriguing possibility is that the instability is similar to the Taylor instability which occurs when a fluid is pushed against another fluid of greater viscosity.

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