Some Observations on the Relationship Between the Effects of Pressure Upon the Fracture Mechanisms and the Ductility of Fe-C Materials

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It has been known for a considerable period of time that the ductility of even quite brittle materials can be enhanced if they are deformed under a superposed hydrostatic pressure of sufficient magnitude. The response of ductility to pressure, however, has been shown to vary considerably between materials. Prior work has shown that the effects of pressure upon the tensile ductility of Fe-C materials depend upon the amount, shape and distribution of the brittle cementite phase. In this current investigation, the effects of pressure upon the fracture mechanisms in a series of annealed and spheroidized Fe-C materials were examined. It was observed that the principal effect of pressure is to suppress void growth and coalescence, retard cleavage fracture and to enhance the ductility of cementite platelets in pearlite. Based upon the observed effects of pressure upon the fracture mechanisms, a proposed explanation for the enhancement in ductility by pressure and for the structure sensitivity of the phenomena is presented and discussed.

THE effect of superposed pressure upon the tensile ductility of a variety of metals has been well documented.[1-12] Some of the results from several investigators are summarized in Fig. 1 where tensile ductility in terms of true strain to fracture (ϵ_f) is plotted as a function of the superposed pressure. As can be seen, a pressure of sufficient magnitude can significantly enhance the ductility of metals. However, Fig. 1 also demonstrates that the response of ductility to pressure and the form of the ductility-pressure relationship varies considerably between materials.

Several explanations have been offered for the observed enhancement in ductility by a superposed pressure. Although no experimental evidence was provided, Bridgman[13] and Bobrowsky[10] proposed that the observed effect was due to the prevention or healing of microcracks or holes. Bulychev *et al.*[14] observed that cracks and voids in initially prestrained copper were healed in the necked region of a tensile specimen upon further straining while under a superposed pressure. Also, Pugh[5] observed that large cavities were suppressed in copper fractured in tension while under pressure.

A second proposal has been forwarded by Beresnev *et al.*[6] This proposal is based upon the hypothesis that a material fails in a brittle manner because the normal tensile stress reaches a critical value before the shear stress is of sufficient magnitude to cause plastic flow. Since a superposed hydrostatic pressure will increase the ratio of shear to normal tensile stress, a sufficiently high hydrostatic pressure should favor plastic flow while retarding brittle fracture.

Galli[15] reported that a superposed pressure shifts the ductile-brittle transition temperature of molybdenum. This was explained based upon the reduction of the normal tensile stress by the superposed pressure. Pugh[5] explained the occurrence of the observed pressure induced brittle-to-ductile transition in zinc in the same manner.

Davidson *et al.*[12] proposed an explanation for the enhancement of ductility by pressure based upon the effects of pressure upon the stress-state-sensitive stages of various fracture propagation mechanisms. Basically, they proposed that pressure will retard cleavage and intergranular fracture by counteracting the required normal tensile stress or will suppress void growth. They observed suppression of intergranular fracture and void growth in magnesium by pressure.

Davidson and Ansell[16] reported ductility as a function of pressure for a series of annealed and spheroidized Fe-C alloys. Fig. 2, from this prior work, demonstrates that the effect of pressure upon ductility is structure sensitive in terms of the amount, shape and distribution of the brittle cementite phase. As shown in Fig. 2, in the absence of cementite or when the cementite is in isolated particle form (spheroidized), the ductility-pressure relationship is linear and the slope decreases with increasing carbon content. In the annealed carbon-bearing alloys wherein the cementite is in the form of closely spaced platelets (pearlite) or in the form of a continuous network along prior austenite boundaries (1.1 pct C material), ductility as a function of pressure is nonlinear (polynomial relationship) in which the slope increases with increasing pressure. At the highest pressures studied (22.8 kbars), the slope of the curves for these materials tends to approach those for the spheroidized material of the same carbon content.

In this current investigation the change in fracture mechanisms as a function of pressure for the materials shown in Fig. 2 has been examined. The possible connection between the observed effects of pressure upon the fracture mechanisms and the effect of pressure upon ductility is discussed.

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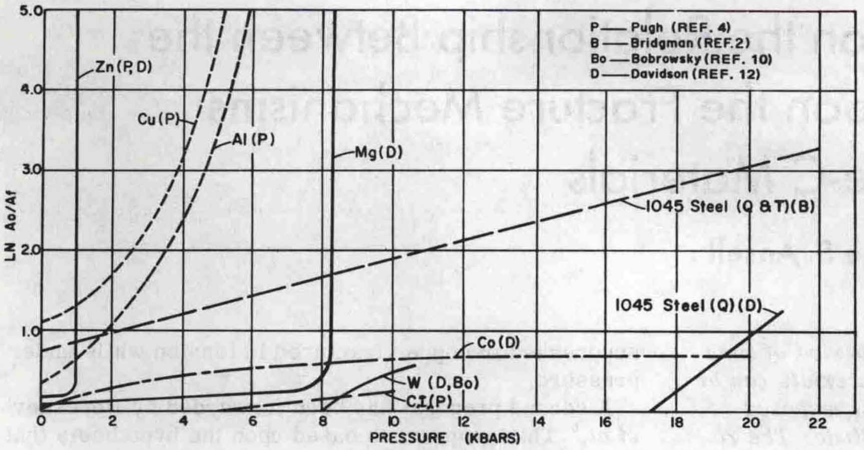

Fig. 1—Ductility vs pressure for various typical materials.

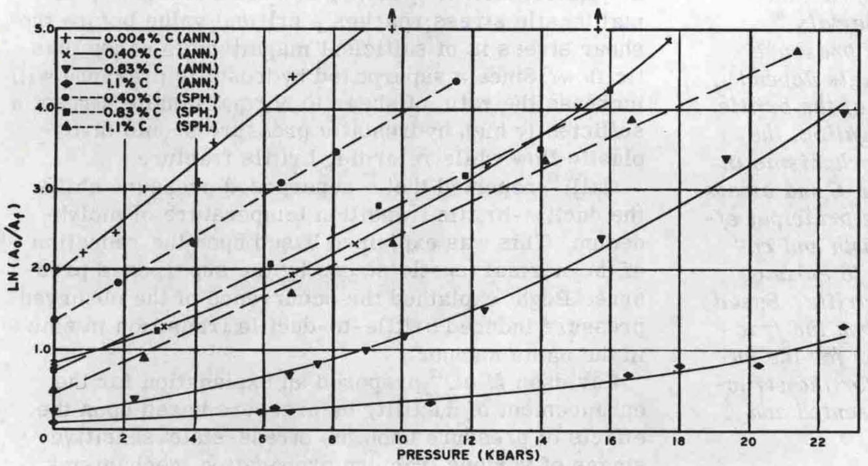

Fig. 2—Ductility vs pressure for Fe-C materials.

MATERIALS AND PROCEDURES

A) Materials. The materials used in this investigation were the same as those previously reported[16] and consisted of a series of iron-carbon alloys of the following carbon contents.

a) Fe + 0.004 pct C
b) Fe + 0.40 pct C
c) Fe + 0.83 pct C
d) Fe + 1.1 pct C

Except for the 0.004 pct C material, the materials were examined in both the spheroidized and in the annealed condition. The 0.004 pct C material was annealed only. Details of heat treatment are given in Ref. 16.

B) Procedures. The fracture appearance studies were conducted on the tensile specimens utilized in the prior work and in the development of the curves shown in Fig. 2. Additional specimens of the same materials were also examined after being strained to near fracture at various pressures in order to gain further insight into the fracture propagation process.

The high pressure tensile testing was accomplished using a Bridgman-Birch type 30 kbar hydrostatic pressure system. This system, along with the specific test procedures, was discussed in detail in previous work.[12] The tensile samples used had a 0.160 in. gage diam with a 0.665 in. gage length.

It should be noted that in the procedure used, the pressure varied by approximately 2 to 10 pct between the onset of strain of the specimen and fracture. The magnitude of the change in pressure depended upon the ductility of the material. The pressure values, shown in Fig. 2 and throughout this current work, correspond to the pressure at the point of fracture of the specimen.

The fracture appearance, from which the fracture mechanisms and their modification by pressure were deduced, was analyzed using two techniques. The first technique involved the optical examination of a longitudinal surface containing the specimen axis and intersecting the fracture surface or the necked region in the case of those specimens in which the strain was stopped just prior to total fracture. In the fractured specimens, the fracture surface was nickel plated to prevent rounding during polishing.

For the longitudinal surface examination, conventional metallographic procedures were utilized. All specimens of a given series, *i.e.*, fractured at various pressures, were polished simultaneously using an automatic polisher. To reduce the amount of flowed metal, which is particularly troublesome in void and microcrack studies, the final polishing step consisted of using 1 μ diamond paste and a hard nylon polishing cloth. The samples were ultrasonically cleaned in alcohol between each of the grinding and polishing steps.

The second examination technique involved the study of the fracture surface using electron fractography. A standard two-stage replication technique was used with 45 deg chromium shadowing.