fracture process, and near the fracture surface the microstructure of this material is effectively the same as the eutectoid composition material except for the lines of cementite fragments.

The electron fractograph, Fig. 12(*c*), is again effectively featureless but does contain some isolated particles which are probably fragments of cementite particles at the fracture surface. These particles, however, do not appear to disturb the fracture surface.

DISCUSSION OF RESULTS

The fracture propagation mechanism is the same in the absence of cementite (0.004 pct C) and in the spheroidized materials and involves the growth and coalescence of isolated voids in ferrite. The spheroidized materials differ from the 0.004 pct C material only in that voids are more readily initiated (cementite particle fracture) and do not have to grow to as large a size for coalescence to occur.

The effect of pressure upon the fracture mechanism in these materials is also similar and involves the suppression of the void growth. It is important to note that the void growth suppression by the pressure is not instantaneous, but is a progressive process. This is because void growth is a shear strain process. Thus, the larger the amount of plastic strain, the greater will be the pressure required to suppress the void growth. In the case of the 0.004 pct C at 15.1 kbars and the spheroidized material at 21.3 kbars, it appears from the examination of the fracture appearance that no voids are present. This tends to contradict the above observation that the void suppression is progressive. A possible explanation is that the pressures are of a sufficient magnitude to suppress the void size to that below the resolution ability of the examination techniques utilized.

The suppression of the void growth by the pressure suggests a possible explanation for the increased ductility as a function of pressure in these materials. This agrees with the proposals of Bridgman[13] and Bobrowsky[10] and the observations of Pugh,[5] Davidson *et al.*[12] and Bulychev *et al.*[14]

The observed effects of pressure upon the fracture mechanisms may also suggest a possible reason for the similarity in the response of ductility to pressure for the 0.004 pct C and spheroidized materials as was shown in Fig. 2. First, the progressive increase in ductility with increasing pressure may be attributed to the progressive suppression of the void growth. Second, the fact that the form of the ductility-pressure relationship is the same for both the 0.004 pct C and spheroidized materials (linear) may be a manifestation of their having the same basic fracture propagation mechanism (void growth and coalescence). Finally, a possible reason for the decrease in slope of the ductility-pressure curves with increasing carbon content may be that as the number of cementite particles increases and the interparticle spacing decreases, the number of voids formed by the fracture of particles also increases and the growth required for coalescence decreases. Thus, it is likely that a higher pressure will be required to suppress the void growth and coalescence with increasing carbon content.

In the annealed 0.40, 0.83, and 1.1 pct C materials, the effects of pressure are to suppress void growth in pearlitic and free ferrite and to prevent cleavage of pearlite and hypereutectoid cementite. Although the fracture of the cementite is not prevented by the pressure, the fracture appears to convert from cleavage to shear. Furthermore, the pressure permits considerable plastic deformation of the cementite platelets in the pearlite prior to fracture. These observed effects of pressure on the various fracture mechanisms suggests why pressure enhances the ductility of the annealed 0.40, 0.83, and 1.1 pct C, materials.

The difference in the fracture mechanisms of the two types of material may also suggest an explanation for the nonlinear pressure ductility relationship and initially lower slope of the annealed 0.40, 0.83, and 1.1 pct C materials as compared to the annealed 0.004 pct C and spheroidized materials which exhibit a linear relationship, Fig. 2. Due to the close spacing of the cementite platelets in pearlite, there is an overlapping of the strain concentration fields of the voids initiated in the pearlitic ferrite. It is likely that a higher pressure is required to suppress this type of void growth as compared to the isolated voids in the 0.004 pct C and spheroidized materials. Also, the occurrence of cleavage in pearlite and hypereutectoid cementite requires a higher initial pressure for suppression. Finally, at higher pressures, the cementite platelets and/or hypereutectoid cementite become so extensively fragmented that the microstructure of the annealed materials tends to approach that of the spheroidized materials, *i.e.*, cementite particles in a ferrite matrix. This then may explain why the slopes of the ductility pressure curves for the annealed 0.40, 0.83, and 1.1 pct C materials increase with increasing pressure and tend to approach the slopes of the curves for the spheroidized materials.

CONCLUSIONS

1) Based upon optical and fractographic analysis, the principal effects of pressure upon the fracture mechanisms in annealed and spheroidized Fe-C materials are:

a) To suppress the growth and coalescence of voids in ferrite.
b) To retard the cleavage fracture of pearlite and hypereutectoid cementite.
c) To impart some ductility to cementite and convert its fracture mode from cleavage to shear.
d) To convert the macroscopic fracture mode from cup-cone, cleavage, or intergranular to a planar shear type.

2) The retardation by pressure of those fracture mechanisms resulting in low ductility suggests a possible explanation for the enhancement in ductility by pressure.

3) The observed structure sensitivity of the form of the ductility-pressure relationship to the amount, shape and distribution of cementite appears related to the differences in fracture propagation mechanisms and their modification by a superposed hydrostatic pressure.

REFERENCES

1. P. W. Bridgman: *J. Appl. Phys.*, 1946, vol. 17, pp. 201-12.
2. P. W. Bridgman: *Studies in Large Plastic Flow and Fracture*, 1st ed., pp. 32-50, 106-107, McGraw-Hill Book Co., New York, 1952.

[3]P. W. Bridgman: *J. Appl. Phys.*, 1953, vol. 24, pp. 560-70.
[4]H. Ll. D. Pugh: Proceedings of Conference on Irreversible Effects of High Pressure and Temperature on Materials, 1964, ASTM Special Technical Publication No. 374, pp. 68-140.
[5]H. Ll. D. Pugh: Recent Developments in Cold Forming, Bulleid Memorial Lecture Series vol. IIIB, pp. 4(1)-4(23), University of Nottingham Press, 1965.
[6]B. I. Beresnev, L. F. Vereshchagin, Y. N. Ryabinin, and L. D. Livshits: *Some Problems in Large Plastic Deformation in Metals Under High Pressure*, Pergamon Press, 1963.
[7]L. D. Livshits, Y. N. Ryabinin, and B. I. Beresnev: *Zh. Tekh. Fiz.*, 1965, vol. 35, pp. 348-54.
[8]T. Pelczynski: *Arch. Hutnictwa*, 1962, vol. 7(1), pp. 3-13.
[9]S. I. Ratner: *Zh. Tekh. Fiz.*, 1949, vol. 19(3), pp. 408-11.
[10]A. Bobrowsky and E. A. Stack: Proc. AIME Conference on Metallurgy at High Pressures and High Temperatures, Gordon and Breach Science Publishers, New York, 1964.
[11]M. Brandes: *Prace. Inst. Mech. Precyzncy*, 1962, vol. 10, pp. 1-17.
[12]T. E. Davidson, J. C. Uy, and A. P. Lee: *Acta Met.*, 1966, vol. 14, pp. 937-48.
[13]P. W. Bridgman: *Research (London)*, 1949, vol. 2, pp. 550-55.
[14]D. K. Bulychev, B. I. Beresnev, M. G. GayduKou, Y. D. Martynov, K. P. Rodionov, and Y. N. Ryabinin: *Fiz. Metal. Metalloved.*, 1964, vol. 18, no. 3, pp. 437-42.
[15]J. R. Galli and P. Gibbs: *Acta Met.*, 1964, vol. 12, pp. 775-78.
[16]T. E. Davidson and G. S. Ansell: *ASM Trans. Quart.*, 1968, vol. 61, no. 2, pp. 242-54.