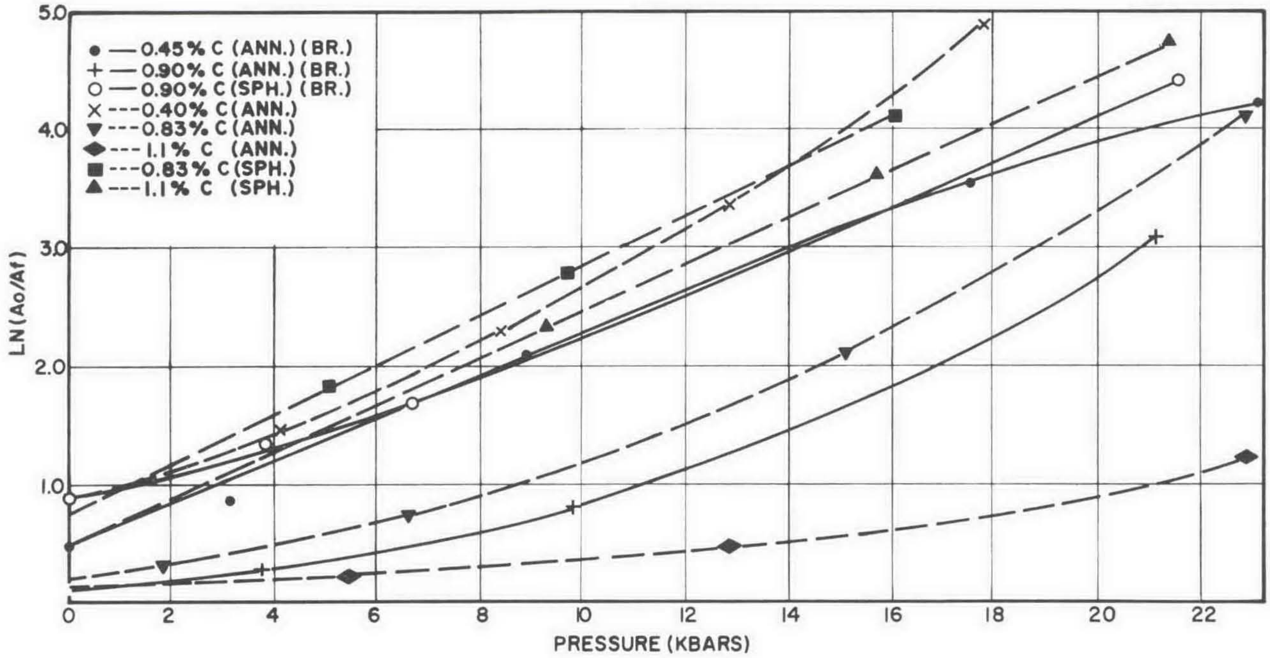

Fig. 4. Ductility vs pressure for Fe – C materials including Bridgman's data.

quite good with our data obtained for the 0.83% C material. The slope is slightly lower due to the higher carbon content, but *B* increases with pressure in the same manner. Bridgman's data for the annealed 0.45% C material is quite linear at lower pressures, but *B* decreases at higher pressures rather than increases as we have found. His spheroidized 0.90% C material exhibits nonlinearity with *B* increasing with increasing pressure, which is in contrast to the fact that linearity was obtained for all of the spheroidized material in this work. It should be noted, however, that there is a small number of data points available to describe Bridgman's curves and, in most cases, they are not uniformly distributed with respect to pressure. Based on the data available, however, it is obvious that these materials do not exhibit a linear relationship between pressure and strain to fracture and the forms of the curves vary considerably both from material to material and as a function of microstructure. Except for the annealed 0.90% C material, the agreement with the results of the present investigation is not good. This may be accounted for by the lack of knowledge of the actual microstructure of his materials and, as previously stated, the lack of usable data.

EFFECTS OF PRESSURE UPON ELONGATION

Elongation as a function of pressure is plotted in Fig. 5 for the materials investigated.

In the case of the most ductile of the materials investigated, that is, the annealed 0.004 and 0.40% C, and spheroidized 0.40% C materials, the elongation increased slightly at lower pressures, then rapidly leveled off with no further observed increase in elongation with increasing pressure. These materials undergo substantial necking even at atmospheric pressure. Pressure does not, in this case, affect the uniform strain, but only enhances the amount of reduction in area obtained in the necked region. Thus, as the reduction in area in the necked region becomes greater as a result of increasing pressure, its contribution to the over-all elongation becomes less significant. This, then, accounts for the effective insensitivity of elongation to pressure at the higher pressures.

In the lower ductility annealed 0.83% C and spheroidized 0.83 and 1.1% C materials, the increase in elongation with pressure was much more extensive and only tended to level off at quite high pressures. This is a manifestation of the smaller amount of necking obtained at atmospheric pressure for these steels. As a result, there is a greater contribution of the reduction in area in the necked region to the over-all elongation as the pressure is increased. The leveling off in elongation observed at high pressure is attributed to the increased degree of necking as previously discussed for the more ductile materials.

For the relatively brittle annealed 1.1% C material, there was a large and continuous increase in elongation with increased pressure with no signs of leveling off. This is likely due to a two-fold effect. First, since there was very little, if any, necking observed for this material at atmospheric pressure, there was a large contribution to the elongation resulting from the substantial necking that occurs under pressure, as will be subsequently shown. The second contribution was due to the fact that this material fractured at very low plastic strains at low or atmospheric pressure. It is, therefore, likely that

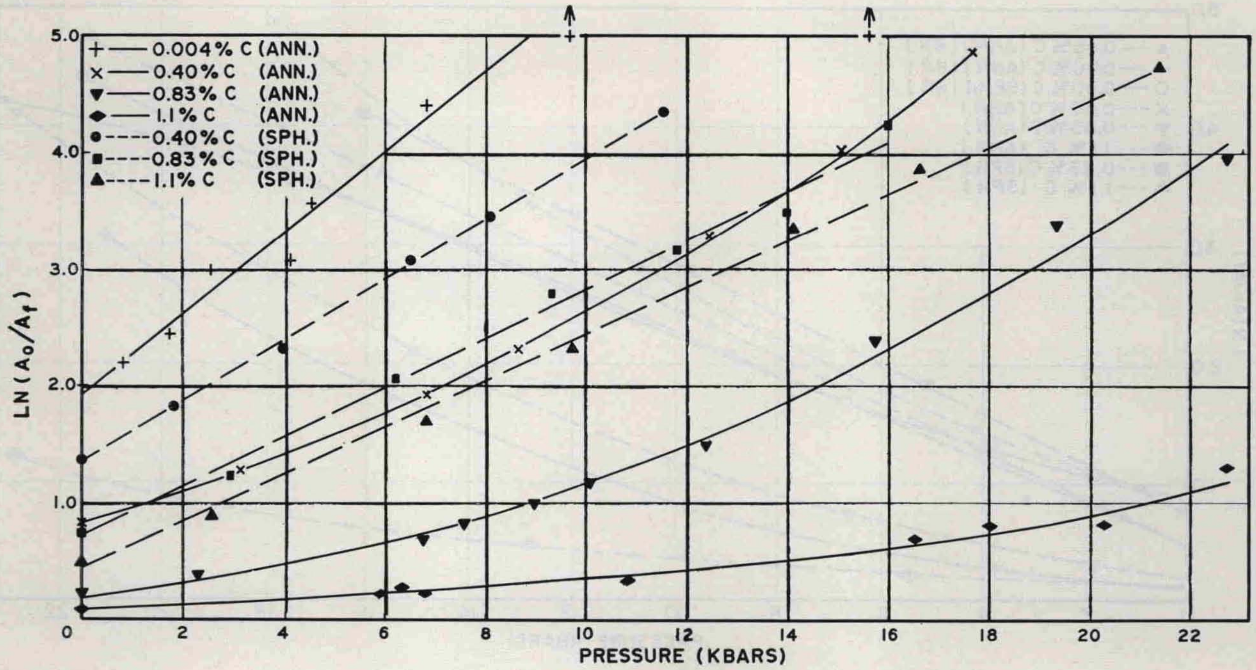

Fig. 3. Ductility vs pressure for Fe – C materials.

0.40, 0.83 and 1.1% C materials when a polynomial fit is attempted. Furthermore, from Table 2 it can be seen that the confidence levels of the polynomial fit exceed 95% and, in fact, are effectively 100% for all three cases. It is apparent, therefore, that the strain to fracture-pressure data for the annealed 0.40, 0.83 and 1.1% C materials are best described by a polynomial rather than a linear relationship.

Several other points are important to note in connection with Fig. 3. In the case of the materials exhibiting a linear relationship, the slope (*B*) progressively decreased with increasing carbon content. Similarly, if one assumes a linear relationship between strain to fracture and pressure for the remaining materials rather than a polynomial fit, they also exhibited a decrease in slope (*B*) with increasing carbon content. The significance of this result with respect to the relationship between the pressure coefficient of ductility and strain hardening coefficient will be discussed subsequently.

A second important point concerns the form of the curve for the annealed 0.40, 0.83 and 1.1% C materials. In these materials, the pressure at the beginning of substantial deviation from linearity increased with increasing carbon content.

Finally, in the case of the materials exhibiting a nonlinear relationship between pressure and strain to fracture, the slope or pressure coefficient of ductility at the higher pressures tended to approach that for the spheroidized materials of the same carbon level. This is readily seen in the case of the annealed 0.40 and 0.83% C materials. It is likely that the slope of the annealed 1.1% C material would also approach that of the spheroidized materials at higher superposed pressures.

In summary then, the effects of pressure upon the true strain to fracture was found to be highly structure sensitive, both in terms of the slope *B* and the form of the relationship between strain to fracture and pressure. Annealed 0.004% C and spheroidized materials exhibited a linear relationship between pressure and strain to fracture, whereas the annealed materials containing substantial carbon exhibited a definite nonlinear polynomial relationship with *B* increasing with increasing pressure. The slopes of the curves *B* all decrease with increasing carbon content. In the case of the annealed carbon containing materials, the slope at high pressure approached that for the spheroidized materials of equivalent carbon content.

As previously discussed, Bridgman primarily used materials that were in the "as-received" or quenched and tempered condition. Of all of his data, two plain carbon steels, that were supposedly in the annealed and/or spheroidized condition (the actual structure is unknown), can be used for comparison with the results of this current investigation. These data of Bridgman are shown in Fig. 4, along with the pertinent curves from our investigation. Bridgeman's actual data points are shown and the best fit curves drawn through these points. For simplicity, the data points from the current investigation have been omitted with the points shown being used only in order to identify the curves. The curves from the current work are dashed with those from Bridgman being solid.

It can be seen in Fig. 4 that the best fit curves for Bridgman's data are not linear as he has stated, but deviate considerably from linearity. In the case of his annealed 0.90% C material, the agreement is