are concentrated over a small area at the point of application, spread out quickly through the conical configuration behind the sample; thus the overall stresses are not large. This concept is the principle of "massive support" developed very effectively by Bridgman. Although the particular equipment described is not used in metal-forming operations, it does

BACKGROUND—*The Discovery of High-Pressure Phenomena*

The effect of high pressure on the properties of metal was first noted by P. W. Bridgman in 1912. His early work, which was described in a paper published in *The Physical Review*, dealt with the behavior of steel and copper cylinders collapsed by immersion in high-pressure fluid.[1] The pressures used ranged up to 180,000 psi. One of the effects noted was that under these conditions the plastic flow was much more extensive than that normally encountered before rupture.

The same year Bridgman also published a paper dealing with the fracture of rods subjected to radial pressure along portions of their lengths.[2] In this work the peculiar effect termed "pinch-off" was first revealed. Pinch-off is the phenomenon by which a radial hydraulic pressure of sufficient intensity causes a rod to sever with a tensile type of fracture, even though the rod may be compressed axially.

Continuing his research into high-pressure physics, Bridgman concentrated on methods of generating high fluid pressures, with which he performed experiments in many areas—such as compressibility, electrical resistance, and phase changes under high pressure. In the course of this work he developed piston and cylinder equipment useful for laboratory experiments at pressures up to 450,000 psi.[3] During the period from 1912 until 1940, however, most of the work had little specific bearing on problems of metal forming. The one exception was a series of experiments measuring the torsional shear of specimens compressed between carbide anvils at pressures up to 750,000 psi; these experiments provided coefficient-of-friction and shear-strength data that are extremely useful in the analysis of certain metal-forming situations.[4]

At the outbreak of World War II researchers at the Naval Research Laboratories observed inexplicable behavior associated with the impact of projectiles against armor plate. As a result Bridgman was consulted and subsequently given research contracts to conduct further studies into the effect of high pressure on metal deformation. During this period he developed his celebrated tensile tests under pressure (see Figure 1) and proved the dependence of ductility on pressure.[5]

Having already developed piston-cylinder equipment for generating fluid pressures up to 450,000 psi, Bridgman found it relatively simple to incorporate a tensile testing setup in which movement of the high-pressure piston encountered one of the grips holding the test specimen and moved it so as to cause elongation. By measuring the pressure in relation to the stroke of the piston he could determine the final plastic behavior of the part at a given pressure. It was characteristic of Bridgman's test that the environmental pressure was not constant but rather increased linearly with the extension of the part. This condition obtained because he depended upon the compressibility of the fluid to allow the piston to move sufficiently to elongate the specimen.

In addition to the simple tensile tests under pressure Bridgman also made uniaxial compression tests and tensile tests on hollow cylinders. Most of this work, and particularly the tensile tests, dealt with alloys of steel. Also, in his search for better piston materials, he made compression tests under pressure on materials such as tungsten carbide, diamond, and sapphire rod. Finally, Bridgman conducted experiments in the use of pressure to punch holes in steel plate,[6] and he made attempts to draw wire under pressure.[7] In general, this period, which culminated in Bridgman's receipt of a Nobel prize in 1946, was extremely fruitful in that it provided much fundamental data relating material behavior to pressure.

Since that time a number of other workers have duplicated and improved on the Bridgman techniques of deforming metal under pressure. In Russia L. F. Vereschagin duplicated the tensile test apparatus and repeated the Bridgman tests on steel.[8] Vereschagin carried the work up to slightly higher pressures and included other metals such as copper, brass, and aluminum. In addition, he was one of the first to extrude round and shaped rods under high pressure. In Scotland H. L. D. Pugh, using similar apparatus, performed both tensile testing and wire drawing.[9] Pugh's tensile apparatus was a decided improvement over Bridgman's in that Pugh found a way to keep the pressure constant throughout extension of the part. He was also successful in photographing the neck region of the specimen during the test. In this country A. Bobrowsky has been performing tensile tests under pressure on difficult materials such as tungsten, beryllium, and molybdenum.[10] He has also made compression, bending, and extrusion tests under pressure. As described in the article, much of the data compiled by these researchers is of fundamental importance to the metal-forming field.

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[1] P. W. BRIDGMAN, "The Compression of Thick Cylinders under Hydrostatic Pressures," *Physical Review*, Vol. XXXIV (1912), pp. 1-24.

[2] P. W. BRIDGMAN, "Breaking Tests under Hydrostatic Pressure and Conditions of Rupture," *Philosophic Magazine*, Vol. XXIV (1912), pp. 63-80.

[3] P. W. BRIDGMAN, *Large Plastic Flow and Fracture*, McGraw-Hill Book Co., New York, 1952, p. 38.

[4] *Ibid.*, pp. 279-292.

[5] *Ibid.*, pp. 39-86.

[6] *Ibid.*, pp. 134-141.

[7] *Ibid.*, pp. 174-179.

[8] E. I. BERESNEV and L. S. VERESCHAGIN (translation by Morris D. Friedman), *Large Plastic Deformation of Metals at High Pressures*, AKAD. MAUK Press, Moscow, 1960, pp. 1-11.

[9] H. L. D. PUGH, "The Mechanical Properties and Deformation Characteristics of Metals and Alloys under Pressure," *NEL Report No.* 142, Mechanical Engineering Laboratory, Glasgow.

[10] A. BOBROWSKY, E. A. STACK, and A. AUSTEN, "Extrusion in Drawing Using High-Pressure Hydraulics," *Technical Paper No. SP*65-33, American Society of Mechanical Engineers, 1964.