by Day and Ruoff.[8] We find that $\sigma_0 = 0.729\sigma_{z=0}$ and yielding begins at the point $z = 0.699a$. If the onset of plastic deformation really starts at a pressure around 110 kbar as mentioned in Ref. 1, the yield strength of cemented tungsten carbide is around 80 kbar. The above result for maraging steel and cemented tungsten carbide is only slightly different from that of Ruoff and Wanagel,[1] although the latter used a relatively crude analysis.

If we had used the Poisson ratio for cemented tungsten carbide from the direct measurement[9] rather than that obtained from the ultrasonic work,[8] namely, $\nu = 0.19-0.23$, we would have $\sigma_0 = 0.726\sigma_{z=0}-0.704\sigma_{z=0}$. Assuming the same value of pressure for the onset of the plastic deformation for the anvils, we obtained the yield strength of cemented tungsten carbide around 80—77 kbar. The direct measured yield strength based on 0.002% offset is approximately 350 000 psi (~24 kbar).[9] This should provide the lower bound of the generally defined yield strength based on 0.2% offset.

For single-crystal diamond, we have used $\nu = 0.103$ for Poisson's ratio, which is obtained from the data of the adiabatic elastic constants measured by McSkimin *et al.*[10] and converted to isothermal ones. We find that $\sigma_0 = 0.781\sigma_{z=0}$ and yielding begins at $z = 0.697a$.

Now, it would be interesting to estimate the maximum pressure one can achieve with the Drickamer-type apparatus by using pistons of these different materials. For pistons made of maraging steels, Ruoff and Wanagel[11] claimed that a maximum pressure of around 85 kbar was obtained, i.e, approximately four times the yield strength of the marging steel; this result is quite interesting, because with strong enough support along the conical flanks of the pistons, one can imagine that toward the center of the highly pressurized zone the state of stress can be approximated by a hollow sphere pressurized inside. Then, the well-known result from elastic and plastic theory that $P = 2\sigma_0 \ln K$ (assuming no work hardening), where K being the radius ratio, would tell us that with $K = 7$ it would give us a maximum pressure roughly four times the yield strength. This is actually the case too with cemented tungsten carbide pistons of $K = 10$, which is a usual design figure for a standard Drickamer-type apparatus, that after heavy deformation one usually has a plastic zone around $K = 7$ or less. If the value of yield strength is correct, namely, 80 kbar, then using cemented tungsten carbide one would obtain a maximum pressure around 300 kbar with $K = 10$. However, it seems that the determination of the onset of plastic yielding by measuring the permanent deformation at the tip of the piston is not a very sensitive method. The estimated yield strength could possibly be lower. And also, due to the fact that stress/strain curves for steel and cemented tungsten carbide are not exactly the same, the analysis made here about the maximum pressure is a rough estimate.

It is understood that in order to effectively use the load toward the center area without too much plastic deformation along the conical flanks of the anvils, one usually uses the optimum design figure $K = 10$. Hence, the maximum achievable pressure estimated here will be based on the value of $K = 10$, which would generally allow a fully plastic zone of $K = 7$ roughly. One certainly can use a value of K much larger than 10. Then he has to provide extremely strong support along the conical flanks of the anvils in order to have a large enough hydrostatic component in that area to prevent the piston from failing. In the latter case, however, a larger fraction of the total load will be taken by the conical flanks of the anvils.

As for the case of a single-crystal diamond, there is no available data on the yield strength. However, it is known for some cases in an indentation test, it could stand pressure as high as 300 kbar. Although the situation is not completely identical to the anvils we consider here, one can roughly estimate a maximum achievable pressure of at least 1.2 Mbar. The recent Mao and Bell[12] experiment with single-crystal-diamond anvils indicated that a pressure of 1.018 Mbar was obtained without any deformation of the diamond. If the claimed pressure is accurate, that would mean a yield strength of 800 kbar which is approximately one-seventh of the shear modulus of diamond. Then the maximum achievable pressure with a single-crystal diamond could be as high as 3.2 Mbar.

Bundy[5] in a recent experiment with a sintered-diamond tip on a cemented tungsten carbide piston has achieved a pressure of approximately 400 kbar without any measurable plastic deformation at the tip. No Poisson rate is available for the sintered-diamond compact; but if the same equation for a single-crystal diamond is used, one can estimate a maximum achievable pressure of at least 1.2 Mbar. Since the sintered-diamond anvils have not been tested experimentally to determine onset of plastic deformation but do show indentation hardness values almost equivalent to those obtained for single-crystal diamond, the ultimate pressure capability may be as high as for a single-crystal diamond.

ACKNOWLEDGMENT

The author would like to thank Dr. R.C. DeVries for critically reviewing the manuscript, Dr. F.P. Bundy for for many helpful discussions, and also Dr. M. Aven for providing the opportunity of summer visiting at G.E. Research and Development Center which makes this work possible.

*Summer visitor at G.E. Research and Development Center from Department of Materials Science and Engineering, National Tsing Hua University, Hsinchu, Taiwan, China.

[1]A.L. Ruoff and J. Wanagel, J. Appl. Phys. 46, 4647 (1975).
[2]A.I. Lur'e, *Three-Dimensional Problems of the Theory of Elasticity* (Wiley, New York, 1964), p. 137.
[3]K.F. Forsgren and H.G. Drickamer, Rev. Sci. Instrum. 36,

1709 (1966).
[4]M. Myers, F. Dachille, and R. Roy, *High Pressure Measurement*, edited by A.A. Giardini and E.C. Lloyd (Butterworth, Washington, D.C., 1963), p. 17.
[5]F.P. Bundy, Rev. Sci. Instrum. 46, 1318 (1975)
[6]D. Papantonis, M.S. thesis (University of Rochester, 1975) (unpublished).
[7]S. Timoshenko and J.N. Goodier, *Theory of Elasticity* (McGraw-Hill, New York, 1970), p. 403.
[8]J.P. Day and A.L. Ruoff, J. Appl. Phys. 44, 2447 (1973).
[9]R.C. Lueth (private communication).
[10]H.J. McSkimin, P. Andreatch, Jr., and P. Glynn, J. Appl. Phys. 43, 985 (1972). Poisson's ratio in this case actually varies with crystallographic orientation. We have obtained the value from $\nu_{21} = C_{12}/(C_{11} + C_{12})$.
[11]A.L. Ruoff and J. Wanagel, Rev. Sci. Instrum. 46, 1294 (1975).
[12]H.K. Mao and P.M. Bell, Science **191**, 851 (1976).