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Diamond anvil cells

Diamond Sculpting Pushes Extremes

Micro-milling gem-quality diamond tips into a toroidal shape has been shown to greatly extend the accessible pressure range of standard diamond anvil cells, opening the way for studies in extreme physics of high-density matter.

Malcolm McMahon

Taking the definition of force applied per unit area, very high pressures can be generated by exerting only modest force on a very small area. In a diamond anvil cell (DAC), two gem-quality diamonds with small (30-300 µm diameter) flat tips, or culets, are used to compress extremely small volumes of the sample that are placed in a small hole in a gasket of thin metal foil between the tips. Using DACs, which are small enough to be hold in one hand, pressures of 3 million times atmospheric pressure (or 3 Megabars) can be generated fairly routinely. Once the sample is compressed, the temperature can also be raised or lowered, and its high-pressure properties can be studied in great detail with x-ray diffraction or optical spectroscopy – despite having a volume of only tens of pico-litres.

The diamond anvil cell will celebrate its 60th anniversary next year [1]. The upper pressure achievable with a DAC had been limited to approximately 4 Mbars since the early 2000s. While this is higher than the pressure at the centre of the earth, it is still lower than what researchers are interested in for exploring the fundamental nature of matter. The upper pressure limit was extended dramatically to 6.4 Mbars [2] and then to above 10 Mbars [3], by using a focussed ion beam (FIB) to create pairs of ultra-small secondary anvils from 20 µm nano-polycrystalline diamond spheres. While this was a great breakthrough, the so-called two-stage DAC remains a highly specialised arrangement, and other attempts to use FIBs to create pairs of ultra-small secondary anvils have not been successful [4]. As the saying goes about buses, you wait ages for one, and then two come along at once. Now writing in Nature Communications, two groups of researchers have, almost simultaneously, devised a way of extending the upper pressure limit of the traditional one-stage DAC, by "sculpting" toroidal rings in the surface of standard anvils using a FIB [5, 6].

The limiting factor in the maximum pressure that can be reached in a traditional one-stage DAC is the large elastic strains generated within the anvil culets, which causes them to deform markedly. The anvil geometry designed by Agnès Dewaele and colleagues [5] is shown in Fig. 1(a) and the one of Zsolt Jenei and colleagues in Fig.1 (b). The toroidal features in both, with dimension of only a few microns, seem to have three beneficial effects. Firstly, the diamond culet diameter is reduced to only 15 µm or less, increasing the pressure generated for the same applied force. Such features also counteract the distortion of the culets under extreme loading, so-called "cupping", preventing them from cutting through the thin gasket foil that leads to their failure. Finally, radial outflowing of the gasket material away from the culets is also prevented, which helps to support and stabilise them [5,6].

The overall result is that this modified design of one-stage toroidal DAC can achieve pressures of 5.5 or 6 Mbars – 2 Mbars higher than traditional DACs, with a remarkably homogeneous stress state within the sample. While this upper pressure limit is less than that of the two-stage DAC, the available sample size, although only ~5 µm in diameter, is larger. This anvil design allows the use of traditional DAC loading techniques, enabling their wide use with samples that are initially solids, liquids or gases [5].

Much of our knowledge of how materials behave under extreme compression comes from experimental studies using DACs – be it an elemental metal or gas, or a material with important geo-planetary implications. However, such studies have, generally, been limited to 3-4 Mbars. While much higher pressures into the Gbar range can be achieved using large lasers such as the National Ignition Facility for compression, such samples are typically heated very much above room temperature and the compression is only maintained for nanoseconds. The development of both two-stage and improved one-stage designs of DACs that enable higher pressure to be achieved, which simultaneously allowing us to study materials at extreme pressures and lower temperatures under static conditions, opens new horizons in materials research. While the samples in such cells are extremely small, new x-ray sources such as the ESRF-EBS synchrotron and the European X-ray Free Electron Laser provide the extremely bright, nano-focussed x-ray beams required for those studies.

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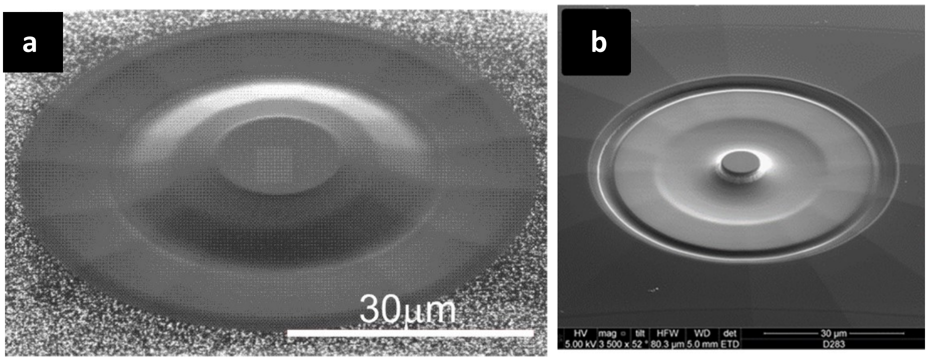

Figure 1: Scanning electron microscope image of toroidal diamond anvils. (a) Anvil geometry reported by A. Dewaele and colleagues. The central flat part of the diamond culet has a diameter of 16 µm, while the toroidal ring extends out to 60 µm. Image adapted from Ref.5, Macmillan Publishers Ltd. (b) Anvil geometry reported by Zs. Jenei and colleagues. The central flat part of the diamond culet has a diameter of 13 µm, while the toroidal ring extends out to 60 µm. Image adapted from Ref.6, Macmillan Publishers Ltd.