Fracture toughness and fracture strain of single-layer freestanding graphene extracted by on-chip testing

Sahar Jaddi[1], Bin Wang [2, 3], Malik M. Wasil[2], Yun Zeng[3], Jean-Pierre Raskin[2,] and Thomas Pardoen[1]
IMMC[1], ICTEAM[2], UCLouvain, Louvain-la-Neuve, Belgium
School of Physics and Electronics, Hunan University, China[3]

Graphene has attracted the attention of the scientific community for the last two decades, thanks to an astounding set of properties such as high thermal conductivity (5000 W/mK), superior electron mobility (250,000 cm^2/V-s), high modulus of elasticity (~1 T Pa), and ultra-high flexibility. Graphene's C-C bonds are sp^2 hybridized providing superior mechanical stability in the basal plane directions. Graphene appears as the perfect material constituent for a wide range of application fields, like in flexible electronics, in electromechanical devices, and in reinforced lightweight composites that rely on both electrical and mechanical performances. It remains crucial to determine the latter properties under realistic and well-controlled conditions to guide the fail-safe design of graphene-based applications.

While the mechanical behavior of graphene has been very much investigated numerically for both perfect and defected lattice structures [1,2], most experimental works remain partly inconclusive regarding the fracture resistance. Nanoindentation of a suspended single layer (SLG) and of multilayer graphene (MLG) on top of holes [3,4], and uniaxial tensile test using the so-called push-to-pull device, are mostly used to deform graphene [8,9]. Testing graphene using a valid fracture mechanics approach is very complex due to the nature of the fabrication, the difficulty of pre-cracking, and the delicate data analysis. Two reports on the fracture toughness of SLG have been published [5,6], while other data are for MLG [7, 8]. The aforementioned works have provided insight into the fracture mechanisms of graphene, using a notch as a starter crack. This can potentially lead to an overestimation of the fracture toughness with a dependence on the notch root radius, which is difficult to deconvolute. Furthermore, the notch is produced by a focus ion beam, which may introduce damage. These tensile and fracture tests relied on external equipment either for loading or sensing, leading to cumbersome manipulation and allowing only a few specimens to be tested, preventing statistical analysis.

In the present work, we report two novel extensions of methods developed in our laboratory to study the mechanical and fracture properties of freestanding SLG. The method relies on the use of residual tensile-stress involved in a beam layer called the actuator beam. This beam is attached to the graphene specimen. Removing the sacrificial layer induces the release of internal stress in the actuator, pulling then on the graphene specimen. Hence, the use of external (electro-)mechanical actuation is avoided. In a first configuration, the actuator layer is pulling on a dog-bone shape or rectangular graphene specimen, from which the uniaxial stress-strain curve is extracted up to fracture [10]. In a second configuration, two actuator beams pull on a notched specimen but using a crack arrest method to determine the fracture toughness suppressing the problem of notch blunting effect at crack initiation [11]. Benefiting from the lithography process, numerous devices have been fabricated hence providing statistically representative data. Our investigation shows fracture strains larger than 10% and tensile strength larger than 100 GPa for specimens with an area larger than 160 μm^2. Brittle fracture behavior is observed with fracture toughness value equal to about 4 MPa $m^{0.5}$ in agreement with literature.

References

1. F. Liu *et al*., Phys. Rev. B 76, 2007
2. A. Shekhawat *et al*., Nat. Commun. 7, 10546, 2016.
3. C. Lee *et al*., Science 321, 2008.
4. H.I. Rasool *et al*., Nature Commun. 4, 2013.
5. Y. Hwangbo *et al*., Sci. Rep. 4, 2014.
6. P. Zhang *et al*., Nature Commun. 5, 2014.
7. X. Wei *et a*l., Nano Lett. 15, 2015.

8. B. Jang *et al*., Extrem. Mech. Lett. 14, 2017.
9. K. Cao *et al*., Nat. Commun, 11, 92020.
10. M. Coulombier *et al*., thin films. Scr. Mater. 62, 2010.
11. S. Jaddi *et al*., JMPS, 123, 2019.