Mechanics of Suspended and Supported Graphene

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Graphene is an ideal 2D crystal which is believed to possess a unique combination of mechanical properties [1] in tension; that is high stiffness (~1 TPa), high strength (>100 GPa) but also high ductility (>20%) [2]. Theoretical works and simulations have indeed confirmed graphene as the stiffest and strongest material ever made but experiments on suspended graphene are scarce and problematic. A seminal work reported in [3] employing a radial tensile field by bending of graphene with an AFM probe, was converted by the authors to axial stress-strain curve by assuming almost zero bending stiffness and quadratic stress-strain relationship. By assuming a thickness of 0.335 nm (the interlayer spacing in graphite) similar values to those mentioned above were derived. However, as it was recently confirmed experimentally [4], when a suspended 1LG graphene is stretched axially then a very different situation is encountered as the suspended flake is expected to exhibit orthogonal (lateral) Euler buckling due to its small thickness. This behaviour is analogous to that observed for all thin membranes and even for biological materials stressed in one direction. Thus out-of-plane phenomena (Fig.1) cannot be ignored for certain modes of loading of suspended graphene.

For simply-supported or even fully-embedded graphene a number of experimental studies have been conducted. Normally, graphene flakes are subjected to a cyclic uniaxial deformation (tension and compression) using flexed beams (cantilever or 4-point). In tension, for both simply-supported and fully-embedded graphene the Raman 2D or G peaks are shifted with strain; the latter also shows splitting with strain due to the lifting of the degeneracy of the E_{2g} mode [4,5]. Using this technique one can load graphene flakes up to ~1.5-1.7% of tensile strain. Judging from the perfect linearity of the 2D peak with strain it is assumed that the supported/ embedded graphenes behave linearly elastic up to that level of strain. In compression, the mechanical behaviour of several simply-supported or embedded monolayer graphene flakes with various length-to-width ratios have also been fully examined [6]. The critical strain to buckling for fully embedded graphene was found to be ~0.6% and independent of the flake's dimensions. This is indeed an extraordinary result for such a thin 2D crystal and its significance for engineering applications will be discussed.

Regarding lateral buckling under uniaxial tension in order to reach such a high value of buckling strain the corresponding axial tensile strain should be higher than ~2.0% (assuming a polymer Poisson's ratio of ~0.35). Another option for effective graphene composites is the geometry of the embedded flakes; since a transfer length of about 2 μm is needed in order to have sufficient stress transfer from the surrounded polymer to the graphene [7] then any ribbons less than twice that value (<4 μm) will not be deformed effectively in the lateral direction and hence out-of-plane phenomena will be restrained. We can turn this effect to our advantage in non-structural (functional) composites for which in many cases large deformations are required in service.

References

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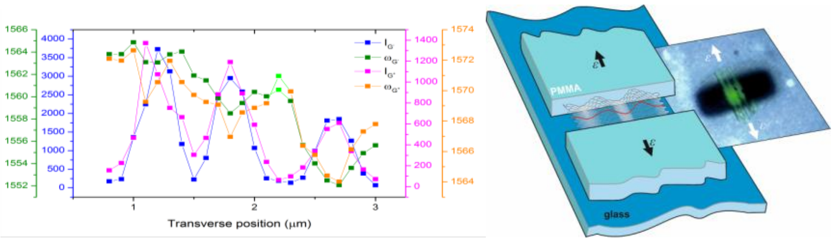

Fig.1 (a) Raman intensity (*I*) and frequency (ω) variation of the G and 2D sub-peaks in the transverse direction to strain axis. (b) Schematic of wrinkle (buckle) formation due to lateral compression and Raman map of the 2D peak intensity of graphene flake, $I(\omega_{2D})$.