Supplementary Information (SI) for Nanoscale.

Tuning Nanoscale Tribological Characteristics of Thermally Evaporated Transparent Polyaniline-Graphene Nanocomposite Thin Films

Soumyasuravi Thakur[a], Debottam Datta[b], Jitendra P. Singh[b], Nitya N. Gosvami*[a] and Nirat Ray*[a]

March 16, 2025

Supporting Information

1 Sample preparation

Table 1 shows the sample labels along with the respective weights of polyaniline (PANI) and graphene used for preparing the composites. All weights are provided in milligrams, with each entry detailing the specific composition of graphene and PANI for the different samples used in the study.

Table 1

Sample label	Weight of PANI	Weight of Graphene
PANI	150 mg	0 mg
5%	142.5 mg	7.5 mg
10%	135 mg	15 mg
15%	127.5 mg	22.5 mg
35%	97.5 mg	52.5 mg

2 Surface Morphology and Physical Properties of Polyaniline graphene Nanocomposite Films

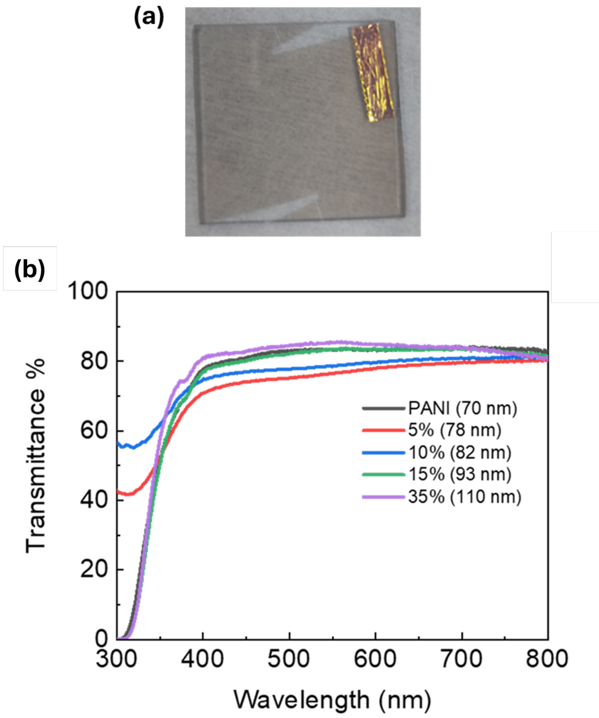

Figure. S1: Optical images (a) of ultrathin PANI-graphene nanocomposite film on the glass substrate. (b) Variation in UV-vis transmittance spectra of nanocomposite films with increasing graphene concentration.

Figure S1 (a) shows the optical images of the ultrathin PANI-graphene nanocomposite film on a glass substrate, highlighting the film's uniformity and transparency. Figure S1 (b) shows the UV-vis transmittance spectra for all nanocomposite films, including Pure PANI film. In general, the optical properties of polymer graphene composites depend on several factors including the film thickness, nature of interaction with the polymer as well synthesis route.

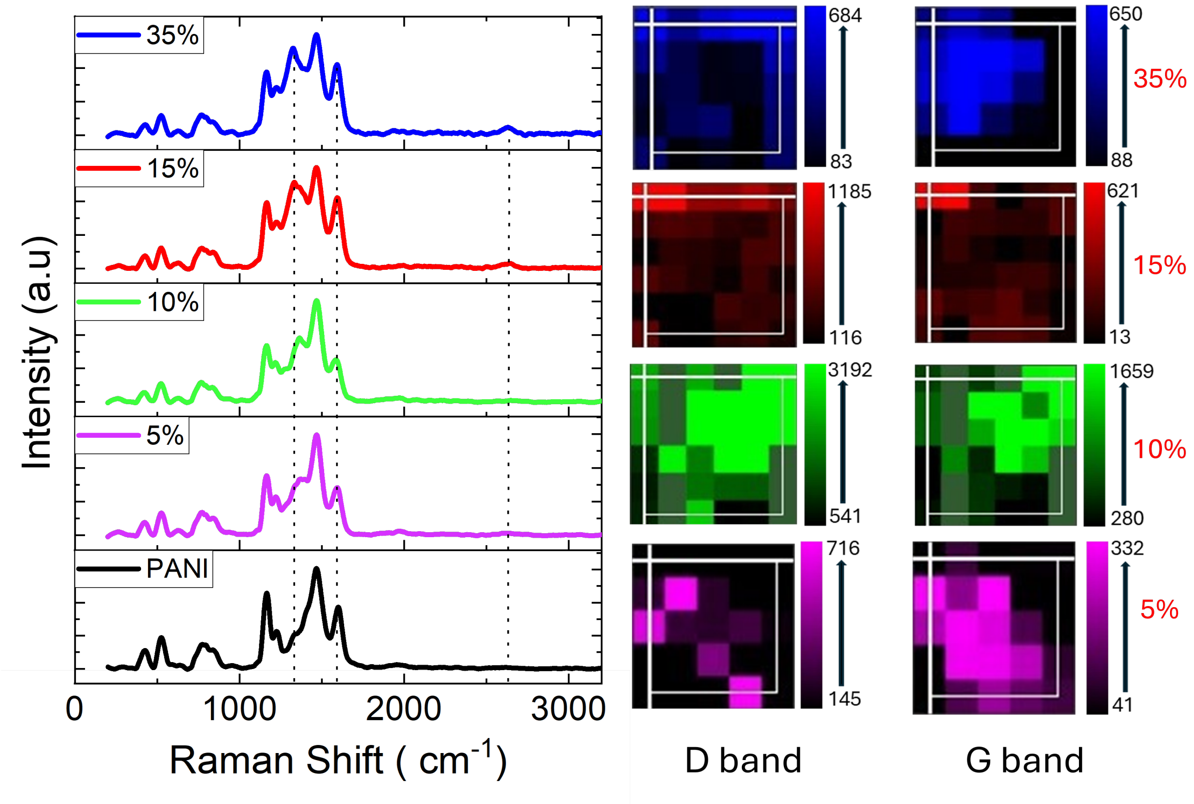

Figure. S2: (a) Raman shifts and intensity maps of the D(1350cm^{-1}) and G(1580cm^{-1}) bands of nanocomposite films confirming the inclusion of graphene in nanocomposite films for varying graphene concentration

Table 2

Graphene(wt%)	Thickness (nm)	Transmittance at 550 nm (%)
0	70	83
5%	78	77
10%	82	79
15%	93	83
35%	110	85

FigureS2 illustrates Raman shifts and intensity maps of the D(1350cm^{-1}) and G(1580cm^{-1}) bands of nanocomposite films, confirming the inclusion of graphene in nanocomposite films.

FigureS3 presents the thickness measurements of PANI and all nanocomposite films, as analyzed using a surface stylus profiler. The results indicate a clear trend of increasing thickness with higher graphene loading.

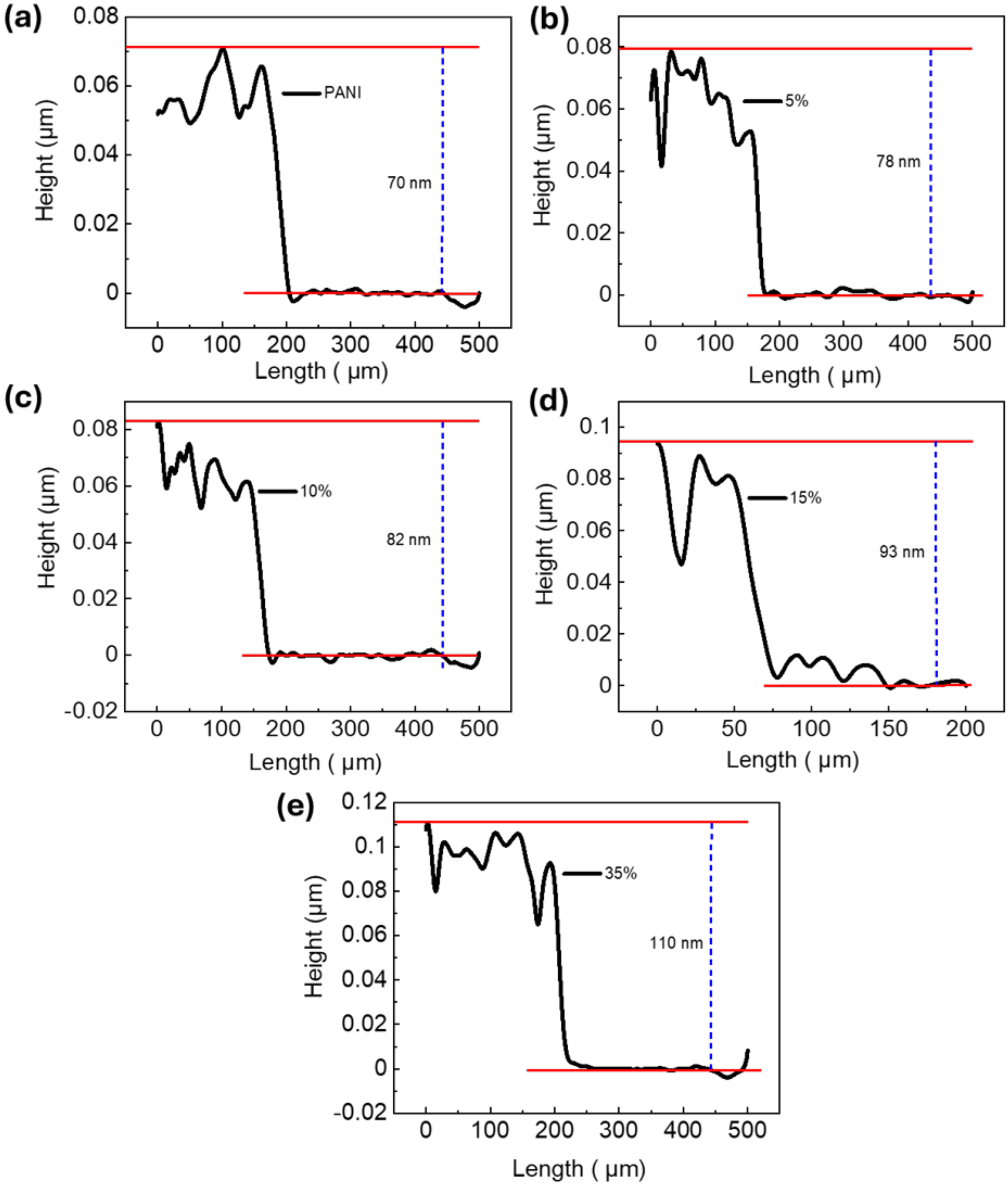

Figure. S3: Thickness measurements of (a)PANI, (b)5%,(c)10%,(d)15%, and (e)35% graphene film analyzed using a surface stylus profiler, showing a trend of increasing thickness with higher graphene loading.

3 Topography and the Lateral Force Maps along with the Friction Loops of 35%, 15%, 10% and 5% Graphene Composite Thin Transparent Film

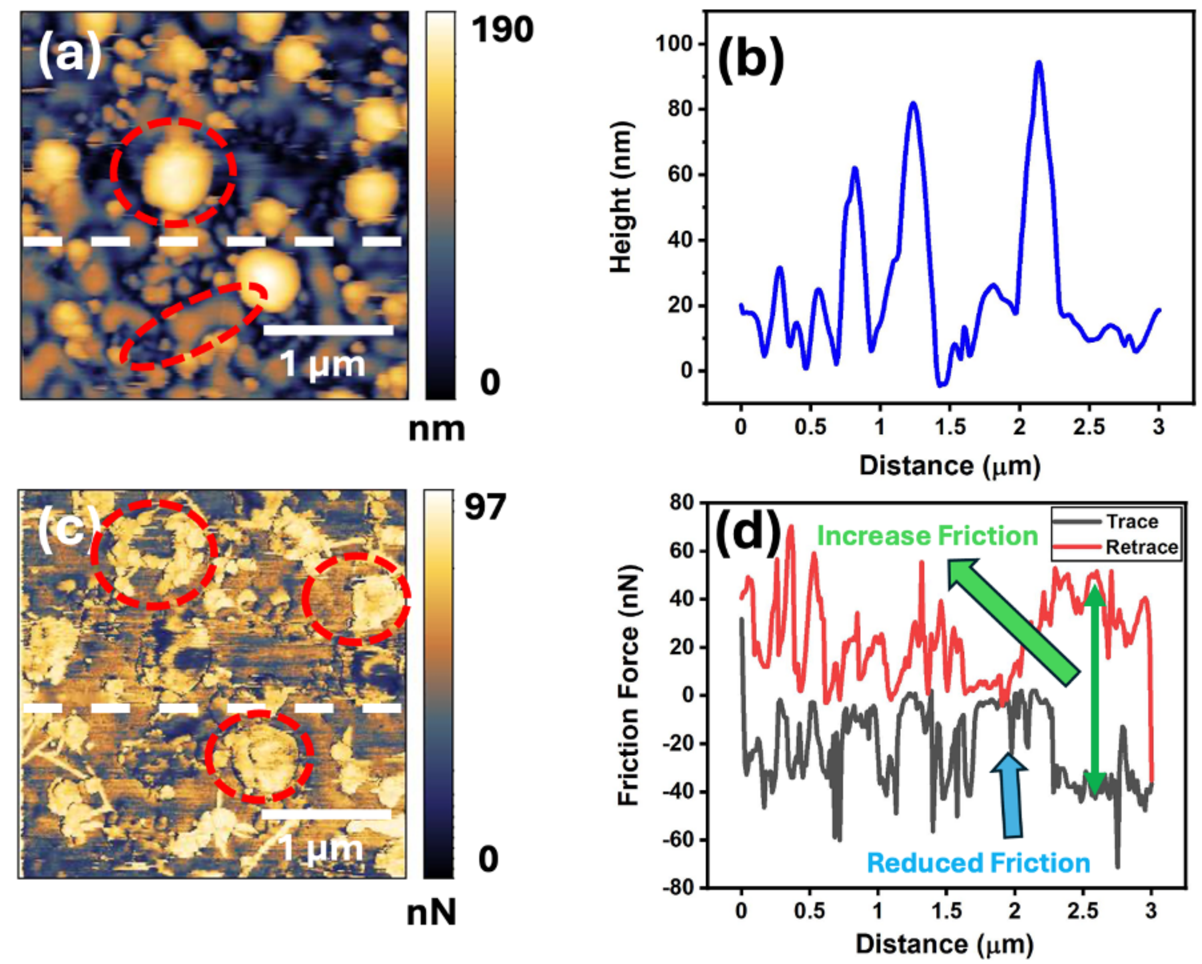

Figure. S4: LFM performed on the 35% graphene composite thin film applying the normal load of 10 nN using a sharp AFM tip, (a) topography of the 35% graphene composite thin film, and (b) the profile of the white line from the image a; corresponding (c) lateral force map (captured during the forward movement of the cantilever/trace motion) and (d) the profile of the white line or the friction loop from the image c. Some of the embedded graphene are marked with red dotted ellipse

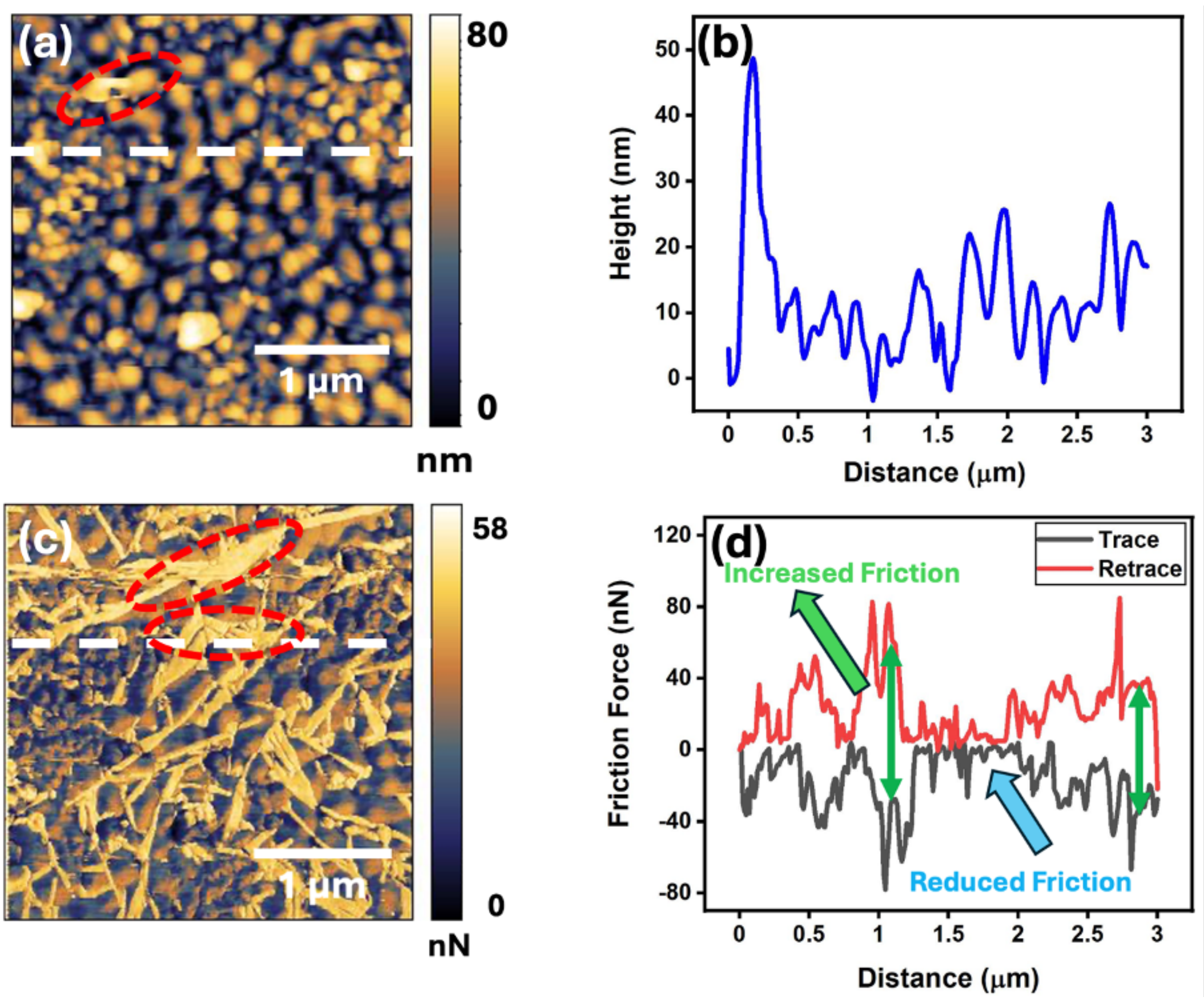

Figure. S5: LFM performed on the 15% graphene composite thin film applying the normal load of 10 nN using a sharp AFM tip, (a) topography of the 15% graphene composite thin film, and (b) the profile of the white line from the image a; corresponding (c) lateral force map (captured during the forward movement of the cantilever/trace motion) and (d) the profile of the white line or the friction loop from the image c. Some of the embedded graphene are marked with red dotted ellipse

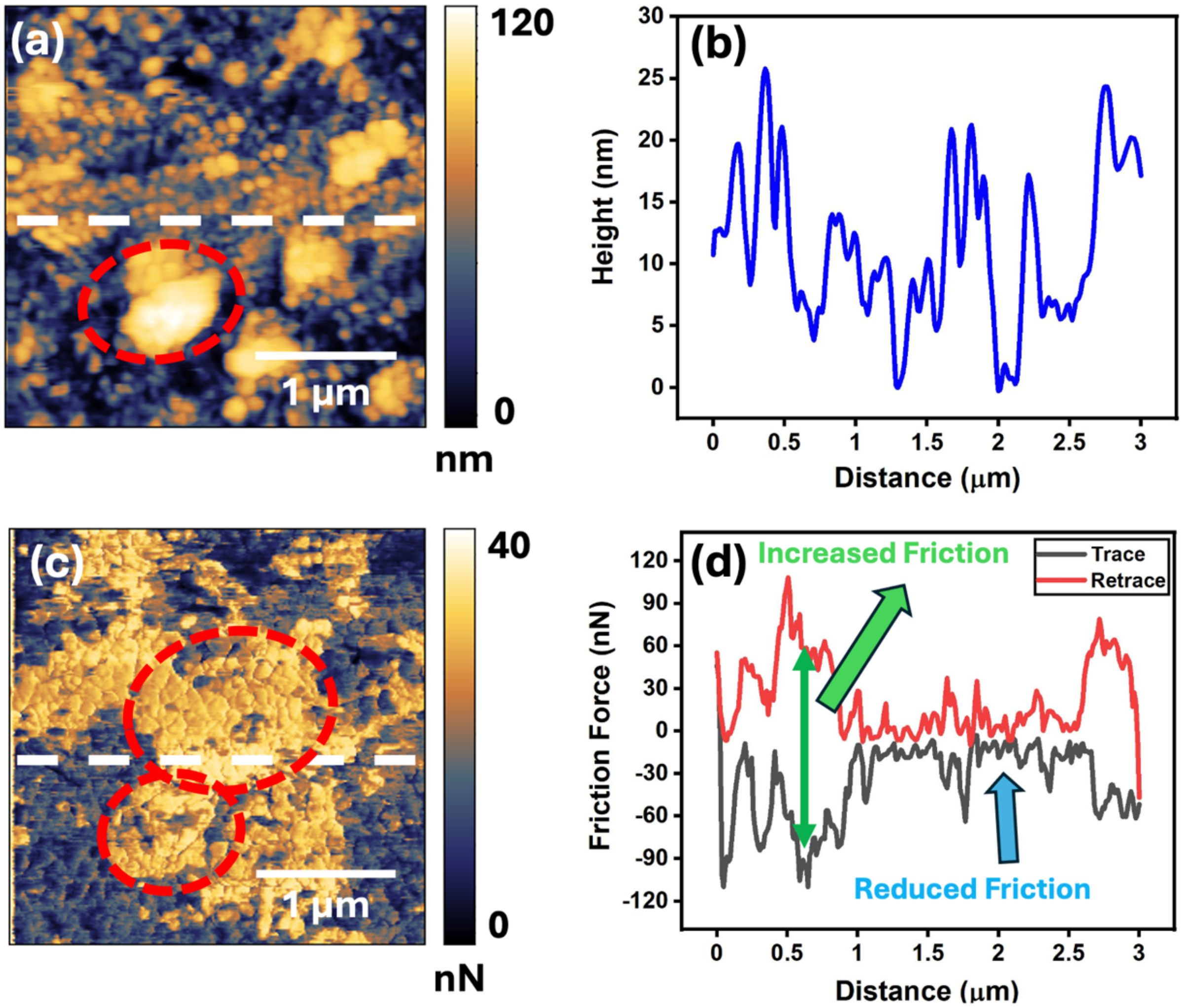

Figure. S6: LFM performed on the 10% graphene composite thin film applying the normal load of 10 nN using a sharp AFM tip, (a) topography of the 10% graphene composite thin film, and (b) the profile of the white line from the image a; corresponding (c) lateral force map (captured during the forward movement of the cantilever/trace motion) and (d) the profile of the white line or the friction loop from the image c. Some of the embedded graphene are marked with red dotted ellipse

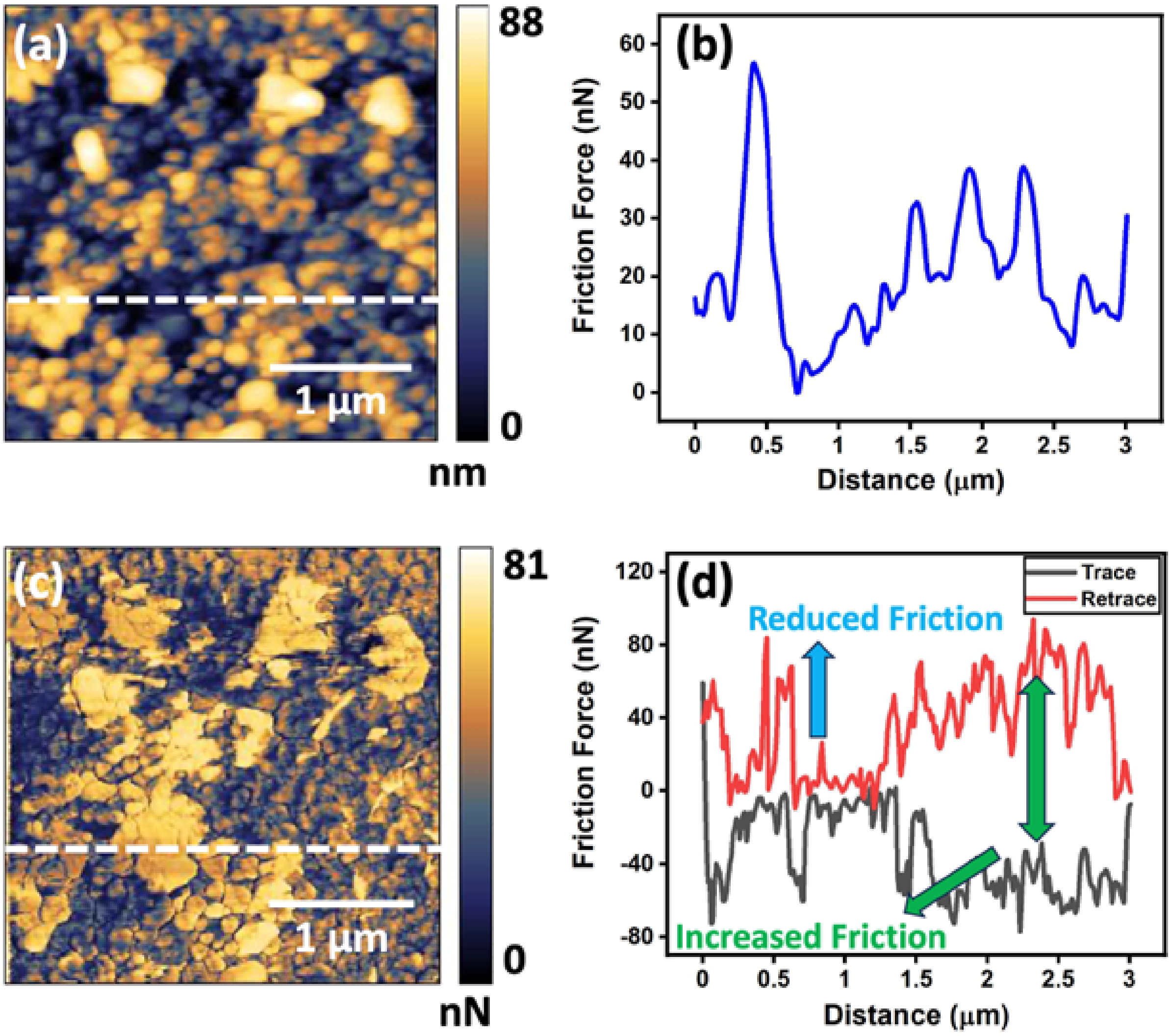

Figure. S7: LFM performed on the 10 % graphene composite thin film applying the normal load of 10 nN using a sharp AFM tip, (a) topography of the thin film, and (b) the profile of the white line from the image a; corresponding (c) lateral force map (captured during the forward movement of the cantilever/trace motion) and (d) the profile of the white line or the friction loop from the image c.

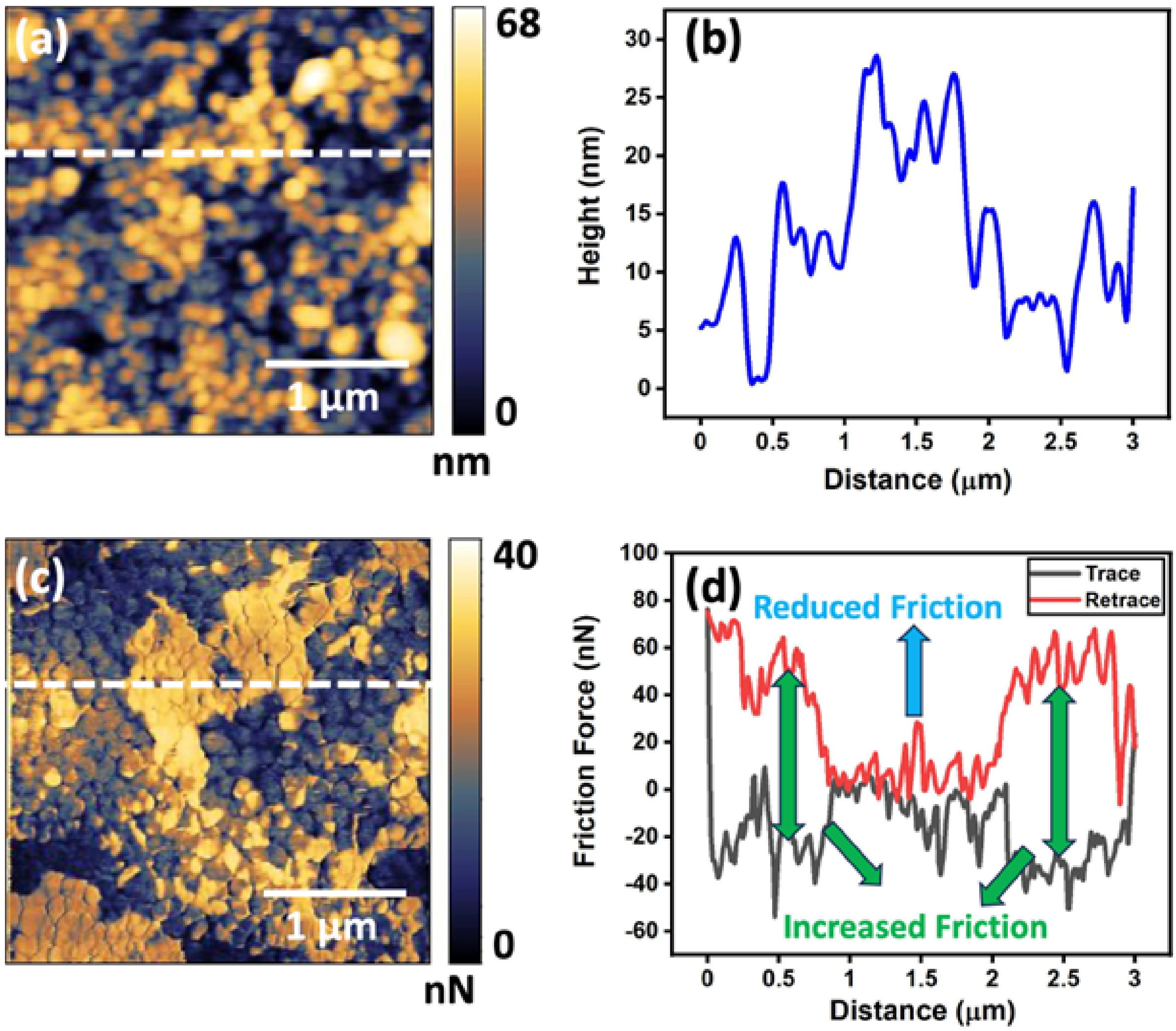

Figure. S8: LFM performed on the 10 % graphene composite thin film applying the normal load of 10 nN using a sharp AFM tip, (a) topography of the thin film, and (b) the profile of the white line from the image a; corresponding (c) lateral force map (captured during the forward movement of the cantilever/trace motion) and (d) the profile of the white line or the friction loop from the image c.

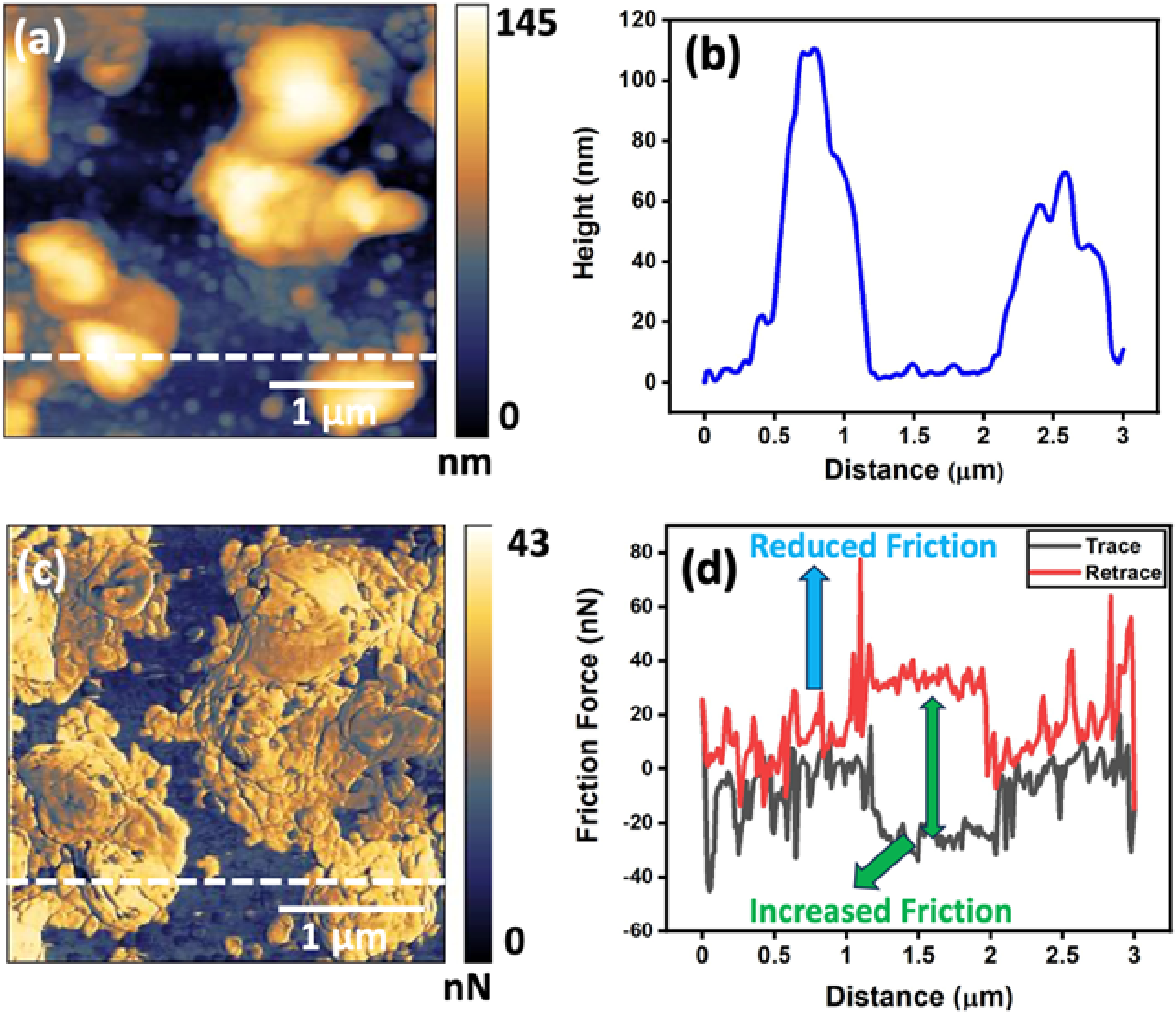

Figure. S9: LFM performed on the 5 % graphene composite thin film applying the normal load of 10 nN using a sharp AFM tip, (a) topography of the thin film, and (b) the profile of the white line from the image a; corresponding (c) lateral force map (captured during the forward movement of the cantilever/trace motion) and (d) the profile of the white line or the friction loop from the image c.

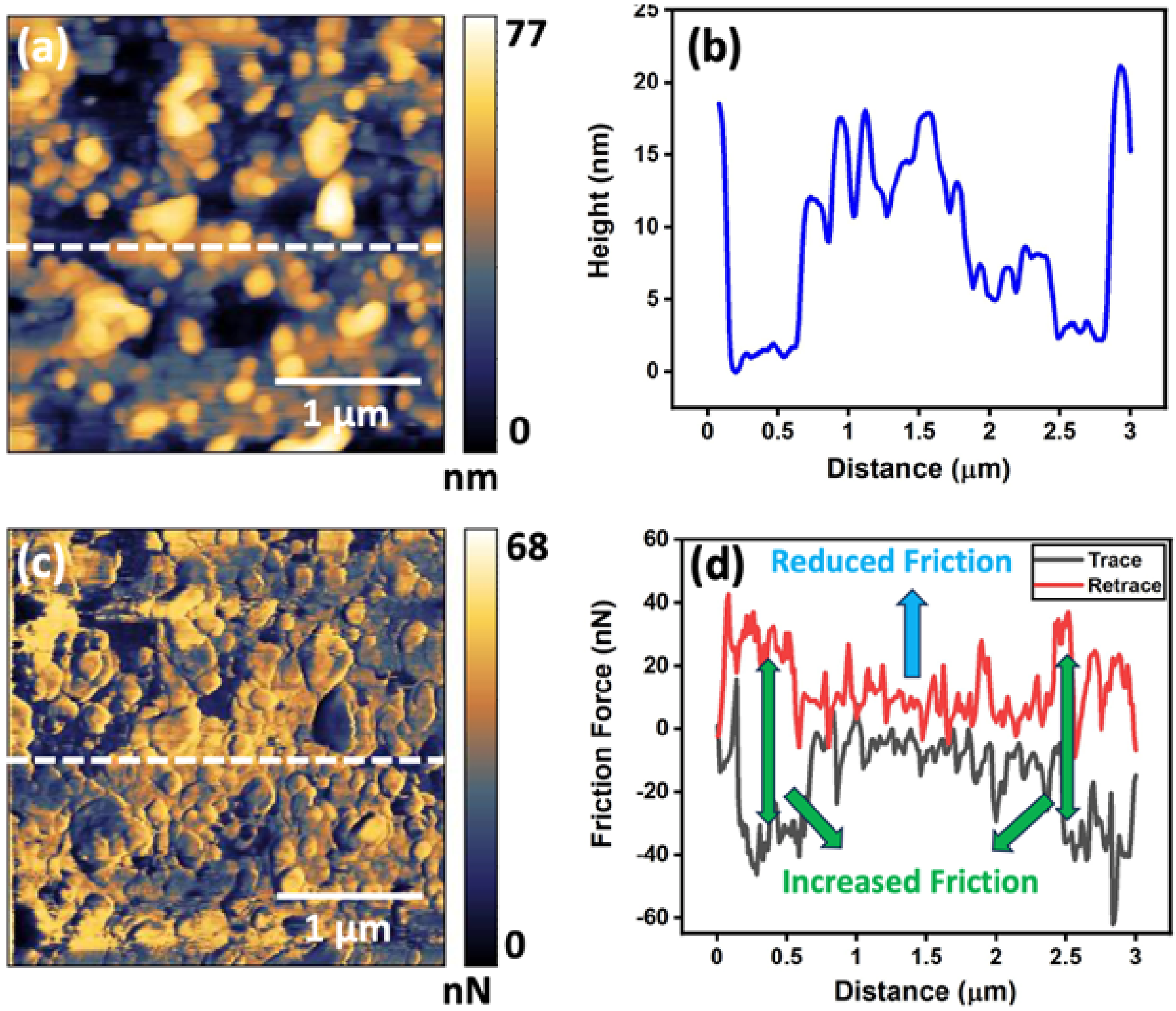

Figure. S10: LFM performed on the 5 % graphene composite thin film applying the normal load of 10 nN using a sharp AFM tip, (a) topography of the thin film, and (b) the profile of the white line from the image a; corresponding (c) lateral force map (captured during the forward movement of the cantilever/trace motion) and (d) the profile of the white line or the friction loop from the image c.

4 Comparative Analysis Lateral Force Maps with the Friction Loops of the 35%, 15%, 10% and 5% Graphene Composite Thin Films

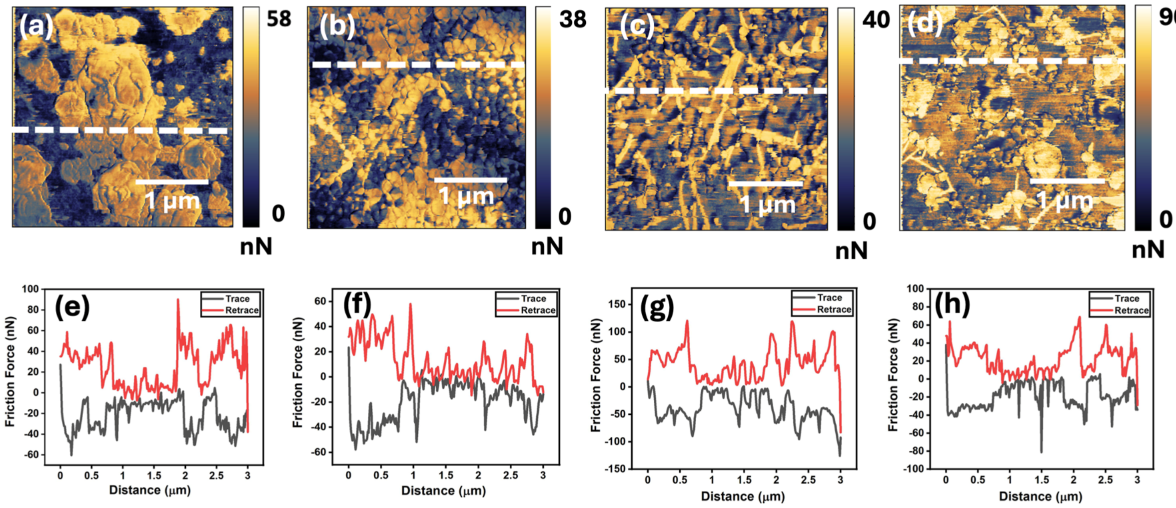

Figure. S11: Lateral force map (captured during the forward movement of the cantilever/trace motion) of the (a) 5% graphene; (b) 10% graphene; (c) 15% graphene and; (d) 35% graphene composite thin films respectively; the corresponding friction loops of (e) 5% graphene, the line profile of the white dotted line marked in image a; (f) 10% graphene, the line profile of the white dotted line marked in image b; (g) 15% graphene, the line profile of the white dotted line marked in image c; (h) 35% graphene, the line profile of the white dotted line marked in image d.

5 Variation of Lateral Force Maps with Increasing Normal loads for the 35%, 10% and 5% Graphene Composite Film and Pure PANI Thin Film

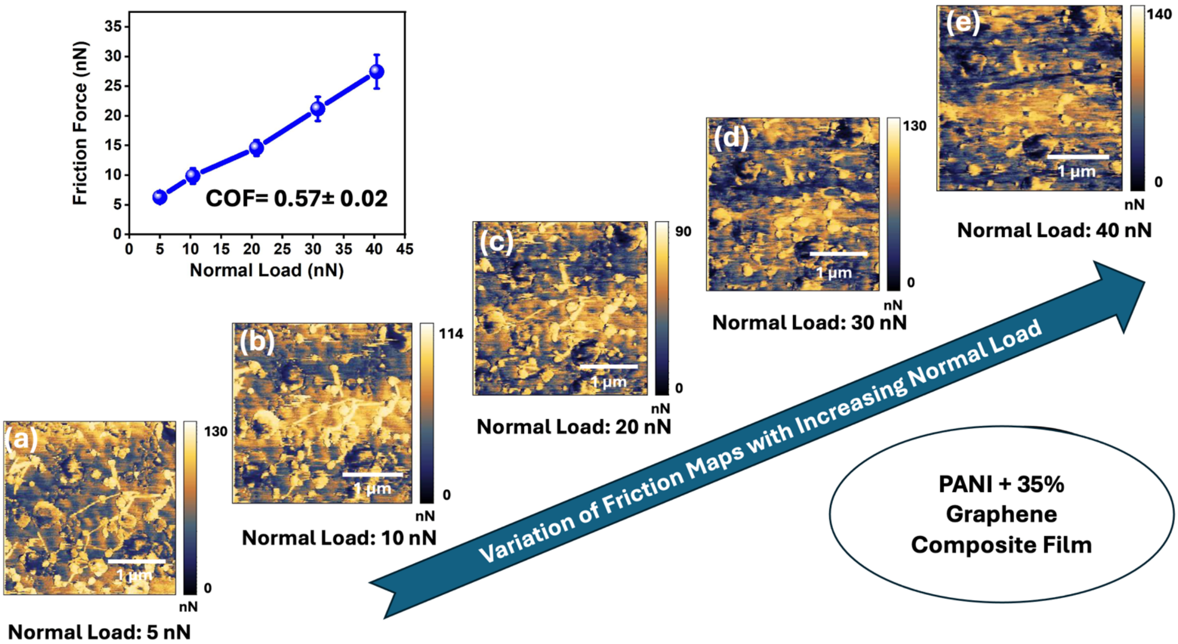

Figure. S12: Variation of friction maps (captured during the forward movement of the cantilever/trace motion) of the PANI + 35% graphene composite thin film with increasing normal loads. The friction maps at the normal of (a) 5 nN; (b) 10 nN; (c) 20 nN; (d) 30 nN; (e) 40 nN respectively. Inset Image: plot of friction force versus normal load for the same thin film.

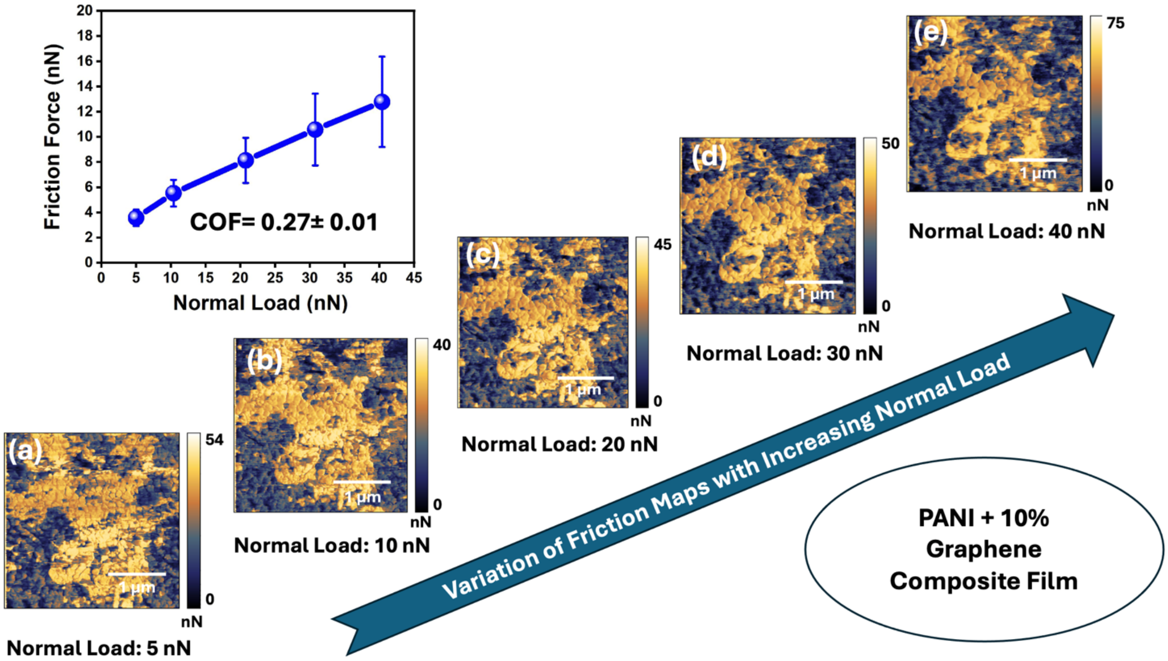

Figure. S13: Variation of friction maps (captured during the forward movement of the cantilever/trace motion) of the 10% graphene composite thin film with increasing normal loads. The friction maps at the normal of (a) 5 nN; (b) 10 nN; (c) 20 nN; (d) 30 nN; (e) 40 nN respectively. Inset Image: plot of friction force versus normal load for the same thin film.

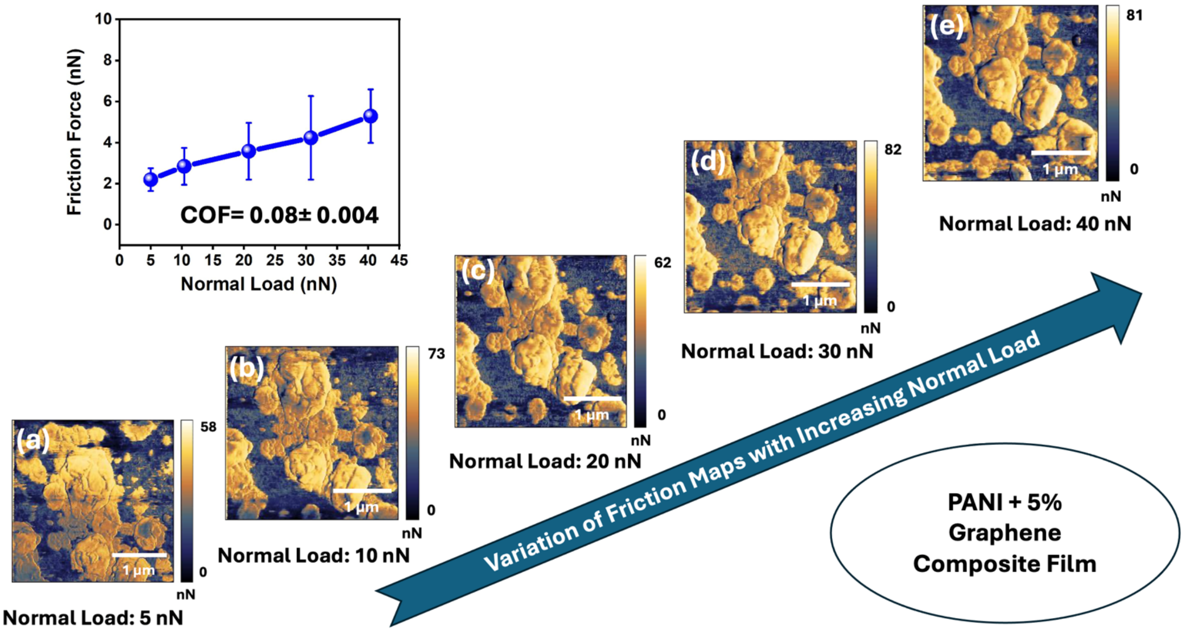

Figure. S14: Variation of friction maps (captured during the forward movement of the cantilever/trace motion) of the 5% graphene composite thin film with increasing normal loads. The friction maps at the normal of (a) 5 nN; (b) 10 nN; (c) 20 nN; (d) 30 nN; (e) 40 nN respectively. Inset Image: plot of friction force versus normal load for the same thin film.

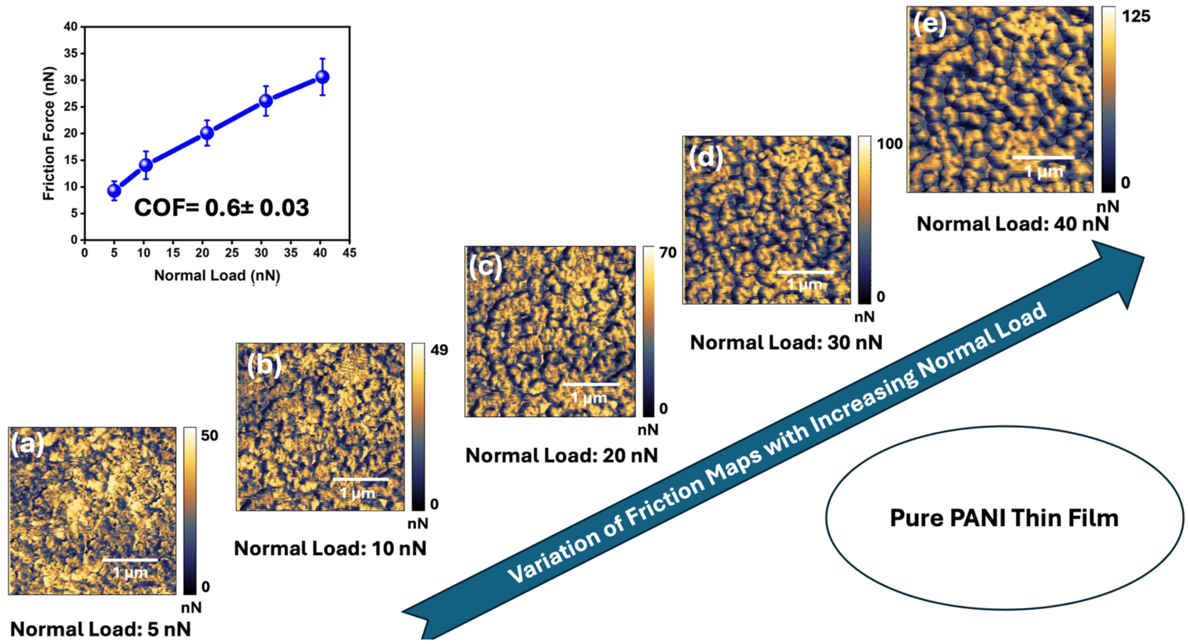

Figure. S15: Variation of friction maps (captured during the forward movement of the cantilever/trace motion) of the pure PANI thin film with increasing normal loads. The friction maps at the normal of (a) 5 nN; (b) 10 nN; (c) 20 nN; (d) 30 nN; (e) 40 nN respectively. Inset Image: plot of friction force versus normal load for the same thin film.