

<b>Institution:</b> The University of Manchester		
<b>Unit of Assessment:</b> 9 (Physics)		
<b>Title of case study:</b> Product enhancement by graphene		
<b>Period when the underpinning research was undertaken:</b> 2001 – 2016		
<b>Details of staff conducting the underpinning research from the submitting unit:</b>		
<b>Name(s):</b>	<b>Role(s) (e.g. job title):</b>	<b>Period(s) employed by submitting HEI:</b>
Konstantin Novoselov	Professor 2013 – present Research Fellow 2001 – 2013	January 2001 – present
Andre Geim	Professor	November 2001 – present
Aravind Vijayaraghavan	Reader 2019 – present Senior Lecturer 2013 – 2019	August 2013 – present
<b>Period when the claimed impact occurred:</b> December 2017 – July 2020		
<b>Is this case study continued from a case study submitted in 2014?</b> N		
<p><b>1. Summary of impact</b></p> <p>The University of Manchester's isolation of graphene has led to an array of products incorporating graphene, which deliver a range of performance improvements, including composite strength and wear resistance, heat management, noise dampening, low material weight, high electrical conductivity and microbial resistance. Graphene is a key component in some of the world's bestselling cars, running shoes and smartphones. Graphene has been fundamental in the development and performance of numerous products that have dominated their individual markets. Within this impact period:</p> <ul style="list-style-type: none"> <li>• Inov8 has sold [text removed for publication] running shoes worldwide [text removed for publication], with their graphene enhanced G-grip soles.</li> <li>• The automotive giant Ford has incorporated up to ten graphene components in the engine compartments of their Mustang and F-150, including fuel rail and engine covers, to improve thermal management, mechanical endurance and reduce engine noise and vehicle weight.</li> <li>• [Text removed for publication]</li> </ul>		
<p><b>2. Underpinning research</b></p> <p>In 2004, research conducted at the University of Manchester (UoM) demonstrated the existence of free-standing two-dimensional crystals, including graphene, boron nitride and an array of dichalcogenides and complex oxides [1]. This went against the Mermin-Wagner theorem, which stated that non-zero temperature thermal vibrations would destroy any 2D crystal at large distances [Mermin N. D., Phys Rev 176, 250 (1968)]. Isolation techniques, initially achieved by rubbing layered nano-crystals against a solid surface [1], and later by mechanical exfoliation [2], offered a simple, cheap and reliable approach for isolation of these 2D materials. This, combined with the promise that the new class of 2D materials would offer a wealth of new physical phenomena for application across a range of industries, led to significant interest in the field.</p> <p>Interest in graphene was further accelerated when Geim and Novoselov demonstrated that graphene's electrical properties offered ballistic transport (negligible resistivity to the passage) of charge, a linear current-voltage (I-V) relationship, and could sustain huge currents [2]. These properties made graphene a target for research in semi-conductor related industries where performance improvements of silicon-dominated technologies were plateauing.</p> <p>In 2016, Iliut <i>et al.</i> demonstrated that graphene oxide and reduced graphene oxide flakes could be incorporated into elastomer latexes for composite production by dip or film casting [3]. The resulting thin-film graphene composites demonstrated significant enhanced strength and elongation relative to pure latex elastomer. It was also shown that uniform dispersion of</p>		

graphene within the matrix, control of graphene particle size, amount of graphene, and appropriate tailoring of the graphene-polymer interface were essential for positive reinforcement.

### 3. References to the research

The award of the Nobel prize in 2010 to Geim and Novoselov is a clear indicator of the international esteem of the research. Citations are from Web of Science (February 2021).

- [1] Novoselov K.S., Geim A.K., Morozov S.V., Jiang D., Zhang Y., Dubonos S.V., Grigorieva I.V. & Firsov A.A. "Electric field effect in atomically thin carbon films", *Science*, 306, 666, (2004) [DOI: 10.1126/science.1102896](https://doi.org/10.1126/science.1102896). (43,099 citations)
- [2] Novoselov K.S., Jiang D., Schedin F., Booth T.J., Khotkevich V.V., Morozov S.V., & Geim A.K., "Two dimensional atomic crystals", *Proceedings of the National Academy of Sciences*, 102, 10451 (2005) [DOI: 10.1073/pnas.0502848102](https://doi.org/10.1073/pnas.0502848102). (8,082 citations)
- [3] Iliut, M.; Silva, C.; Herrick, S.; McGlothlin, M.; Vijayaraghavan, A., "Graphene and water-based elastomers thin-film composites by dip-moulding", *Carbon*, 106, 228-232. (2016) [DOI: 10.1016/j.carbon.2016.05.032](https://doi.org/10.1016/j.carbon.2016.05.032) (13 citations)

### 4. Details of the impact

UoM has had direct and indirect influence on global advancement of graphene-related products. This includes the initial isolation of graphene [1, 2] (without which no impact at all from products could have occurred), and direct development of graphene products to the benefit of specific companies [3].

Products available on the market that explicitly use graphene to increase strength and wear whilst reducing overall weight of their composite components include: motorcycle and bicycle helmets (e.g. MOMO FGTR Graphene 1.0 jet Helmet, Catlike Mixino); bicycle tyres (e.g. Vittoria Corsa G+ Clincher graphene road tyre); cycle shoes (Catlike Whisper line); bicycle wheels and frames (e.g. Vittoria Qurano, Dassi Interceptor frameset); fishing rods (e.g. Century Graphex Lure ); golf balls (e.g. Callaway Chrome Soft Truvis Red Golf Balls); tennis racquets (e.g. Head Graphene Touch Speed Lite); wristwatches (e.g. RM 50-03 chronograph); earphones (e.g. MediaDevil BC-01, Zolo Liberty and FiiO F3); thermal rubbers (AvanGRM rubbers) and cars (e.g. Briggs Mono R sports car, Ford F-150 and Mustang (discussed below)) [A].

This case study uses examples from three companies to describe the extent of the impact from using graphene in their products, detailing the improved performance achieved in each case. These examples are:

#### 4.1 Innov8 running shoes

Publication [3] drew the attention of Inov8 Ltd who, in 2017, engaged in a Knowledge Transfer Partnership (KTP) with UoM to explore the benefits of graphene composites for the outsoles of sports footwear [B]. The graphene-enhanced composite developed from this KTP [text removed for publication] was commercialised as the G-grip outsole, as part of the G-series and other footwear products launched by Inov-8 for challenging pursuits such as fell running, ultra-marathons and high-intensity training.

The first running shoes to feature G-grip were launched in June 2018, followed by hiking shoes in Dec 2018. [Text removed for publication].

#### 4.2 Ford insulating foams

Automotive giant Ford, in collaboration with Eagle Industries and specialist graphene supplier XG Sciences in the USA, has formulated a range of graphene-doped polyurethane products for under the bonnet parts [Ci]. Graphene serves as a nucleating agent, producing a more reliable urethane structure made up of more consistent and smaller bubbles. The reduced density of the

doped foams lowers the mass of polyurethane required for the product, offsetting the cost of the graphene and making adoption of the improved product cost neutral [Cii]. Dopant levels of less than 0.5 weight% graphene lead to foams with a 30% improvement in heat endurance, 17% reduction in noise transmission, 20% improvement in mechanical properties and an increase in compression strength between 20–30% [Ci] when compared to traditional non-graphene equivalents. The company's senior lead for emerging materials confirms the importance of graphene; "*It is a win-win for everybody: the customer gets a quieter car with a more heat-durable under-hood foam*" [Ci].

By the end of 2018, the Ford Mustang and F-150 both incorporated up to ten graphene components around their engines, including fuel rail and engine covers, to improve thermal management, mechanical endurance and reduce engine noise and vehicle weight [Ci, Ciii]. Improvement of these features, crucial to reliability, fuel efficiency, performance, assurance of safety, and marketability were all achieved without additional material cost [Ci, Cii], and have been used in the (approximately) 1,500,000 mustangs and F-150s sold since the end of 2018 [Ciii, Civ].

#### 4.3 [Text removed for publication]

Further products utilising graphene for its heat dissipation properties include: ski jackets (e.g. Colmar G+ Raptor), solid-state drives (T-Force Cardea Zero M.2 PCI-E), graphics cards (MSI RTX 3000), concrete additives (e.g. GS Graphene concrete modifier), air conditioners (The Elesia Air Cooling Unit EL-ACU-1000) and heated mattresses (Xiaomi blankets) [A, G].

Alongside these examples other products have reached the market exploiting additional properties of graphene. These include microbial resistance, exploited in antimicrobial coatings (GrapheneCA antimicrobial coating [G]) and electrical conductivity. This has been developed in a range of products including: inks (GRAPHINK, Cambridge Graphene inks [G] and Vorbeck materials inks [Aii]), antistatic bags for protection of electronics (GXT-EST bags [G]) and diagnostic sensors (Nanomaterial Diagnostics NHS Agile biosensor chip [Ai], VIS-SWIR linear array detectors [G], CN2 Nanobioelectronics Q-Sense GO [Aii]).

#### Summary

The three companies provide examples of the reach of impact from using graphene in their products; all three have resulted in the improved performance capabilities of products. Using estimates for total cumulative graphene production revenue (just for the material itself) within the window 2013 to 2020 [H], and using a conservative estimate for product mark-up of a factor of 100, the total revenue generated, in this REF period, from products containing graphene would be in the range of between GBP5,000,000,000 and GBP50,000,000,000.

#### 5. Sources to corroborate the impact

- [A] Compilation of Graphene-info.com web-pages:
- i. *10 graphene-enhanced products already on the market* (December 2017) Available at <https://www.graphene-info.com/10-graphene-enhanced-products-already-market>;
  - ii. *Graphene products introduction and market status* (April 2020) Available at <https://www.graphene-info.com/graphene-products>.
- [B] Letter of support from Chief Operating Officer, Inov-8, February 2021.
- [C] Compilation of media sources to support claims of impact on Ford Motors:
- i. Rubbernews.com article "*Ford finds graphene helps PU rise to challenges*" (February 2019) Available at: <https://bit.ly/3tKHqz3>;
  - ii. Rdworldonline.com article "*Ford XG Sciences Go Under the Hood with Graphene*" (January 2019) Available at: <https://bit.ly/3jASYQJ>;

iii. Motorauthority.com “Ford Mustang is the world’s best-selling coupe again” (April

2020) Available at: <https://bit.ly/370VIlv;>

iv. Autoweek.com “Ford averages over 100 F-150 Pickups Sold per Hour, 24/7” (June

2020) Available at: <https://bit.ly/3awKM15;>

[D] – [F] [Text removed for publication]

[G] Graphene Flagship website (December 2020) “*Graphene Product Gallery 2019 and 2020*” Available at: [https://graphene-flagship.eu/innovation/products/.](https://graphene-flagship.eu/innovation/products/)

[H] Reiss, T., Hjelt, K. & Ferrari, A.C. (2019) Graphene is on track to deliver on its promises. *Nat. Nanotechnol.* 14, p907–910 DOI: [10.1038/s41565-019-0557-0.](https://doi.org/10.1038/s41565-019-0557-0)