SUSTAINABLE MULTIFUNCTIONAL COMPOSITES: FROM ENERGY EFFICIENT MANUFACTURING TO SMART APPLICATIONS

H. Zhang[1*], Y. Liu[1,2], Y. Wang[1], X. Yao[1], S. Huo[1], E. Bilotti[1], T. Peijs[3]

[1] School of Engineering and Materials Science, Queen Mary University of London, Mile End Road, London, E1 4NS, UK, [2] Department of Materials, Loughborough University, Loughborough, LE11 3TU, UK, [3] Materials Engineering Centre, WMG, University of Warwick, Coventry, CV4 7AL, UK

* Corresponding author: han.zhang@qmul.ac.uk

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ABSTRACT

In this presentation, recent advancements in sustainable multifunctional composites research will be discussed. Specifically, we will focus on the development of an energy efficient and safe out-of-oven composite manufacturing process, based on a smart nanocomposite surface layer consisting of graphene nanoplatelets and polymer matrix. Self-regulating heating for composite curing has been achieved via the positive temperature coefficient (PTC) effect of the surface layer, with a significantly enhanced energy efficiency compared to traditional oven curing. The underlying mechanisms of PTC effect as well as the tuning strategies to achieve a double PTC effect for two-stage epoxy curing will be explored. This approach not only offers a highly energy-efficient method for manufacturing composite materials but also integrates multifunctional properties to the composite structures such as strain/damage sensing for online structural health monitoring and de-icing.

With the increasing amount of advanced composite materials employed in various fields like aerospace, automotive and renewable energy, the environmental impact of composite industries has gained more attentions than ever. It is well acknowledged that high performance fibre reinforced plastics (FRPs) can provide lightweight solutions in many structural applications, especially compared to the traditional metal counterparts to achieve higher fuel efficiency and less environmental impact during their usage period. However, in order to stimulate sustainable development of composite materials, both manufacturing stage of FRPs and components' end-of-life options should be borne in mind, where energy efficient manufacturing methods are of great necessity. From energy and capital intensive autoclave few decades ago, to nowadays out-of-autoclave manufacturing methods like vacuum assisted resin infusion and vacuum assisted resin transfer moulding, great efforts have been made in this field to the reduce end-use energy in composite manufacturing.

The advance of carbon nanomaterials like carbon nanotubes (CNTs) and graphene nanoplatelets (GNPs) over last decade has enabled another step towards energy efficient manufacturing of composite materials, with out-of-oven curing performed based on Joule heating effect of percolated conductive network [1-4]. Lee et al. reported an out-of-oven curing technique via resistive heating of an aligned carbon nanotube film, which could be detached after curing. The energy consumption was reported to be over two orders of magnitude lower (14 vs. 0.1 MJ) as compared to the oven cure baseline [2]. Xu et al. fabricated a large scale CNT film as heating source to perform the in-situ curing of glass fibre reinforced plastics (GFRPs), leading to outstanding uniformity in thickness, surface resistance and temperature, using only one seventh of the energy consumption of the oven curing process [3]. Although the extremely high heating rate together with high thermal conductivity of these carbon nanomaterials have also brought safety concerns and risks of overheating and subsequent burning and fire hazards.

In this presentation, a highly energy efficient and intrinsically safe out-of-oven manufacturing method that has been developed for advanced composites [5] will be presented at the conference. Self-regulating heating based on positive temperature coefficient (PTC) effect has been achieved with percolated GNPs in HDPE matrix [6-7]. The fabricated GNP/HDPE nanocomposite film with intrinsic self-regulating heating capability has been embedded and employed to perform curing of thermoset based composites without risk of overheating and without an oven as well.

Both temperature and energy consumption during the out-of-oven curing process have been monitored and recorded, with a more than 90% of energy consumption saved compared to traditional convection oven curing (Figure 1). Systematic characterisation such as DSC and DMA have been performed to examine the curing degree as well as thermal mechanical properties like Tg, with no obvious different between two curing methods.

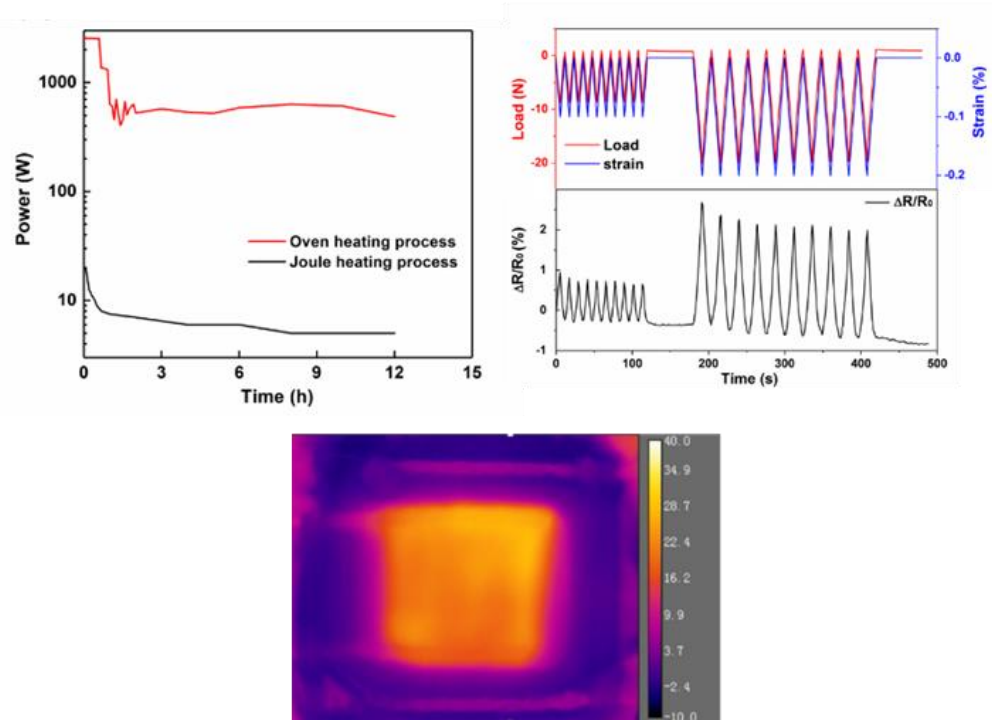

Figure 1. Power consumption comparison between oven curing and current sustainable out-of-oven curing; strain sensing performance under cyclic flexural loading; and Joule heating based de-icing performance [5].

After the composite laminate was cured, the nanocomposite layer is embedded on the surface of the laminate and being utilised as a smart multifunctional layer. Figure 1 (top right) shows the *in-situ* electrical sensing signals for the current multifunctional composites under flexural loading conditions, with clear and consistent sensing signals upon each loading cycle. The de-icing capabilities based on Joule heating has also been examined and presented in Figure 1, indicating very good heating capabilities based on embedded nanocomposite film. To satisfy two stage curing of many high performance resin system, a binary polymer matrix consisting of HDPE and PVDF has also been developed for GNP nanocomposites, achieving double PTC effect for two-stage curing requirements.

In short, the current sustainable and safe out-of-oven manufacturing based on the PTC effect of nanocomposite layer provides not only a highly energy efficient manufacturing method for composite materials, but also integrated strain/damage sensing capabilities for online structural health monitoring, as well as de-icing for extreme environment. The multifunctional composites also provide great flexibility for complex shape manufacturing since polymer nanocomposite films can be easily made with desired dimensions. Capital costs also can be saved compared to autoclave or oven curing methods. The great preservation of laminate original design with no effects on internal structures has also enables high compatibility with current composite manufacturing and applications, providing great potential for sustainable development of composite industries with reduced end-use energy from manufacturing stage.

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REFERENCES

[1] B. Mas, J.P. Fernández-Blázquez, J Duval, H Bunyan, J.J. Vilatela. Thermoset curing through Joule heating of nanocarbons for composite manufacture, repair and soldering, Carbon 63 (2013) 523-529.
[2] J. Lee, X Ni, F Daso, X Xiao, D King, J.S. Gómez, T.B. Varela, S.S. Kessler, B. L. Wardle. Advanced carbon fiber composite out-of-autoclave laminate manufacture via nanostructured out-of-oven conductive curing, Composites Science and Technology 166 (2018) 150-159.
[3] X. Xu, Y Zhang, J Jiang, H Wang, X Zhao, Q Li, W Lu. In-situ curing of glass fiber reinforced polymer composites via resistive heating of carbon nanotube films, Composites Science and Technology 149 (2017) 20-27.
[4] T. Xia, D Zeng, Z Li, R.J. Young, C Vallés, I.A. Kinloch. Electrically conductive GNP/epoxy composites for out-of-autoclave thermoset curing through Joule heating, Composites Science and Technology 164 (2018) 304-312.
[5] Y. Liu, T. van Vliet, Y. Tao, J Busfield, T. Peijs, E. Bilotti, H. Zhang. Sustainable and self-regulating out-of-oven manufacturing of FRPs with integrated multifunctional capabilities, Composites Science and Technology 190 (2020) 108031.
[6] Y. Liu, H. Zhang, H. Porwal, W. Tu, J. Evans, M. Newton, J. Busfield, T. Peijs, E. Bilotti. Universal Control on Pyroresistive Behavior of Flexible Self-Regulating Heating Devices, Advanced Functional Materials 27(39) (2017) 1702253.
[7] Y. Liu, et.al., Pyroresistivity in conductive polymer composites: a perspective on recent advances and new applications, Polymer International 68(3) (2019) 299-305.