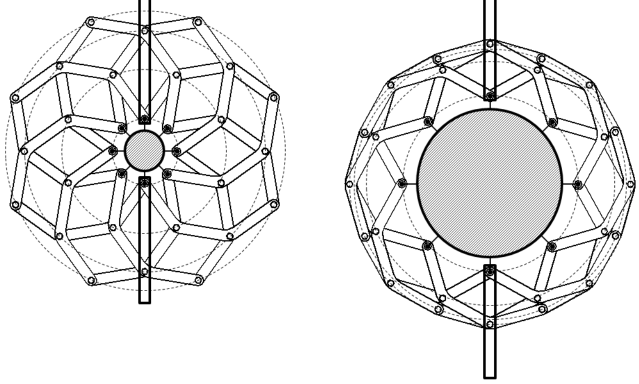
Streamlining a testing process

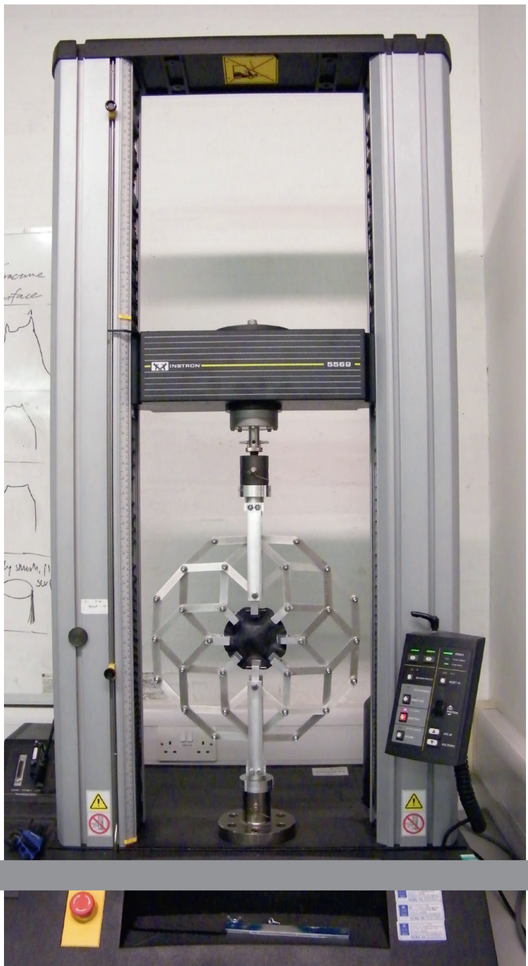
Rhiannon Garth Jones talks to Dr Davide De Focatiis about the development of a novel mechanism for biaxial testing at the University of Nottingham.



Biaxial tests replicate conditions of biaxial stress, such as the inflation of a balloon, or of a pressurised container. Engineering components are generally subjected to multiaxial stress states in service and the availability of biaxial data helps in the design of such components, as well as adding confidence to material models intended to capture such complex stress states. However, very few laboratories house full-scale biaxial testing machines, in part because of the expense. Dr Davide De Focatiis, from the University of Nottingham, UK, has developed a simple attachment that retrofits onto uniaxial testing machines to allow biaxial tensile tests of sheet materials. This mechanism is a simple and inexpensive route, enabling biaxial material data to be obtained easily from polymer films, fabrics and rubbers.

The University of Nottingham has its own full-scale biaxial testing machine, in De Focatiis' research group, but frequent requests for external testing drove him to look for an alternative. Given that most laboratories involved in materials testing have uniaxial test machines, could an adapter be employed to allow everyone to carry out biaxial tests with their existing uniaxial equipment? This has been the focus of the group's research over the past two years, and they believe they have successfully devised such a mechanism. When the adapter is attached directly to a uniaxial testing machine, biaxial tensile stress data can be obtained.

Several prototypes based on the same family of mechanisms have now been built from simple components and employed to test sheet materials from rubber and polymer sheets. The test fixtures are easy to operate and require only circular disc specimens, reducing training and sample preparation times. De Focatiis says the data from these is reliable and in agreement with data obtained on a full-scale biaxial machine. The fixtures are currently being applied to help with the design of elastomeric and polymeric components in the manufacturing and energy sectors.



Opposite: **A sheet of silicone rubber sputtered and held in an 8-clamp biaxial stretching device ready for digital image correlation strain mapping.**

Left: **The first biaxial stretching prototype, mounted in a standard uniaxial testing machine.**

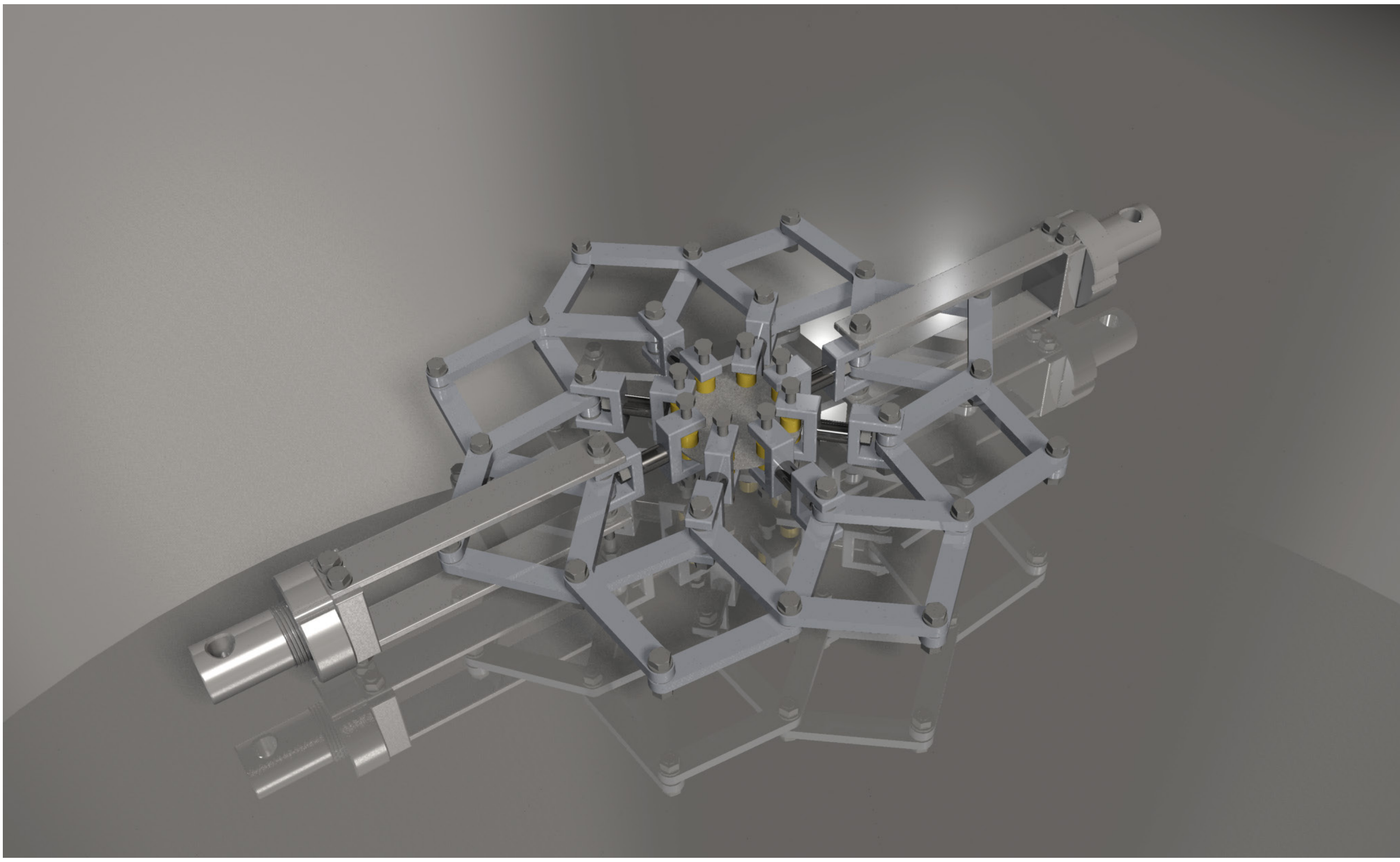
Getting started

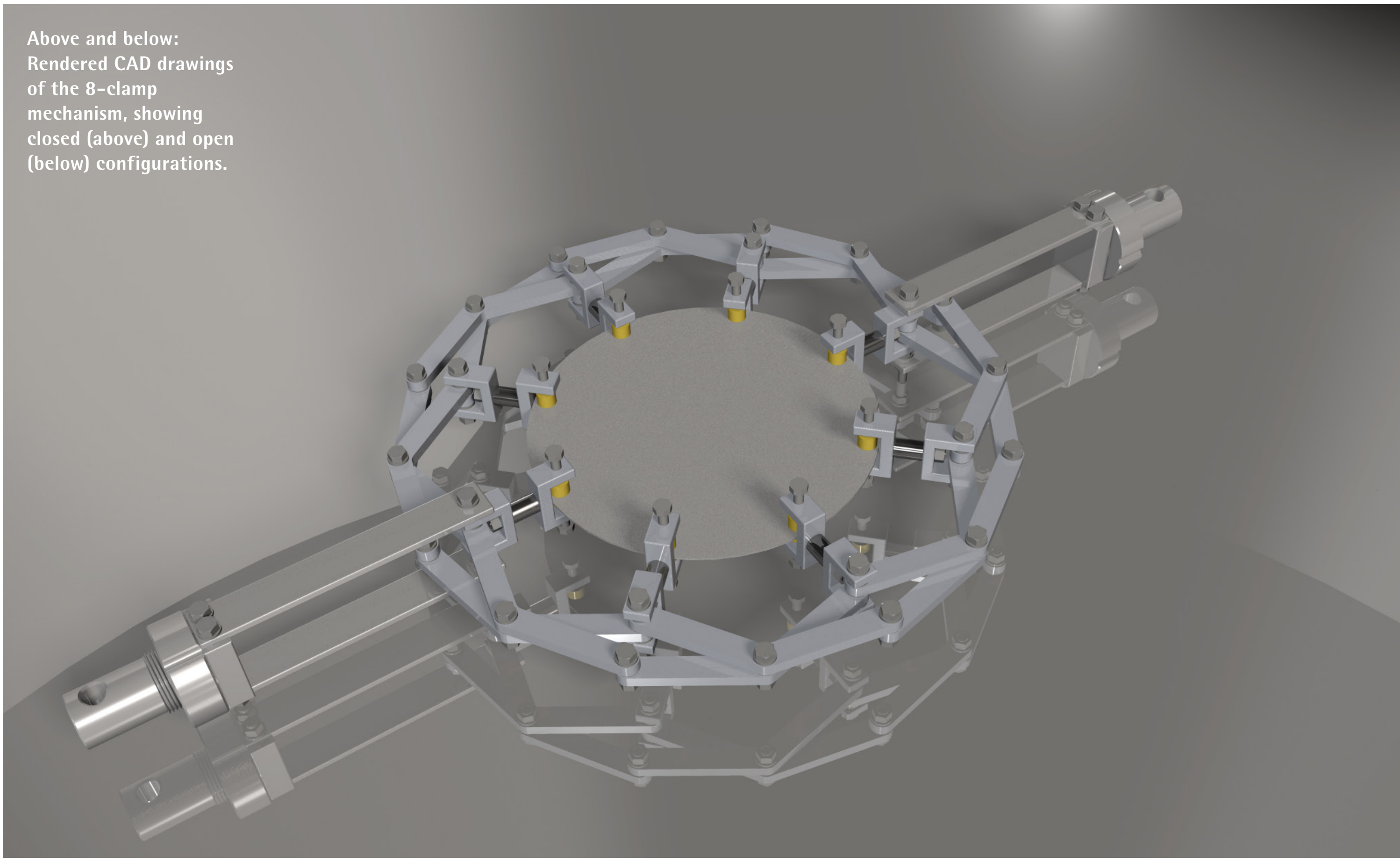
Although uniaxial stress testing is used extensively in industrial and research environments, biaxial stress testing equipment has historically been scarce, expensive and complex. Typically, commercial biaxial machines consist of two perpendicular uniaxial machines and require customised geometries known as cruciform specimens. Some custom-built sheet-stretching biaxial machines exist, but there is as yet no standard for biaxial testing in the industry. Few laboratories can afford the cost of ownership and of running such machines. Ideally, biaxial testing would be carried out on existing uniaxial machines, using only an adapter, which is why De Focatiis and undergraduate engineer Sam Kelly set out to create such a prototype in 2014.

Several attempts have already been made at devising mechanisms that could convert a rectilinear motion from a uniaxial machine to some form of biaxial extension, but they all suffer from problems, ranging from friction to poor sample accessibility. De Focatiis was aware of a theoretical study of cyclic mechanisms by Zhong You and Sergio Pellegrino, then both at the University of Cambridge, UK, based on the timeless principle of the lazy tongs. One family of these mechanisms had all the prerequisites for application to biaxial testing, and they quickly began to adapt the design and build a prototype.

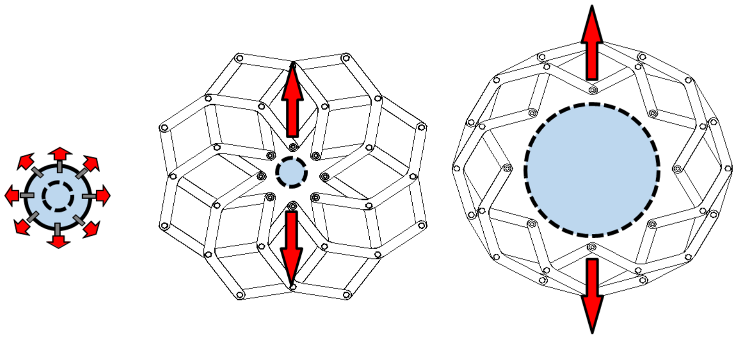
The first adapter they constructed was assembled from 16 identical angled bars, pinned together at the joints using nuts and bolts. At the centre were eight identical material grippers arranged in a circle, where the test specimen was attached. Two diametrically opposite grips were connected directly to the uniaxial test machine, using rigid linking bars. When the uniaxial machine moved its cross-head, the mechanism's single degree of freedom ensured that all the grips moved radially outwards. This resulted in an equibiaxial expansion of the material held in the grips, and hence a biaxial state of stress.

Working in the University's Faculty of Engineering, what the team discovered was that, for isotropic materials, both biaxial stress and strain could easily be computed using the displacement of the cross-head and the existing uniaxial machine's load cell. Only simple circular specimens were required, and the mechanism's design allowed unimpeded access to the specimen throughout the test, useful for video strain monitoring, heating and other *in situ* characterisation.





Above and below: Rendered CAD drawings of the 8-clamp mechanism, showing closed (above) and open (below) configurations.



Crossing into commercialisation

This caught the attention of the University's Technology Transfer team and, after Kelly's graduation in the summer of 2014, funding was put in place to expand the research further and to develop commercialisation opportunities. Potential users were sought, and representatives from rubber component manufacturers Trelleborg Industrial AVS and Fenner Precision came on board to assist.

The focus of De Focatiis' research group is the study of solid-state properties of polymers, and facilities include a custom-made twin-axis biaxial machine originally designed, built and refined by Professor Paul Buckley and colleagues at the University of Oxford, UK, over many years. Tests from this biaxial machine could be used as a direct comparison to data obtained with the new mechanism. After some minor technical improvements to the gripping arrangements, additional load cells were placed at the grips, and biaxial experimental data was collected on three types of sheet rubber materials using both instruments. Considering that the new mechanism was built for a few hundred pounds in a few weeks using simple components, the agreement in the data obtained from the two devices was remarkable.

The availability of biaxial test data for rubbers is essential in the process of fitting hyperelastic models. The use of both uniaxial and biaxial experimental data provides more confidence in material parameters for models intended to predict multiaxial deformations in real components such as anti-vibration mounts and diaphragms. According to De Focatiis, the ease with which the biaxial data can now be obtained ensures that new material formulations can be considered more quickly and that simulations are more accurate.

In 2015, the team was able to put the prototype to use in collaboration with Dr Lee Harper from the University's Polymer Composites group. This group collaborates with several UK automotive manufacturers on vacuum pre-forming of carbon composite parts. The forming machines use silicone diaphragms to help shape carbon fibre fabrics into pre-forms, prior to resin infusion. Using the new mechanisms, biaxial tensile stress data was collected in a few days to compare the performance of several silicone diaphragm candidate materials. Material models were fitted to the combined biaxial and uniaxial data, and complex forming simulations could be run to compare the final forming performance, with confidence that the complex 3D deformation of the diaphragms could be relied upon.

De Focatiis and Kelly also identified several variants of the mechanism that allowed different numbers of grips to be fitted. This influences the homogeneity of the biaxial strain in the test specimen, an aspect the team explored using new prototypes and digital image correlation equipment. In addition, the number of grips, and hence of mechanism links, also affects the maximum biaxial extension that can be achieved – with current prototypes, this is greater than 100% strain and could be increased further. The team filed a patent application in early 2015.

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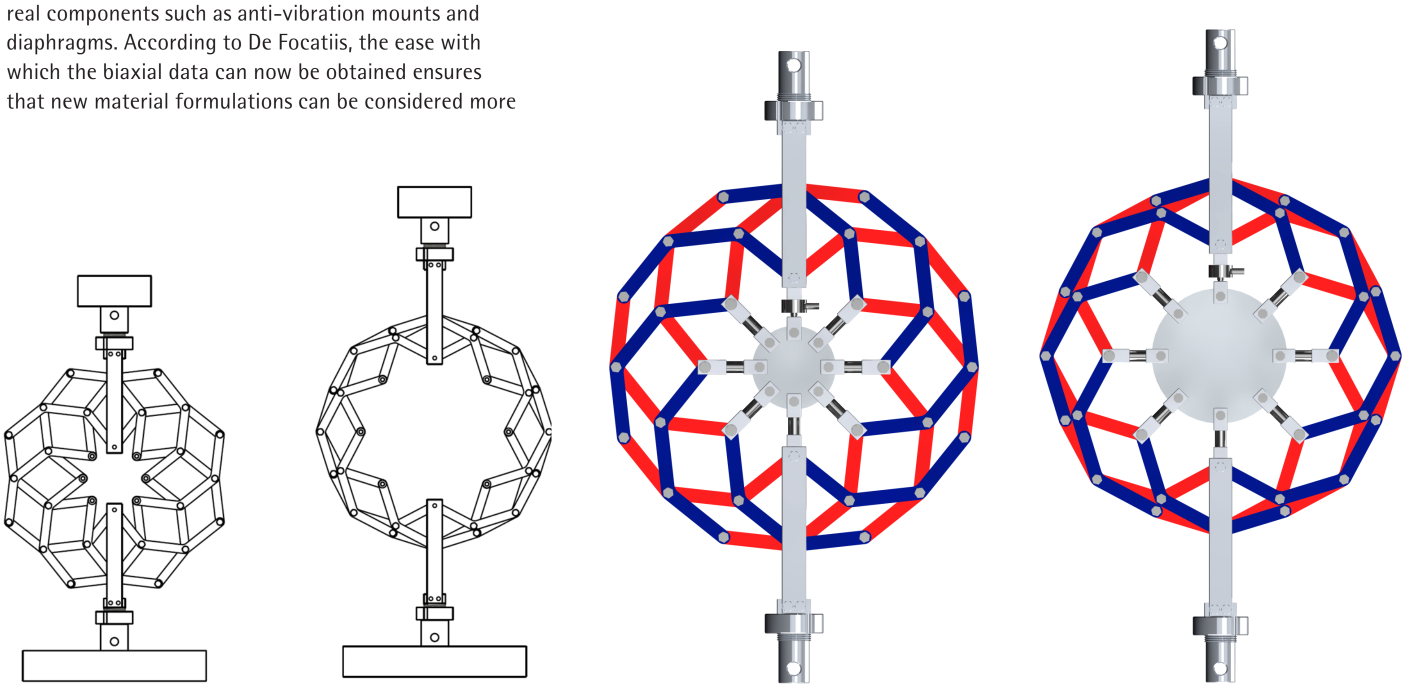

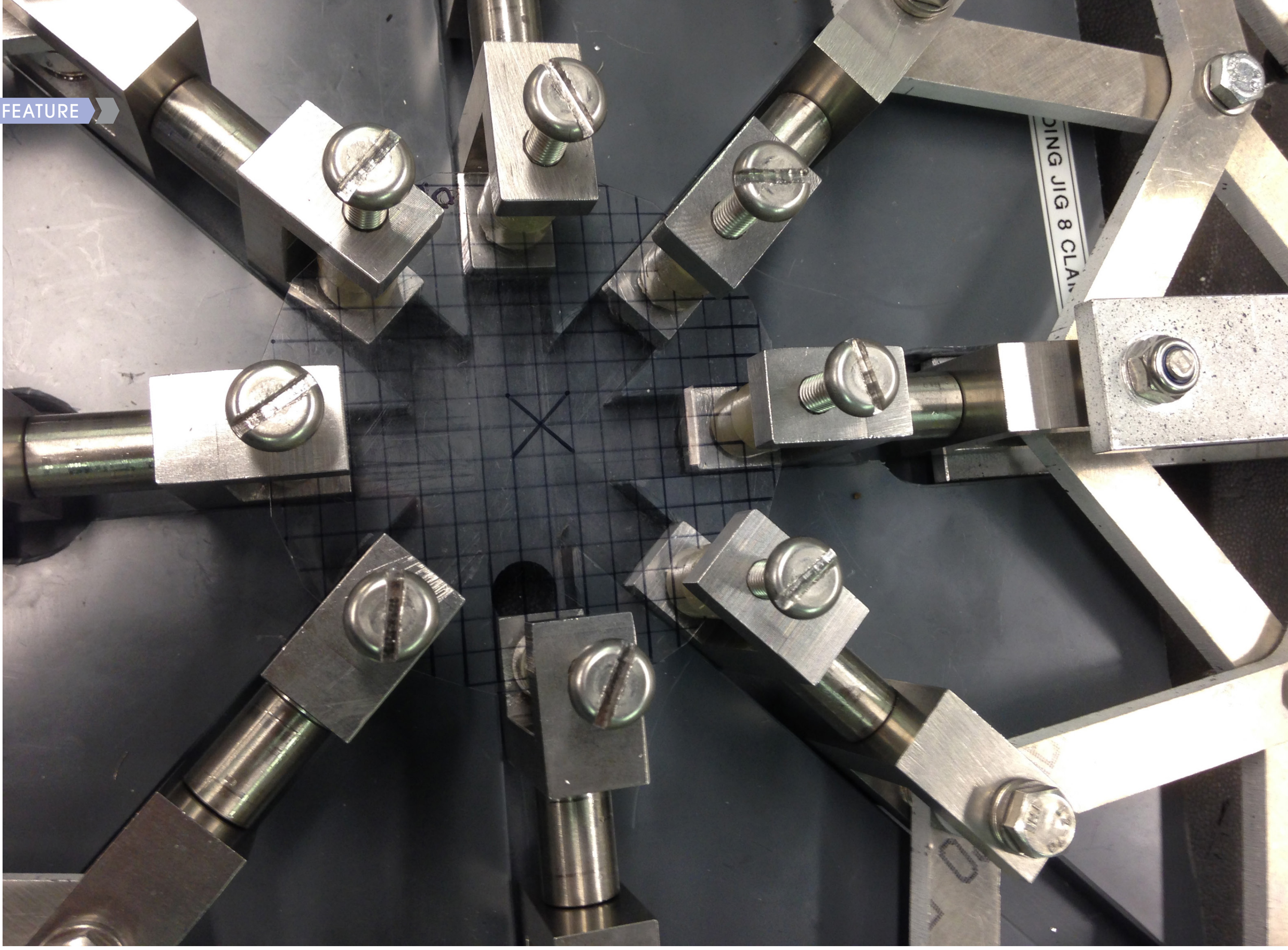

Above: **A specimen of bottle-grade PET film marked up and mounted in the 8 clamps prior to heating and biaxial stretching.**

The next step

Currently, the prototypes assembled are only suitable for carrying out equibiaxial tests, where the deformation is equal in two perpendicular directions. A twin-axis biaxial machine does not have this restriction. The team has now engaged the help of Dr Andras Lengyel, an expert on mechanism kinematics from the Budapest University of Technology and Economics, Hungary, to explore whether this restriction can be relaxed using a more complex arrangement of bars. Nevertheless, using embedded load cells in the grips, it is currently possible to quantify material anisotropy. This arises in extruded polymer films, rolled rubbers, and fibre-reinforced materials.

More recently, the biaxial mechanism has been applied to a collaborative project with Dr Lorenz Gubler, leader of the Membranes and Electrochemical Cells group at the Paul Scherrer Institute, Switzerland. The Swiss group produces an economical ion exchange membrane that could greatly reduce the cost of electrochemical energy storage and conversion cells such as fuel cells, by functionalising commercially available ethylene-tetrafluoroethylene (ETFE) films. Smaller versions of the biaxial mechanism can fit directly inside environmental test chambers, and were successfully used to stretch PET film close to its glass transition, simulating the bottle-blowing process. Here, the mechanisms are used as a process rather than a test, helping to lock in molecular orientation. It is hoped that hot biaxial stretching of ETFE films could lead to similar improvements in mechanical performance as those seen in PET, and hence to improved cell performance and longevity.

Costs and complexity have limited the availability of biaxial testing and stretching equipment in material testing laboratories. The simple mechanisms adapted for this purpose by the University of Nottingham's researchers have real potential to become a standard add-on to uniaxial test machines. The increased use of such testing is certain to improve understanding of material performance, and should, over time, promote the development of biaxial test standards. The team is now working with the Technology Transfer Office at the University of Nottingham to engage with partners interested in commercialising the mechanisms.

For more information, email **davide.defocatiis@nottingham.ac.uk**

Dr Davide De Focatiis is Associate Professor in Engineering at the University of Nottingham. He is a graduate of the University of Cambridge, and obtained his DPhil in Engineering at the University of Oxford, where he also worked as a Research Assistant. In 2009 he was appointed to a Lectureship at the University of Nottingham.

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