Cranfield University

Manufacturing and materials week

The green recovery

30 November-3 December 2020

Report

Manufacturing 2075

Post Covid-19 paradigms in manufacturing of material

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Foreword

Professor Mark Jolly
Director of Manufacturing,
Cranfield University

Manufacturing and materials week included a mix of live debates, lectures, workshops and pre-recorded videos, looking at the challenges the industry faces right now, as well as how we must adapt and innovate to support future global challenges such as achieve a Net Zero manufacturing sector by 2050.

The inaugural week-long event that built upon long standing events such as the Manufacturing alumni awards, the National Manufacturing Debate and Manufacturing 2075 gave the opportunity explore the pivotal role of manufacturing in everyday life. Taking these events to the next level, the week showcased that society needs to accept manufacturing as part of our lives and how it can support our future. Our digital devices, tables and chairs, right down to our pots and pans – all part of manufacturing! But they use resources, materials and energy, and so as a population, we must be responsible custodians of our planet for the sake of future generations.

Through research and teaching, Cranfield University, alongside industry is working to solve problems of the future. Post Covid-19, manufacturing has the potential to address important psychological and social challenges.

Manufacturing 2075

Post Covid-19 paradigms in manufacturing of material

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Welcome and introduction

This year's Manufacturing 2075 event was centred on post Covid-19 paradigms in manufacturing and materials. Welcoming a broad audience of senior business decision makers, academics, members of the industry, and Government, Krzysztof set the challenge for the day: to analyse manufacturing resilience and consider strategies to support our future.

Professor Krzysztof Koziol
Head of Enhanced Composites and Structures Centre, Cranfield University

We have learnt many lessons over the past ten months. Covid has made us stop and think about the materials we use and the products we manufacture. How can what we have learned over the past year help us to prepare for future disruptions?

Krzysztof touched briefly on his own experiences. During the pandemic, we saw an increase of 115 million in the requirement for surgical rubber gloves, presenting both a massive manufacturing challenge and creating a major environmental impact. Synthetic rubber takes over a 100 years to biodegrade and with the equivalent of 25 Empire State buildings filled with gloves used this year alone, Krzysztof and his students have been working with Malaysian company, Meditech Gloves, to create a long-term solution using natural rubber.

It is clear that in this post Covid-19 paradigm shift, healthcare will be a major beneficiary. Covid has presented opportunities for the rubber industry far beyond gloves. To make manufacturing more resilient and able to prepare for the future, we must look at the entire supply chain and create a centralised approach.

Keynote presentations

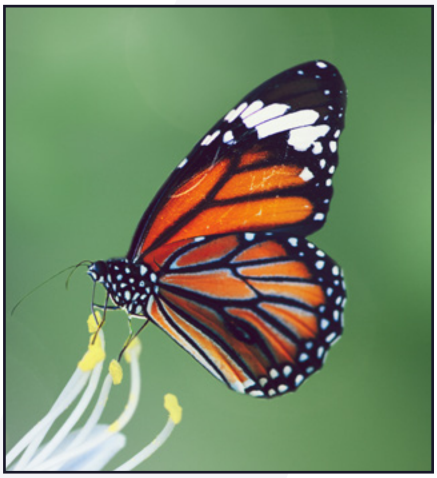
Professor Oliver Pearce
Consultant Orthopaedic Surgeon,
Milton Keynes University Hospital

In his presentation, Oliver presented the challenge of surface infections in medical implants. In the UK we complete 200,000 hip and knee replacements per year, with ten times this completed in the United States. There is an infection rate of 1%, meaning that in the UK we have to deal with 2,000 infections per year at a cost of between £20,000-£100,000 each to successfully treat. This presents an annual bill of between £40-£200 million!

While acute infections are relatively easy to diagnose, chronic or late infections are not as straight forward. Investigations to diagnose infections range from blood tests, X-rays, scans, fluid aspirations and laboratory tests. The treatments also differ depending on early or late infections of the prostheses. Early diagnosis (up to three months) seeks to preserve the prosthesis, washing out the wound and treating with IV antibiotics for up to six months. As you might expect, late presenting infections require more invasive treatment, with two stages of revisions, including an operation to remove the metal and infected tissue, and a second to re-implant the prosthesis.

It is very difficult to eradicate prosthetic infection. Bacteria on prostheses are able to defend themselves from antibiotics and the immune system. The bacteria is a biofilm that acts as a mechanical barrier to antibiotics. If the biofilm is well established, washing out the wound simply won't work.

What has this got to do with materials and manufacturing we may ask? Oliver worked with Cranfield University on an article in the Applied Physics journal on the bactericidal (kills bacteria) effects of nature - in this case a dragonfly's wing - and how we can apply these in medical treatments. The dragonfly wing, due to its surface nanopillars, is actually harmful to any bacteria it comes into contact with.



Orthopaedic nirvana

A material surface that can actually kill bacteria and stop infections - this is simply brilliant and as Oliver exclaims, "Orthopaedic nirvana!". The question is, how can we create biomimetic surfaces, those which mimic those found in nature, for our purposes here?

There are examples of super hydrophobicity (repels water, in this context preventing bacterial adhesion) in the lotus and taro leaf as well as the butterfly wing. Shark skin has antibiofouling (prevents adhesion) properties. It is not just in the organic world that we see materials with bactericidal properties. Copper and silver chemically are chemically bactericidal and can (and has) be used to coat prostheses.

On these surfaces bacterial movement results in the membrane tearing, with nanopillar heights and diameter determining whether a surface is more or less bactericidal. Bacteria is generally negatively charged and if the surface is also negatively charged, repulsion will be dominant - meaning that the more positively charged the bacteria, the more bactericidal the substrate is.

There are two types of bacteria: Gram positive and Gram negative. The former has a thicker cell wall than the latter. Therefore they exhibit different properties in response to different surface topgraphies and we may require different designs to treat different types of bacteria.

Oliver's vision for prosthetic surface topography in broad principles focus on not changing the material of the implant (cobalt chrome, titanium, stainless Steel) as these are well proven, long lasting, and bio-inert. Instead we should look at changing the surface topography of these material to be bactericidal through additive or subtractive methods.

Oliver concluded with a call to arms to the engineering community. "You are the high precision engineers and chemists. This is a scientific challenge and we, the doctors and our patients, will benefit from your help."

The UK has a quicker readiness for smaller reactors if the volume is there and this encourages investment from the supply chain. All the advanced methods that are being developed in manufacturing can be put into a smaller reactor plant that is not yet even at final design stage. While larger reactors are already designed, for the smaller reactors we are yet to determine that method and so this offers massive opportunities for the UK supply chain.

In conclusion, while there are capacity challenges, the UK can manufacture small reactors. This will require investment through the supply chain and timing will be key; to develop the reactors against the timescale, to achieve net zero targets and to enable export opportunities. The infrastructure and innovation is all there already but we need to work better and smarter, towards a shared objective.

Dr Iva Chianella
Senior Lecturer in Advanced Functional Polymers, Cranfield University

Point of care diagnostics are put simply, tests carried out via portable devices or simple kits at home or in a clinic. They do not require us to send patient tests to a laboratory. Iva's presentation focused on point-of-care diagnostics, their material requirements and the future trends.

By analysing disease biomarkers, these tests can support the detection of disease including cancer, as well as infectious outbreaks. These technologies also allow us to develop personalised care, with the quantification of disease biomarkers helping to set drug levels as well as enabling patients to self-monitor and manage a disease, resulting in an improved quality of life.

These point of care diagnostic tests need to be inexpensive and quick, easy for the patient to use and as sensitive and specific as a lab test, giving quantitative results. They also must be reliable, have a long shelf life and critically, be profitable for the companies who manufacture them.

The majority of the point of care diagnostic market share is currently covered by a bio-sensor glucose meter for diabetes. Others include pregnancy and fertility tests, as well as tests for malaria, HIV, cholesterol and as we have seen recently, the antibody test for Covid-19. These rapid diagnostic tests rely on antibodies. Cheap, quick, disposable and easy to use, however there are also high incidences of false positive and negative and by simply giving qualitative data, it does not allow personalised care or chronic disease management.

Iva's work is considering alternative support materials to determine the content or quality of a material. Can we replace antibodies with more robust receptors eg. aptamers, to reduce false positives and negatives? Can we use other materials, novel nanomaterials (quantum dots) for example, to generate a signal and biosensors to offer a simple read out system?

Bio-sensors are currently well used in clinical applications, environment, security and food. It is a device or a test which can be used to detect the presence or concentration of a biological analyte, such as a biomolecule, a biological structure or a microorganism. Bio-sensors consist of three parts: a component that recognises the analyte and produces a signal (enzymes, antibiotics, synthetic receptors), a signal transducer (electrochemical, optical for example), and a reader device (smartphone).

The glucose meter has been the most successful point of care diagnostic test developed to date. Using a simple low cost strip and a cost effective, portable reader, the test reacts with glucose presence in blood - a catalytic reaction using a strong robust enzyme generating an electrochemical signal. As there is a high concentration of glucose in the blood, the sensor doesn't need to be highly sensitive and the test is generally accurate - as such it is a highly profitable for pharmaceutical manufacturers.

What can materials do to create similar bio-sensor devices for other analytes? Biomarkers for cancer are present in smaller amounts in the body. Nanomaterials (such as metal nanoparticles or graphene) could be used to increase the sensor surface area. For cancer diagnostics we would need to quantify a group of biomarkers using a novel transducer such as photonics crystals or optical fibres. Put simply, for it to work and be worth producing, the novel material must be low cost, robust, and suitable for mass production.

In conclusion Iva considered future trends. Even prior to Covid there was a marked increase in the development of point-of-care devices. Now we are seeing an even steeper curve to create more. Yet developing these devices is not just a challenge for material scientists. We need to work with the biologists, chemists, and computing experts - it must be based on the collaboration of multiple skill sets.

In 2018 Gatwick Airport was awarded the title of 'Most Innovative Airport in Europe'. Abhi started off his presentation sharing the scary newspaper headlines we have become accustomed to over the past few months. However he then pointed out that in fact these headlines were not from 2020, rather the 2017 winter season.

Abhi Chacko
Head of Innovation and Commercial IT Services, Gatwick Airport Ltd

Over the last year, the effects of Covid-19 have been unprecedented. We have suffered from two distinctive waves, the first being one of the most devastating. As we reach the end of our second national lockdown, we must start to take personal responsibility to improve our health and immunity because, though life has changed, air travel will return and we must work together to keep a balanced perspective to restore confidence in passengers who use our services.

It is hoped that the Government will begin to ease travel restrictions, so as an innovative airport, Gatwick has been preparing for the reopening of the airport.

Airports are centred around three things: passengers, bags and planes. Across all three areas, Gatwick is looking to the future:

- **For passengers:** Robotic car parking, autonomous bus/buggy, far-UVC light for disinfection, biometric journeys, and security screening to ensure passenger safety and comfort.
- **For bags:** Cabin bag screening using AI, UV tunnels to disinfect security rays, autonomous bag transfer, as well as digital lost and found.
- **For planes:** AI enabled aircraft turn, autonomous jet bridges, electric aircrafts, and foreign object debris detection - this is just the start.

Dr Abigail Hird
Knowledge Transfer Manager,
Manufacturing, KTN

In her presentation, titled 'Back to the future' Abigail used the popular Hollywood film trilogy to remind us that the past, present and future are wholly interconnected.

"Who controls the past controls the future; who controls the present controls the past."
George Orwell, 1984

Abigail started by questioning the notion that technology is the basis for the industrial revolutions we have seen over the past few centuries. Up until 1800, productivity and population were stable, with people living in a state of constancy. The shift came with war and the need to generate money to fund these endeavours overseas. Here in the UK we had access to coal and a massive labour pool, giving us a sense of control over the world around us. The mechanisation of processes created cumulative innovation. During the second industrial revolution we built the infrastructure to support building trade with the Far East, moving away from subsistence living, towards increased consumerism and alongside this, a massive population explosion. The third revolution saw automation, and the creation of intelligent connected learning systems - one of the major drivers of this being the space race.

Looking over the past year, we saw high energy costs and low unemployment - quite the opposite of the first revolution. So was technology the primary driver? Have there been multiple industrial revolutions - or is there just the one industrial revolution, one that we are still experiencing and living through today?

With 2020 having been a 'cracker of a year', with a global pandemic, political instability, climate change, and much fake news, what might the future look like if we look ahead to 2075? Clean, low-cost energy, and diminishing raw materials?

Perhaps we need to go back in order to progress forward. Could we earn and spend less? Should we adopt older models of industry? This is maybe a romantic aspiration but consider this: local manufacturing, shorter supply chains, lower volume production, smaller firms, more focus on material lifecycles, design for disassembly and reuse, greater automation, flexible employment models - this all sounds rather positive!

Abigail concluded with her thoughts on how we can prepare for the future:

- Don't overplay role of technology as driver of change.
- Develop skills for dealing with uncertainty.
- Re-conceptualise material lifecycles.
- Seek out views and perspectives that are different to our own.

Q&A

The pandemic has had a great impact on our lives, economy and society. What lessons can we learn from antibacterial surfaces that are transferable to virology?

Oliver Pearce - There are not many antibiotic surfaces in clinical use presently. The biggest one is silver coating. For example, in treating bone tumours we have to remove entire bone and replace with metal. The infections rates for this are close to 14%! Silver coating implants are now being used and this has reduced infections to 8%. However silver does not incorporate well into bone, so infection is reduced at the expense of bone incorporation. It can also be toxic to the liver and kidneys. Changing the surface may help one area but hinder another and cause unintended consequences.

How will you balance profitability with future needs of recycling materials? How do we tackle the increase in disposable plastics?

Iva Chianella - In order to be profitable there needs to be a disposable part of test or device. In the case of the glucose meter, for example, patients need to replace strips each time. In the future we need to look at biodegradable plastic. Material engineers can address issues and look to replace non-biodegradable with biodegradable material. However we haven't reached the next stage yet.

What type of policies/laws/support do we need from UK and overseas Governments to be more prepared in potential future events like another pandemic?

Abhi Chacko - Governments need to be prepared to deal with these situations in the future. The pandemic has seen a balance between keeping the economy open and managing hospital capacity. There will be more pandemics and lockdowns and so this balance needs to be addressed carefully. In terms of travel, I would encourage some sort of revenue recovery/tax in normal times which can support the industry through pandemics especially when it is the Government imposing restrictions. In the good times we are going to see more low-cost carriers launch, and yet with the slightest disturbance they fail. We need to create some balance.

We have to care for the future for the sake of our children, but how does this affect innovation?

Abigail Hird - Engineers love technology and sometimes we can be single-minded about its development. However we can't develop technology at the exclusion of the wider environment and market. We cannot assume that technology is the answer on its own.

Workshop outcomes - briefings by session facilitators

Technology and skills development of future role models
Dr Mohammed Afy-shararah, Cranfield University

This group looked at the factors that might impact manufacturing and materials as we look towards 2075. They identified the need for technology to improve our capability to reclaim precious materials, and to accelerate hybrid and additive manufacturing. A major concern was the growing cost of energy and power, with the workshop members looking to how the circular economy could be applied effectively.

On the skills required, the group focused on systems thinking and digital intelligence, but also recognised the need for these to work alongside softer skills to encourage communication and greater collaboration.

When asked how we can foster and encourage the development of skills, there was a diverse range of votes as to the most important factor. This ranged from collaboration, to a focus on STEM teaching in our schools, to encouraging technologists to meet across organisational and sector boundaries.

Manufacturing resilience to adverse perturbances
Dr Claudiu Giusca, Cranfield University

In this workshop the group considered how manufacturing resilience will be challenged in future. A current topic, they looked at the demand on NHS and how best to control supply chains moving forward. Should this be centralised or use localised smaller suppliers across the country? In general terms they identified that the biggest challenges are around collaboration within supply chains as well as needing to encourage young people to choose manufacturing as a career path.

They went on to consider which of these would have the most impact on the three areas companies look at in terms of risk: finance, supply and demand and their people.

- Demand for NHS - we need to increase the local availability of PPE, using smaller suppliers and localised supply chains. AI should also be utilised more in healthcare.
- Collaboration through the supply chain - agreed a similar focus to the ways in which we can deal with the demands on the NHS, alongside the use of on-demand systems by smaller local suppliers
- Encouraging young people into manufacturing - since the 1970s manufacturing has been seen as blue collar work but this is not the case anymore. Machining and materials have developed and we need to focus on continuing to change the image of the sector from blue to white coats.

Design of compliant long-life implants for minimum post-op intervention
Professor Oliver Pearce, Milton Keynes University Hospital

In this workshop Oliver set a challenge to solve the problems of infection in prostheses. While under no illusion this problem would be solved in a short workshop, the group did identify some high level thoughts on how this could be tackled.

They examined ways of finding the infection, not just passively but also being more active. For example a reactive detector on the surface of the prostheses to assess PH levels; whereby the surface releases a nano chemical when it becomes acidic. It will be toxic to bacteria but not to the organism.

They considered whether this should take the form of an antibiotic or nanoparticles, for example copper or silver, used to kill bacteria but not harm the patient. These could be structures that contain chemicals that can be naturally excreted by kidneys or detoxified by liver.

Concluding remarks

Professor Krzysztof Koziol, Head of Enhanced Composites and Structures Centre, Cranfield University

It is abundantly clear that this pandemic has been a disaster for people's lives and livelihoods. However we have to consider it a wakeup call to stop and think how we prepare for the future. It is a statistical certainty that this type of event will happen again.

Yet we must not allow whatever comes next to take us by surprise again. We must be prepared. As Oliver referenced, we must design materials better to make them more multifunctional and responsive to the environment. Sustainability and the biodegradable aspect is important. We cannot use materials that will cause problems in future.

As Abigail shared, collaboration and the creation of softer skills is fundamental. As is supporting our NHS, especially in terms of the local availability of materials that we need during a pandemic. The theme of localised manufacturing and the supply chain that enables this is a whole new session in itself - one for next year perhaps?

Restoring passenger confidence in flying post COVID-19: the role of technology and materials

Dr Thomas Budd
Lecturer, Centre for Air Transport Management and Academic Lead for Digital Aviation Research and Technology Centre (DARTeC), Cranfield University

Covid-19 and the resulting travel restrictions have had a devastating impact on the global air traffic industry. The reduction in passenger numbers across the industry, with many airlines grounding their entire fleets, and airports left empty, has dwarfed any of the air travel disruption we have seen in the past.

ICAO estimate that by the end of 2020 there will have been a decline in world traffic of between 57%-61%. The hope is that the demand for air travel will recover but it is clear that things will look rather different for the industry for some time.

The key to recovery rests in restoring passenger confidence, or bio-confidence, as it is often referred to, in travel. There are significant concerns among passengers around contracting the virus at some point during their air travel journey. A recent study by the global trade body for airlines, IATA, shows that the vast majority of people still feel concerned about contracting the virus while travelling. This is despite the significant efforts by the aviation industry to communicate scientific research that shows that air travel is less risky that other forms of public transport, particularly with regards to the on-board experience. The ventilation of air in the cabin and the high efficiency particular air filters used in modern aircraft designs are hugely effective in filtering out bio aerosols and other pollutants. Yet passengers remain concerned about sitting next to an infected person, being in crowded areas, such as the buses or trains that take you to and from the aircraft, and using restroom facilities. Air travel needs to address these areas in order to restore confidence.

Not just an issue as a result of Covid, this presents the industry with an opportunity to ensure greater health and safety benefits across the passenger journey, and to try and reduce aviation's role as a vector for communicable diseases. There are three sources of infection from air travel:

- Direct contact through coughing, sneezing and talking. This is likely to occur at congested areas, such as the gate, at security, boarding and disembarking.
- Indirect contact through touching contaminated surfaces, items or people. This can occur in touchpoints along the passenger journey, such as toilets, touchscreen check-in, security and In Flight Entertainment systems (IFE).
- Vectors such as mosquitos, flies or ticks, occurring in open air spaces where they can live and breed.

The focus of Tom's presentation was around indirect contact, with materials and technology able to play their role in removing physical touchpoints. Technology and smart systems are key facilitators of this, including gesture and motion control sensors for toilet doors, IFE or elevators. This type of technology is prevalent already but we are now seeing it increasingly applied in an air transport context. Biometrics, facial or iris recognition technology can be used for border and security control. Again, these were already starting to be applied in airports prior to Covid, but now there is a real motivation to employ these to reduce queuing and touchpoints.

We are seeing existing smart technologies applied in a bio-health, Covid-19 related context. Smart systems are also being used for cleaning and service provision. Sensors can be used to detect areas that are in high use in the terminal (toilets, seating areas) and this can trigger a decision to increase cleaning and sanitation in that specific area. That could take the form of a manual cleaning team, but also automated systems via AI and robotics to clean large areas of a terminal.

Other major areas relate again to cleaning and disinfection. There are two major areas:

Active cleaning

'Enhanced' cleaning of surfaces including the use of traditional disinfectants and also the use of UV-C light, used to kill bacteria and help against the spread of the virus. Cabin design can also play a role with an increased focus on the physical design of the cabin to create smooth surfaces (seats, cabin products) that are easy and quick to clean. Ryanair has removed seat back covers that hold magazines, with this really improving and speeding up the cleaning process.

Passive cleaning

Applying antimicrobial films and adhesives to existing assets. Some airlines have applied antimicrobial layers to their tray tables, with a visual identifier to reassure the passenger that this has been done. With a limit to what can be retrofitted in this way, there may be a role for incorporating antimicrobial additives and agents into the manufacturing process of those new assets from the outset - new trays, new on-board luggage storage. This of course comes with a price tag and will take time.

There are challenges ahead but with these come huge opportunities. Research and development will require financial investment, and operationally these interventions must drop into existing regimes with anything causing major change, unlikely to be successful.

On this journey we need to remain in contact with passengers, appreciating and understanding what they perceive to be safe and a benefit to them. Aviation is rightly renowned as a safe industry, with this reputation built on a rigorous and robust safety standards process. Any changes to air travel or to an airport environment will have to undergo considerable certification procedures which will take time.

Find out more about DARTeC's 360 VR conceptualisation of the future aircraft cabins.

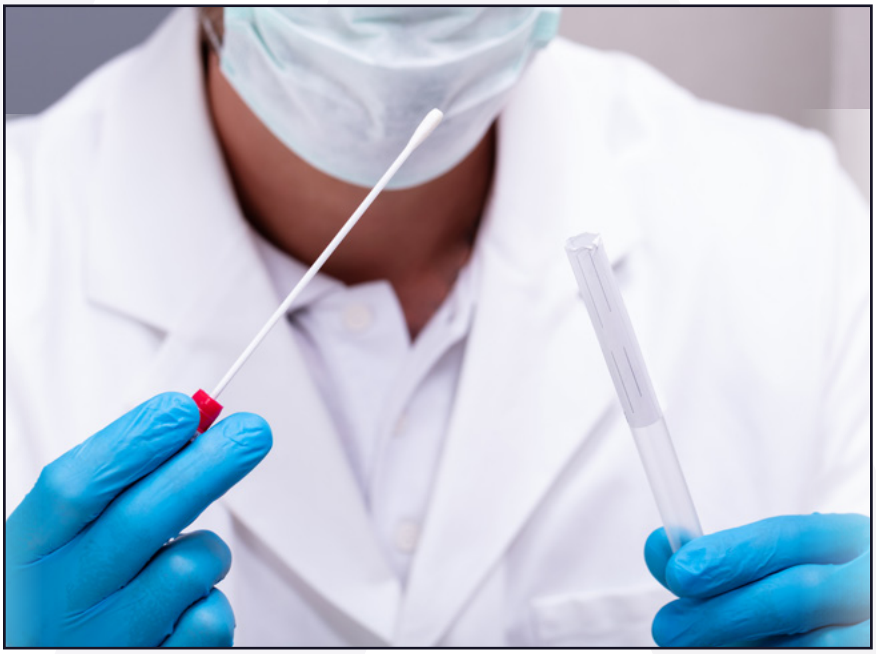
Professor Krzysztof Koziol
Head of Enhanced Composites and Structures Centre, Cranfield University

Sustainable production of rubber gloves

Cranfield is well known in terms of collaboration with industry and working to solve major problems that the industry faces. Head of the Enhanced Composites and Structures Centre at Cranfield, Krzysztof, is working on a project to sustainably produce surgical rubber gloves.

MediTech Gloves is one of the world leaders in examination and surgical rubber gloves and their aspiration was to create a sustainable process, eliminating some of the waste, both materials and energy, from the factory. The collaboration with Cranfield started more than two years ago but during the Covid pandemic this partnership strengthened significantly. MediTech found themselves in huge demand for their rubber gloves, with production doubling overnight.

There are two challenges around the creation of natural rubber gloves. One is the material and the second is the process. Cranfield's team helped MediTech improve the manufacturing process efficiency, and therefore also the time to get the final product. Rubber glove manufacturing is a complex process and to date there has been little innovation in this area, with the process taking about an hour from beginning to end.



PhD student Afiqah Salim Musa explained that the formulation of latex is critical, with some key ingredients and processes behind the formulation. In the latex there are naturally occurring protein species which can cause allergic reactions to more sensitive users. This has meant that historically people have opted for synthetic latex gloves. Yet as Krzysztof explains, natural rubber is far superior to synthetic in terms of sustainability. Synthetic gloves take more than 100 years to biodegrade, while natural latex biodegrades 100 times faster, in just one year. At Cranfield the team is working to remove the offending protein from the latex in order to encourage a greater use of natural latex gloves.

Furthermore, the team at Cranfield has perfected a new formulation for the manufacturing process that halves the time in which the gloves can be made. If there is another surge for gloves or a pandemic, the companies using the formulation from Cranfield will produce the gloves much faster. However the use of natural rubber cannot be increased overnight. We rely on plantations to produce the rubber and as such there is a whole supply chain that needs to gear up for the supply of natural rubber latex.

The latest reports show a figure of 780 billion gloves produced annually. If we were to switch entirely to natural rubber, considering the raw material and how it is made, we would save approximately 50% of the excessive CO_2 currently entering our atmosphere. It is not just about recovering from Covid, it is about aligning with our climate commitments. Natural rubber is the perfect opportunity for the industry to focus on sustainability. This clearly won't happen overnight but there is a real future in creating large enough supply chains in raw latex, not just solving the immediate problem of material availability but also providing the perfect product to support our efforts against the climate emergency. In using natural rubber as a material, the factory is as ecological as manufacturing gets - the factory itself is a tree, using carbon dioxide from the atmosphere, water from the ground, and energy comes from the sun.

Manufacturing and Materials Week closing remarks

Professor Mark Jolly
Director of Manufacturing,
Cranfield University

No one could have envisaged that in postponing our National Manufacturing Debate we would still be in lockdown in December 2020. A concept that grew out of a forced hand has opened up tremendous possibilities and led to a week of events with international speakers and audience that has benefited from the online format.

Twice this event, we heard reference to Industry 5, first by Dr Ayotunde Coker, winner of our Distinguished Manufacturing Alumni 2020, and during Manufacturing 2075 by Dr Abigail Hird of KTN. The reality is that 2075 will come around very quickly - some of you in this week's audience will be around to see and be part of it we hope! It really is up to you!

Save the dates

Manufacturing and materials week 2021
29 November–2 December 2021

National Manufacturing Debate
1 December 2021

Manufacturing 2075
2 December 2021

www.cranfield.ac.uk/manufacturingweek

Graphene commercialisation conference
15 March 2022

www.cranfield.ac.uk/grapheneconference

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