Continuous flow strategies for accelerated materials discovery

Polymerisation reactions play a crucial role in the design and optimisation of new materials for many existing and emerging technologies. The large commercial demand for tailored polymers requires developing innovative synthetic approaches that afford precision, control, and automation, while addressing environmental and workplace safety concerns. Dr Tim Erdmann and colleagues at IBM Research, Almaden Lab (USA), are exploring new synthetic routes based on continuous flow reactors for the synthesis of polyurethanes, integrating high product yields, fast processing, and exquisite control on materials properties. This work is part of the combined Accelerated Discovery programme at IBM Research, exploiting new approaches for the automation of chemical synthesis along with state-of-the-art computational methods and next-generation AI-based workflows for materials discovery.

Polyurethanes are one of the most important types of commercial polymers, with applications in a wide variety of industrial fields, including elastomers, coatings, adhesives, sealants, foams, hard plastics, and textile fibres. At a fundamental level, polyurethanes present a structure in which individual organic units (monomers) are joined together through chemical links (carbamate, or urethane groups) and impart their characteristic stability. Diverse classes of monomers with different physical properties can be used for the creation of these polymer chains, which ultimately allows for the creation of polyurethanes with a variety of chemical properties and an equally wide range of practical applications.

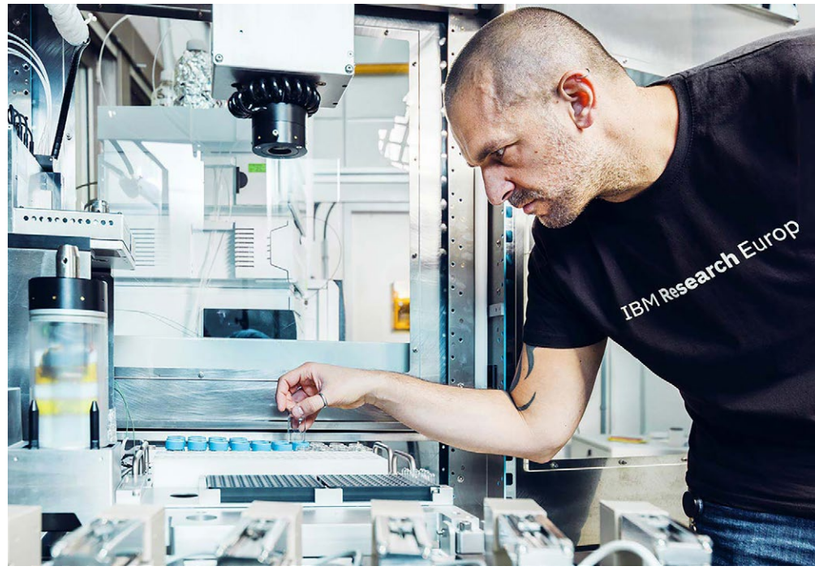
POLYURETHANE BATCH PRODUCTION

The industrial synthesis of polyurethanes exploits a process known as polyaddition, a polymerisation mechanism in which monomers initially form dimers, trimers, oligomers, and eventually create polymers with higher molecular weights. This synthetic route allows the properties of a product to be tailored for specific applications through a precise choice of starting materials, compositions, and post-processing methods.

Traditionally, polyadditions are carried out using batch reactors, in which large amounts of reactants combine to form the product polymer. Despite its versatility, polyurethane batch production has several limitations. For instance, imbalances in the relative concentrations of the reactants, the highly reactive nature of some of the chemical groups driving the polyaddition (such as the isocyanate group), and the exothermic nature of the reaction, can cause batch-to-batch variations and promote secondary reactions. These effects decrease the degree of control over the polymerisation and affect materials' properties and reproducibility.

CONTINUOUS FLOW

As an alternative to batch production, Dr Tim Erdmann and his collaborators at IBM Research have been exploring the application of continuous flow chemistry in the synthesis of polyurethanes. Flow chemistry is a class of production methods in which tubular reactors are used to constantly mix reactants and to run the reaction by continuously passing the reactive fluid through the reactor configuration. This allows for constant production, with no need to operate on distinct batches. Continuous flow processes have been applied as a robust alternative to tradition batch production in the chemical industry, in view of several remarkable advantages, including efficient mixing within the reaction medium, excellent heat transfer and temperature control, safe handling of hazardous species, and the ability to directly monitor the reaction parameters and to scale the reaction for mass production. Faster experiment turnaround also creates an opportunity for efficient AI-driven materials and process optimisation. Continuous flow systems have been used with outstanding outcomes in the synthesis of small molecules and polymers. However, their use in step-growth polymerisation reactions has been so far rather limited, owing to intrinsic complications for this class of reactions, such as the removal of condensates, the long reaction times, and the potential high viscosity of the reaction mixture.



IBM researcher Dr Teodoro Laino preparing the robotic tool integrated into IBM RoboRXN, a cloud-based AI-driven lab for materials synthesis.

REAL-TIME PROCESS CONTROL

The IBM team developed a series of continuous flow reactor configurations that enable the synthesis of linear polyurethanes with tailored soft to hard segment ratios at room temperature in three to five minutes. By using flow reactors the excellent heat transfer characteristics additionally allow for straightforward scalability of the reaction – the amount of polymer produced per time. Furthermore, their approach makes it possible to monitor in real time the conversion process using conventional spectroscopic methods, such as attenuated total reflection sampling in Fourier transform infrared spectroscopy (ATR-FTIR) along with custom software for device operation and data processing. This has allowed the IBM team to develop reaction-control strategies that render their approach dramatically superior to batch processing, in terms of materials quality, process costs and reproducibility. This work provides robust guidelines for the straightforward creation of libraries of commercially relevant polyurethane materials, with virtually unlimited possibilities for applications. For instance, continuous flow synthesis of polyurethanes can be of relevance in supporting emerging technologies such as 3D printing, for which it can provide on-demand high-quality polyurethane resins with customisable properties tailored to the printing process and product features.

ACCELERATING MATERIALS DISCOVERY

The IBM team's development of efficient and robust continuous flow technologies for polyurethane production is providing an approach for the creation of alternative manufacturing processes for large-scale production of on-demand polymeric materials. Current work within the research group focuses on extending continuous flow synthesis to polymerisation reactions with different underlying mechanisms. In particular, ring-opening chain-growth polymerisation reactions were extensively analysed in previous work. Group at Stanford University, has shown that, in continuous flow conditions, highly controlled polymerisation occurs at very high speeds and can readily be scaled up to yield the desired products at a rate of tens of grams per minute. Using different catalysts and an efficient catalyst switch strategy made it possible to create a library of 100 well-defined distinct copolymers in only nine minutes. Traditional approaches would have required one to two months to achieve the same result, making this a 5,000-fold speedup. This work demonstrates the substantial benefits of combining chemical innovation in (organo)catalysis with the use of flow reactors and customised software to develop more efficient ways for polymer synthesis and to broaden the scope of materials accessible.

Continuous flow reactors achieve superior efficiency in polymerisation reactions and afford virtually unmatched control over the polymerisation conditions.

The goal of this effort is the programmatic synthesis of polymeric materials with different characteristics, using inline real-time analytics techniques and the implementation of programmable continuous flow reactors enabling the high throughput preparation of materials libraries. To increase the materials output, reactors will be engineered to be remotely operated by software with minimum downtime between operations. In the case of polyester and polycarbonate homopolymers and block copolymers, the IBM team, in collaboration with the Waymouth

ARTIFICIAL INTELLIGENCE

It often takes more than ten years to design, synthesise, test, and introduce a new polymer material into the market.

IBM Research is forging the way ahead for modern materials discovery.

A variety of computational methods, such as combinatorial screening, generative models, or inverse design, can be exploited to accelerate the design of a new polymer. However, these methods generate huge numbers of potential molecules, which require screening by subject-matter experts, with the goal of selecting promising candidates for further investigation.

IBM Research has proposed a new approach based on an expert-in-the-loop methodology, in which candidate molecules are ranked according to a utility function that is trained through the continuous interaction with a subject-matter expert, but is also constrained by specific chemical knowledge. In practice, an AI model of a scientist's decision-making process for selecting promising candidates is trained and applied electronically. This can reduce screening times of 500 hours or more to less than one hour. Using this approach, the IBM team has been able to generate two new polymers with the desired properties from the dataset used in the evaluation, along with ten novel polymers of potential relevance in other application domains. In this work, AI has been applied to identify optimal catalyst/monomer matching based on sparse historical experimental data as well as to streamline the production of customised monomers that avoids the use of hazardous reagents, like triphosgene or chloroformate in the case of cyclic carbonate monomers.

The increasing integration of robotics and automation is central to IBM's programme for Accelerated Discovery.

NEW PARADIGMS IN MATERIALS DISCOVERY

The IBM team has shown the crucial roles of computational methods, AI, and innovative approaches to chemical device engineering in modern materials discovery. The work continuously carried out at IBM Research aims to extend these findings by creating synergistic workflows in which traditional human intensive work is augmented by automated processes, intensified use of robotics, big-data mining, and intelligent AI agents leveraging the knowledge behind the extreme amount of data.

One of the most important aspects of this effort is the ability to make use of the fast-growing literature on materials discovery and characterisation, in the form of papers, reports, and datasheets, to extract data and structure it for query and downstream use. IBM has developed a specific platform (DeepSearch) for this purpose. The data extracted from existing literature is vast but frequently incomplete, and it must be complemented by simulation. In this context, traditional physics-based approaches to materials properties, which can be very accurate but computationally intensive, can be bypassed using AI. These methods can be used to make accurate predictions about materials stability, solid-state properties and even the structure of proteins. AI can also be used to aid molecular design using generative models, which collaborate with human experts to widen materials design spaces and explore unexpected new structures.

Finally, at the end of a design cycle, one needs to accelerate the synthesis and testing of a potentially large number of candidate materials. This calls for the development of autonomous synthesis platforms. The work presented here is one of the most recent efforts together with RoboRXN, which integrates cloud computing, AI, and commercial automation to assist chemical synthesis. With faster, cheaper experiments, AI approaches like reinforcement learning will be used to quickly optimise synthetic strategies and reaction parameters. Emerging technologies, like quantum computing, will be integrated in these powerful and innovative frameworks, shaping the future of materials discovery.

The synergistic use of big-data analysis, machine learning, and automated synthesis is providing powerful new methods and tools for materials discovery.

Behind the Research

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Research Objectives

IBM Research is dramatically accelerating the materials discovery process. Its Accelerated Discovery approach harnesses the power of four fields of computing: AI, high performance computing, hybrid cloud, and quantum computing.

Detail

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Personal Response

What are the most important innovations that will impact materials discovery in the near future, particularly concerning polymerisation reactions of industrial relevance?

" In the near future, the improvement and intelligent integration of (i) automated robotic tools to run experiments, (ii) automated sample analysis, and (iii) multi-modal AI agents into fully autonomous Lab-of-the-Future systems with respectively designed databases, will allow for an immense acceleration of materials discovery through manifolding the efficiency in experimental throughput, data quality, and the probability of success in sequential decision-making processes.

Connecting multiple Lab-of-the-Future systems with each other and with expert knowledge graphs through hybrid cloud technologies will allow for additional acceleration, before the application of quantum computing will furthermore drastically improve the quality of our AI simulations and predictions by the ability to appropriately describe matter.

IBM Research is driving research and development in all three categories and applying these technologies to impactful use cases within healthcare and life sciences, climate and sustainability, and computing and nanotechnology. "