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Combination of Novel Virtual and Real Prototyping Methods in a Rapid Product Development Methodology

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Abstract

The applicability of novel rapid prototyping methods and techniques for improving various stages of rapid product development is described in this study. In addition to the conventional prototyping, functional prototypes with various properties may be generated. Finite element simulations and novel experimental techniques are successfully used for improve the prototyping process both on a macroscopic and on a microscopic scale. The 2 component prototyping offers new options for 2k industrial component design and for biomodelling.

KEY WORDS:
prototyping
rapid product development
real
virtual

KLJUČNE RIJEČI:
proizvodnja prototipova
brzi razvoj proizvoda
stvarno
prividno (virtualno)

Kombinacija novih prividnih (virtualnih) i stvarnih postupaka proizvodnje prototipova i metodologija brzog razvoja proizvoda

Sažetak

Ovaj rad opisuje primjenjivost novih postupaka brze proizvodnje prototipova i metoda za poboljšanje raznih stupnjeva brzog razvoja proizvoda. Osim konvencionalne proizvodnje prototipova mogu se načiniti i funkcionalni prototipovi različitih svojstava. Metode simuliranja s konačnim elementima i nove eksperimentalne metode uspješno se upotrebljavaju za poboljšanje proizvodnje prototipova na makroskopskoj i mikroskopskoj razini. Dvokomponentna proizvodnja prototipova nudi nove mogućnosti za 2k konstruiranje industrijskih dijelova i za biomodeliranje.

Introduction and objectives

The fabrication of tools and various articles for personal and industrial usage is one of the main goals of the humans during their history. However, there is a wide gap between a single piece fabrication/hand-made products and serial manufacturing of various commercial and industry goods. However, in all cases either natural or artificial materials must be shaped by various technologies. There are many (four ways) to shape, create or manufacture a product.[1]

- you can cut it from a bulk solid (splitting of the first *stone* tools, machining (lathing, milling, drilling);
- deform to a specified shape (forging of a sword, deep drawing of a packing for beer);
- mould it in a cavity (from cannon and bell founder to injection moulding), and
- build it layer by layer (rapid prototyping).

The most common method of producing parts made of plastic is injection moulding (mould it in a cavity). This process includes the injection or forcing of heated molten plastic into a mould (cavity) which is in the form of the part to be made. Upon cooling and solidification, the part is ejected and the process continues. The injection moulding process is capable of producing an infinite variety of part designs containing an equally infinite variety of details. However, due to the significant tooling efforts and high costs, the injection moulding is typical for large scale production. For a low number of items or for prototypes other methods are needed.

Conventional and functional prototypes play an important role in the product development process of polymeric parts. To produce plastic product prototypes in a fast, accurate and cheap way, various rapid prototyping technologies have been developed and successfully applied.[2] The essential prerequisites of the spread of the rapid prototyping were the development of computer aided design (CAD) and the mechatronics (control and positioning). The object/product can be generated in a virtual space and every material point is defined by a specific algorithm. An arbitrary shape of a product involving both analytical surfaces (simple mathematical description) and free surfaces (complex mathematical description) or all of these can be combined and a hybrid model can be designed. One of the main advantages is that rapid prototyping methods do not require additional tools. There are many methods and these methods use different materials.

Based on the above considerations, the objectives of this paper are:

- to demonstrate the capabilities of a 2-component (2K) printing by various practical engineering applications,
- to show the integration of the prototyping in various product development processes, and
- to develop guidelines and methodologies for these applications.

Design of polymeric components (support of product development) - application fields and examples

Rapid prototyping methods are successfully applied for supporting design efforts over a wide scale of product range. The prototyping can be integrated either in a straightforward or a reverse engineering process. While the straightforward process starts primarily with the generation of CAD file, the reverse engineering process involves 3D measurements of the part geometry, the determination of point cloud and the transformation of the surface data to real CAD file formats. To improve the process and in addition to the conventional prototyping, functional prototypes with controlled mechanical behaviour might be produced. The schematic representation of this process is shown in Figure 1.

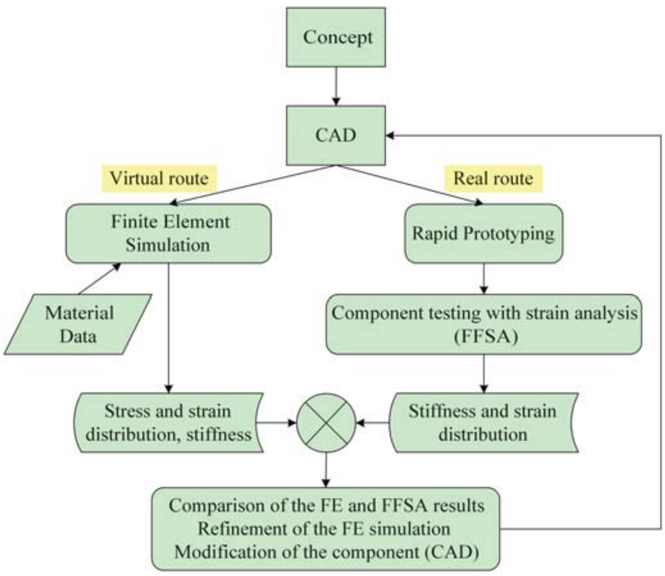


FIGURE 1 – Schematic representation of the integrated rapid prototyping concept

Various rapid prototyping systems were applied in this study. First, the fused deposition modelling method (FDM) was used and various parts were fabricated applying a *DimensionPlus* machine (*Stratasys*, *MN*, USA). ABS materials in well controlled quality and in different colours were used for printing of various parts.

Furthermore, a novel rapid prototyping technology called *Polyjet Matrix* 3D printing was also used in this study. Basically, this technology involves jetting a liquid photopolymer from an array of small nozzles and then immediately curing the liquid with a high intensity ultraviolet light source. >AA<Q<This technology can be realized using an *Objet Connex350 3D* printer.[3] This printer is the first 3D printing system that jets multiple (two different) model materials simultaneously. It offers a completely unique ability to print parts and assemblies made of multiple model materials, with different mechanical or physical properties, all in a single build. As a very unique feature of this system, both hard (modulus of tension about 3,000 MPa) and soft (modulus of tension less than 10 MPa, Shore Hardness from 27 to 95) can be produced by using this 3D printer. Furthermore, this technology can work with any mix of rigid and flexible model materials in terms of mechanical properties with attributes that are not commercially available (digital materials). The 3D printer has a build volume of 350 · 350 · 200 mm (X·Y·Z) and creates parts with a resolution of 16 · 16   16 µm (X·Y·Z). The 3D printer along with the printing head is shown in Figure 2. This machine was recently purchased and installed in the *Laboratory of the Institute of Polymer Product Engineering.*

FIGURE 2 – Multijet 3D printer (*Connex350*, *Objet*)

Prototyping of a complex testing device by applying hard (stiff) single material printing

As one of the main research activities of the *Institute of Polymer Product Engineering* is the development and implementation of instrumented component test systems for testing of various polymeric components, prototypes of fixtures and testing devices may be developed and fabricated for various experimental test set-ups. Magnetic particle filled elastomers (magnetoelastomers) are tested under complex mechanical, thermal and magnetic loading conditions in a research project. To get a controlled and nearly uniform magnetic field around the test specimen, a strong permanent magnet was integrated in the fixturing device. The device was designed by CAD and printed out using the *Objet 350* printer within a stiff modelling material *(VeroWhite®*) and it is shown in Figure 3. The prototyped device was later successfully applied for testing of magnetic particle filled elastomers under small strain dynamic loading conditions (dynamic mechanical analysis) and over a wide test temperature and test frequency range.

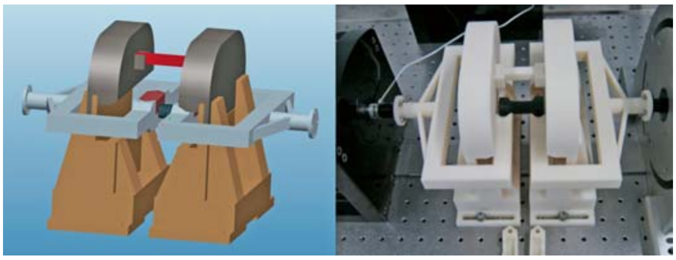


FIGURE 3 – Fixture and holder for combined dynamic mechanical magnetic experiments

Product development chain, integration of prototyping into a model PDM system

To demonstrate the capabilities of product data management (PDM) software tools, a model of rapid product development process was carried out both virtually as well as applying real materials. A juice squeezer was designed. The geometry of the squeezer head is shown in Figure 4a. The squeezer was designed for various sizes of juice fruits and for fixing them on a component test system. This component test system consists of both rotational and linear actuators and transducers. While the linear actuator generates the axial pressure force, the rotational actuator generates the squeezing movement. The instrumented system is shown in Figure 4b. The instrumentation means in this case that the axial force, displacement and the torque were simultaneously measured during the squeezing. All the steps of the virtual and real product development process were integrated into two different PDM software tools (*WindChill, PTC/TechSoft*, Linz and *TeamCenter Siemens PLM*, Linz). In spite of a rather facetious character of this project, all basic objectives were achieved. The rapid product development process was successfully demonstrated, the steps were integrated into the PDM tools and last but not least, fresh orange juice was produced.

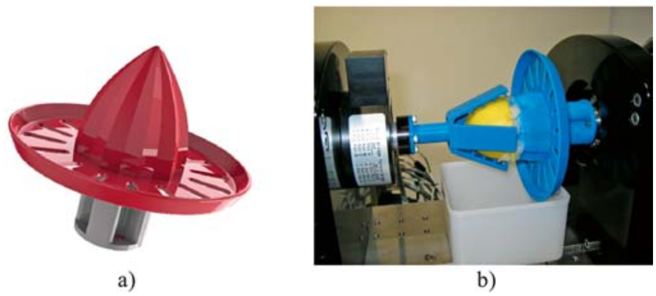


FIGURE 4 – Orange juice squeezer; a - CAD shape and b - realization of an *instrumented* squeezer using prototyped components (in blue)

Application of soft (elastomer-like, compliant) material

As previously mentioned, the *Connex* system is able to print out elastomeric materials with varying hardness. Hence, in addition to conventional rigid prototypes, various flexible parts, coatings and 2K system may be produced. Pure shear specimens are frequently used for characterizing the fatigue crack growth behaviour of elastomers. A large pure shear specimen was previously designed by the authors group and used in many experiments[4]. However, due to the large size of this pure shear specimen, high amount of material is needed. Hence, the specimen size is unsuitable for research materials which are available only in a limited amount. To overcome this limitation, a small size pure shear specimen was designed. The prototypes were realized by using different model elastomer grades. Both monotonic fracture and cyclic fatigue tests have already been started and the results will be used for verifying complex fracture mechanics theories by experiments.

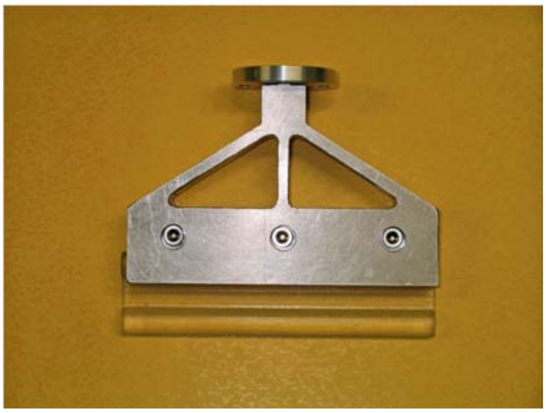


FIGURE 5 – Pure shear specimen for elastomer fatigue tests

2K prototyping of 2K injection moulded parts

2K injection moulding is frequently used for various industrial parts. Thermoplastic elastomers are integrated with conventional thermoplastic materials into components and provide additional functions to the entire components. Pipe segment with integrated elastomer seal was developed by a company partner and was investigated in a project. The 2K part was prototyped by using the *Connex350* machine and this part is shown in Figure 6.

FIGURE 6 – Two components rapid prototyping of an integrated pipe sealing

To determine the time-dependent change of sealing forces due to the relaxation process, finite element simulation was carried out and combined with the rapid prototyping. The geometry model developed and the spatial distribution of the principal strains are shown in Figure 7.

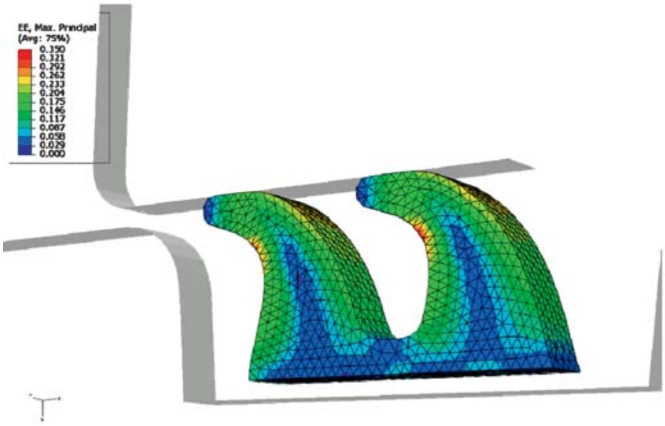


FIGURE 7 - Finite element simulation of the seal

The prerequisite of the simulation is the knowledge of an adequate material model with accurate parameters. An example is provided in the next section.

Digital materials

As previously mentioned, the basic hard and soft prototyping materials (*VeroWhite*® and *TangoBlack*®, *Objet*®) may be combined and so-called digital materials can be produced. Hence, both components with various stiffness (ranging from soft elastomer-like to rigid) and gradient materials may be produced. Representative nominal *stress-strain* curves are shown in Figure 8a for these digital material grades. Based on these *stress-strain* curves various material models might be derived.

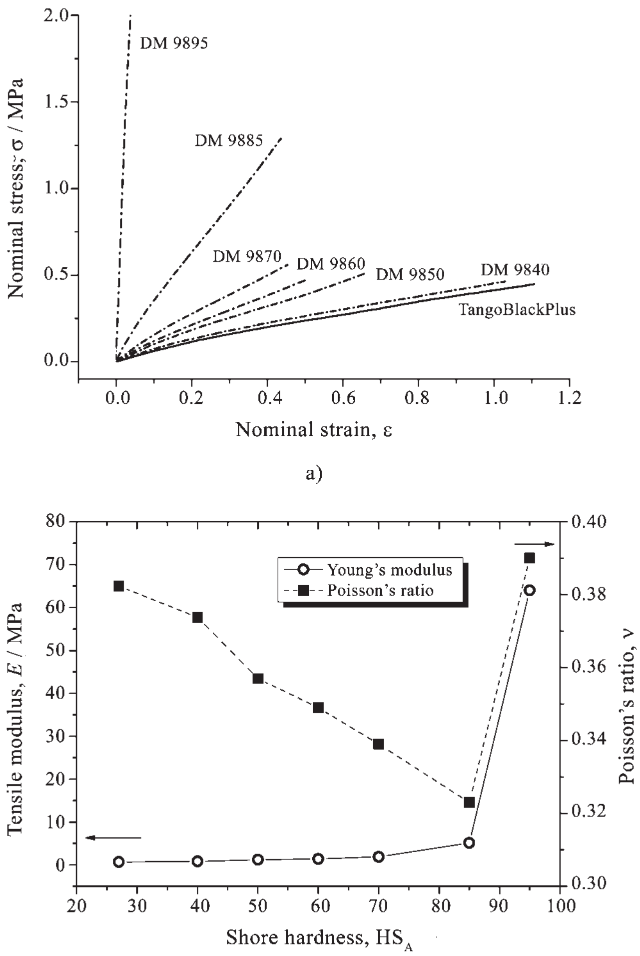


FIGURE 8 – Mechanical properties of the digital materials: a - Stress-strain curves (from DM 9840 to DM 9895), and b - corresponding tensile modulus and Poisson´s ratio values of the digital materials

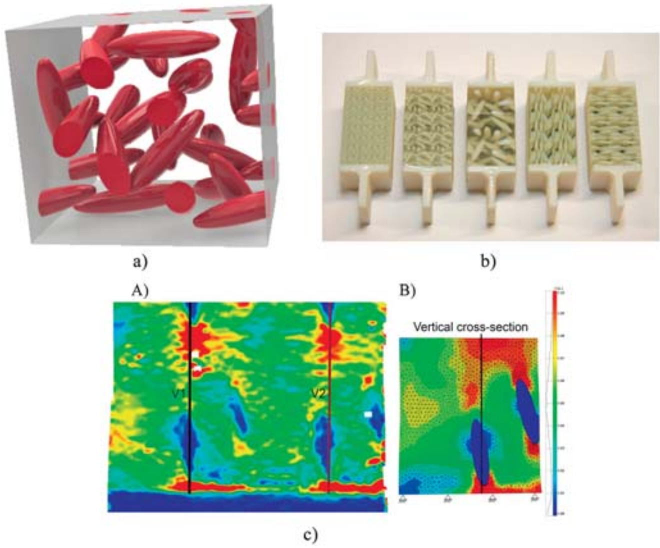
For the most simple, elastic models, tensile modulus and Poisson's ratio values were determined and plotted in Figure 8b. A more detailed characterization along with models used and model parameters determined has been found in the previous paper of the authors.[5]

Support of material development by prototyping of structures for fibre and particle reinforced polymers (microcells)

In addition to the conventional macroscopic scale single material or 2K component prototyping, a novel material micro-structure prototyping method was developed and implemented and described in reference 6.[6] As particle and fibre reinforced polymer matrix composites are frequently used in many demanding industrial and consumer applications (e.g. automotive, electronics, industrial and home appliances), the proper characterization of the deformation and failure behaviour of these materials is of high practical importance for reliable product design. Furthermore, due to the injection moulding process, fibre orientation distribution and fibre length distribution may be observed. Moreover, the mechanical behaviour of these components highly depends on these distributions. Micromechanics-based simulations using mean field homogenization and finite element methods along with a novel software tool were applied for determining the deformation behaviour of representative micro-cells for various particle-filled polymer matrix composites. Microcells are generated in micromechanics software tool (*DigiMat* FE) and transformed into a CAD file. The microcells in various configurations have been printed out directly or integrated by using periodic boundary conditions in test specimens. These test specimens were tested under tensile/compressive loading and the experimental and the simulation results were compared both on a global (load-displacement curves) and on a local scale (strain distribution around the particles). The detailed description of the methodology along with the results generated is described in reference 6.[6] Three essential elements (CAD of the microcell, the prototyping of specimens containing these microcell variations and the experimental testing and finite element simulations) are shown in Figure 9.

Virtual (CAD) model of 80% oriented microcells are shown in Figure 9a. This cell contains 10 vol % ellipsoid fibre-like particles with an aspect ratio of 1:5. The matrix material was a *TangoPlus*® and the ellipsoid-like particles were printed using *VeroWhite*® (both *Objet Geometries* Ltd., Rehovot, Israel). Furthermore, 3D printed microcell prototypes can be shaped both as a test specimen (e.g. tensile, compressive, bending or torsion) and as a model component with specific geometry and subsequently loaded using a mechanical testing system. The configuration of the macroscopic model specimen which consists of the various microcells is shown in Figure 9b. Specimen rectangular and cylindrical geometries were printed, but the microcells could be more easily integrated into the rectangular one, and the full field strain analysis is also significantly simpler with this specimen geometry. Moreover, the finite element simulations were carried out on these microcells and both the load-displacement response and the local strain and stress distribution was determined. Finally, for verifying these simulations, full-field strain analysis during the mechanical loading was performed and the strain distribution on the specimen surfaces was measured. For more information regarding these experiments please refer to reference 7.[7] The comparison of a selected result of the full-field strain analysis experiments with a finite element simulation is shown in Figure 9c in terms of strain distribution images. The major strain values are depicted in both images in the same size and strain range scale. As it is clearly seen in Figure 9c (comparing the left and the right side image), a good agreement between the simulation and the experimental strain analysis was observed.

The methodology described above is used for supporting the material development and design method development efforts. Furthermore, due to high accuracy of the printer and the advantageous physical properties of the materials applied (semitransparent), these specimens can be used as calibration tool for further development of non-destructive devices and methods (optical coherence tomography, OCT). This technique is described in the following paper.



FIGURES 9 – (a) Microcell CAD model, (b) the microcells are integrated into prototyped specimens and (c) comparison of simulation and strain analysis results; (A) experimental strain analysis and (B) finite element simulation

Summary, conclusions and outlook

Modern rapid prototyping methods offer new options for various novel applications: (a) macroscopic prototyping of one or two material component injection moulding parts, (b) microscopic prototyping of material microcells for heterogeneous compounds, and (c) biomodelling of human organs for education and counselling purposes.

In addition to the simple visualization and the generation of haptic feeling of such objects, the real material properties of the prototyping materials can be determined and implemented into adequate material models. Finite element simulations are performed using proper material data and component tests are carried out using novel non-contact methods (i.e. digital image correlation) for verifying these simulations. The comparison of these results may lead to a feedback process in which either the material models are refined or the component geometry is changed. Furthermore, all these activities along with the results can be integrated into the product data management process.

Moreover, in addition to the conventional macroscopic scale prototyping, material microstructure models may be designed and prototyped. Due to the increasing resolution of the prototyping systems, these microcells approach the size of the real materials. The main applications of this methodology are:

- microcells, verifying of simulation results;
- support material development;
- calibration for non-destructive testing and evaluation (NDTE) development.

Finally, biomodelling is probably the most promising field for high quality two components prototyping. Biological structures contain both hard and soft tissues and again gradient-like materials. Both the shape and up to some extent the inner structure of healthy, injured, diseased or degraded human parts can be created. The integration of medical imaging, reverse engineering, prototyping can provide high accuracy and expressive biomodels for education and patient counselling purposes. The expertise generated here may support further tailor-made prostheses development efforts. Moreover, scaffolds revealing a wide variety of microstructure, material grades and surface roughness can be created by rapid prototyping. The scaffolds are sued for supporting the cell adhesion and development and formation of complex tissues in tissue engineering applications. These investigations are ongoing and the details of the methods and the results will be reported in the next paper of the authors.

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Zajamčen posao nakon tehničkih studija na *Sveučilištu Johannes Kepler*

Guaranteed job after finishing technical studies at Johannes Keppler University

Technical-natural University Johannes Kepler *in Linz, (*JKU*), Austria, is well-known for its research aspirations, providing courses of application-oriented education with great prospects for getting a job.*

The first step study Polymer-technique *has to be particularly emphasised. This study program encloses all activities connected with plastic and rubber productions and processing. The polymeric and supporting industry promptly needs well educated professionals in these fields. Therefore, there is great demand for the students of these profiles on the market.*

Tehničko-prirodoslovni fakultet (*TNF*) *Sveučilišta Johannes Kepler* (*JKU*) u Linzu prepoznat je u svijetu po svojoj istraživačkoj djelatnosti, a ponuđeni smjerovi studiranja jamče primjenski orijentirano obrazovanje s velikim izgledima za zapošljavanje. Kako bi se odgovorilo potrebama znanosti i industrije, ponuda se stalno aktualizira.

Posebno se ističe preddiplomski studij *Tehnika polimerstva*, osnovan u listopadu 2009. godine. Preciznije, riječ je o programu koji obuhvaća aktivnosti vezane uz proizvodnju plastike i kaučuka, njihovu konstrukcijsku primjenu te proizvodnju plastičnih i gumenih dijelova. Industrija hitno traži izvrsno obrazovanu stručnu snagu s navedenih područja i zbog toga su na tržištu rada jako traženi apsolventi tog usmjerenja, uz velike izglede za zapošljavanje.

Karijera sa završenim usmjerenjem *Tehnika polimerstva*

Široka temeljna izobrazba u matematičko-prirodoslovnim i tehničkim disciplinama oznake su preddiplomskog studija tog usmjerenja. Uravnoteženim spojem teorije i prakse studenti dobivaju optimalnu pripremu za svoje zvanje. Područja kao znanost o materijalima, kemija polimera, proizvodnja i potrebna oprema za pravljenje plastičnih i gumenih dijelova te konstruiranje s navedenim materijalima sadržaj su izobrazbe. Studenti na kraju konstruiraju i prerađuju nove polimerne proizvode i materijale, razvijaju nove uređaje, strojeve i kalupe te ostalu opremu za pravljenje plastičnih i gumenih tvorevina. Od akademske godine 2012./13. moći će nastaviti studij na magistarskom programu.

Na *JKU* provodi se i magistarski studij *Ekonomija u tehnici polimerstva* (*Wirtschaftsingenieurwessen in Kunststofftehnik*), koji je kombinacija gospodarsko-prirodnih znanosti i sadržaja iz područja polimerstva te nudi izbor između težišta na tehnici polimerstva ili menadžmentu. Studij se temelji na preddiplomskim studijima kao što su *Tehnika polimerstva*, *Tehnička kemija, Tehnička fizika, Mehatronika, Postupci prerade, Strojarstvo, Tehnička matematika* i slični jednakovrijedni studiji. Dvogodišnji magistarski studij izvodi se pretežno na engleskom jeziku.

Novi studij *Kemija polimera*

Magistarski studij *Kemija polimera* na *JKU* jedinstven je u Austriji. Njime se stječe znanstveno obrazovanje za zvanje visokokvalificiranoga polimerijskoga kemičara, čije je glavno područje razvoj i karakteriziranje novih monomera i polimera. Nastava na tom studiju, koji je prvenstveno namijenjen onima koji su završili prvi stupanj studija *Tehnička kemija, Tehnika polimera* i *Biokemija*, održavat će se na engleskom jeziku, čime dobiva međunarodni značaj. Takva znanstvena kvalifikacija omogućava ispunjavanje zahtjevnih djelatnosti akademskih, privatnih i otvorenih istraživanja u lokalnim, regionalnim ili međunarodnim institucijama u kemijskoj, farmaceutskoj ili industriji plastike i gume, ali također u građevinarstvu, u području pakiranja, zrakoplovnoj i svemirskoj industriji, izradi sportske opreme, automobilskoj i elektroindustriji.

Sve informacije o ovim studijima dostupne su na adresama www.kunststofftechnik.jku.at i www.polymerchemie.jku.at.

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