Dedicated to Professor Dr.-Ing. Georg Menges on the occasion of his 90th birthday.
Posvećeno profesoru dr. ing. Georgu Mengesu povodom 90. rođendana.

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Quo vadis Injection Moulding: State-of-the-Art of Science and Technology

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Summary

Caught between the conflicts of economic constraints due to the continuing globalisation and technological standards of maximal product quality, the plastics industry in high-wage countries has to face more challenges than ever. To encounter these challenges of producing in an economical way in the future, further developments of already existing processes as well as new developments are required. Using the example of current developments in the key field of the injection moulding processes at the *Institute of Plastics Processing* (*IKV*) at *RWTH Aachen University* such as lightweight construction, integration of functions, production of polymer optics and surface functionalisation new perspectives of an economic and industrial production in the future Europe shall be pointed out. This paper is based on research made in *IKV* over the last ten years, so here are given only the references out of *IKV*.

KEY WORDS:
Injection Mould
Injection Moulding
Plastics
Plastics Processing
Process Technology

KLJUČNE RIJEČI:
injekcijsko prešanje
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plastika
prerada plastike
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Quo vadis injekcijsko prešanje – stanje znanosti i tehnike

Sažetak

Uhvaćena između konflikata ekonomskih ograničenja zbog stalne globalizacije i tehnoloških standarda maksimalne kvalitete proizvoda, industrija plastike u zemljama s visokim plaćama mora se suočiti s više izazova nego ikada dosad. Kako bi mogla odgovoriti na te izazove proizvodnje na ekonomičan način u budućnosti, potreban je daljnji razvoj već postojećih postupaka, kao i novi razvoj. Koristeći se primjerom trenutačnog razvoja na ključnom polju postupaka injekcijskog prešanja u *Institutu za preradu plastike* (*IKV*) na *RWTH Sveučilištu u Aachenu* kao što su lagane konstrukcije, integracija funkcija, proizvodnja polimerne optike i funkcionalizacija površine, naglasak će biti stavljen na nove perspektive ekonomske i industrijske proizvodnje u budućoj Europi. Ovaj se rad temelji na istraživanju provedenom u *IKV*-u u posljednjih deset godina, tako da su ovdje dane referencije samo iz *IKV*-a.

The plastics industry in Europe

At the present time, plastics already have a secured position as economic and innovative construction materials in daily use as well as technical processes. In addition to the development of new and efficient construction materials, the processing procedure plays a key role in the economic and sustainable use of plastics. In the recent past, not only the plastics industry but also the entire producing industries in Europe were greatly challenged by the economic crisis in 2008 and 2009 and the current economic uncertainties in the European Union. Nevertheless, the current forecasts of the plastics industry are considered positive, which is shown in the development of the plastics industry (Figure 1). Last but not least this positive forecast can be led back to application-oriented research and development activities of companies and especially research institutes such as the *IKV*.

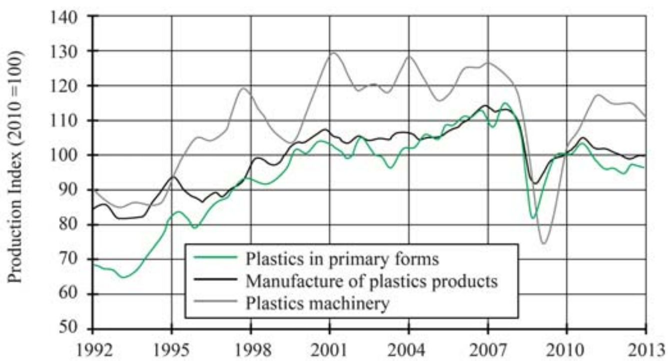

FIGURE 1 – Development of the plastics industry according to business segments since 1992 (Source: *PlasticsEurope*)

The continuously increasing demand for European plastics and rubber processing machines in the Asian markets in particular still shows the promising position of the European plastics industry. According to the *VDMA* in 2011 a new record in shipping volume of 766.4 million euro stands for a growth rate of 30.5 percent in comparison to the previous year (Table 1).

Trends and potentials of injection moulding

These developments as well as the challenges arising from the global mega trends of population growth, urban development, mobility as well as water-, food- and energy supply lead to an increase of demands for efficient and sustainable production processes and construction materials (source: *PlasticsEurope*). This is in particular applicable to moulded products. The injection moulding process is one of the most advanced production technologies of our times. In addition to the high automation and continuous advancements in energy efficiency, this process enables the fabrication of products with outstanding mechanical, optical, weight-specific and haptic properties. Furthermore, the large potential of integration of functions is one of the main reasons for the application of plastics. Due to the high potential of integration in entire production lines as well as direct combination with other technologies, this process has not yet reached its full potential to face the current trends of intelligent and adaptive cross-linking of systems. In order to be able to produce plastic products in an economically and environmentally compatible way, special efforts in the fields of material performance, weight-reduction of products, production efficiency and economisation of resources have to be made.

TABLE 1 − Exports of German plastic and rubber machines according to sales region in 2010 to 2011 (Source: *PlasticsEurope*)

Sales region	2010, %	2011, %
EU27	27.4	26.7
Rest of Europe	11.3	11.8
Africa	3.2	2.7
Asia	37.8	38.3
North America	11.1	11.2
Middle and South America	8.4	8.6
Australia/Oceania	0.8	0.7

In view of these tightened demands, a persistent optimisation and further development as well as deduction of new production concepts are essential to enable economical production in Europe. Using the example of current innovations as well as industrially established developments at the *Institute of Plastics Processing* (*IKV*) at *RWTH Aachen University* in the field of injection moulding a comprehensive overview of the possibilities and potentials of plastics processing for a sustainable, economical and intelligent use of construction materials and technologies in future Europe shall be provided.

Functionally integrated parts and processes

Injection moulding with micro structured surfaces

A special way of functional integration is the production of plastics parts with micro structured surfaces, which can make the existing functions more efficient or enable completely new functionalities. Numerous applications range from self-cleaning effects and flow optimised surfaces to optical components, which for example are used in metrology sensors or modern LED lighting units. In addition to the functionally integrated products, the two steps of part moulding and surface functionalisation are combined in an integrated one-step process.

In the last years, innovative processes have been developed at the *IKV* in order to replicate the micro structured surfaces in large quantities. In this context, the cavity wall temperature could be identified as a key aspect in the moulding of micro structures.

Especially during filling, increased cavity wall temperatures are beneficial for the moulding accuracy. *Variothermal* mould tempering is used to combine these high temperatures with low temperatures for demoulding in short cycle times. For this purpose, external inductive heating as well as laser-based mould heating, which can be applied externally or mould-integrated, were developed and investigated in detail. With these techniques, a fast local heat-up of the cavity surface can be achieved. Since the heating is always limited to the near-surface, the amount of heat transferred to the mould is kept small for fast cooling.

Alongside the requirements of the injection moulding process, a holistic view on the entire process chain is often necessary. Together with research partners, mould structuring and coating are also taken into account. The interaction between these steps makes it possible to produce surfaces with a self-cleaning effect in a one-step injection moulding process (Figure 2). The special surface topography of the structured cavity surface in combination with dynamic cavity wall temperature control enable production of stretched micro structures with extremely high aspect ratios, showing an excellent water repelling effect with contact angles of more than 160°.

FIGURE 2 − Part with water repelling surface – produced in a one-step injection moulding process (*IKV*)

Injection moulding of hybrid plastic-metal parts

In collaboration with industrial partners, the *IKV* develops an innovative adhesive system for hybrid plastic-metal components made in injection moulding. To replace the common interlocking features used to connect plastic to metal, an adhesive bond is to be created based on a bonding agent coated to the metal surface. The metal part just needs to be overmoulded to create a lasting connection. The hybrid components can be used for highly loaded structural applications. As part of the joint research project *Hylight* the benefits of this new technology will be demonstrated by a weight reduced automotive front-end.

This optimisation is achieved by mapping the mechanical behaviour of the adhesive layer in interaction of the sheet metal and the plastic component in an FEM-Simulation. For the determination of the material properties tensile and torsional strength a new test specimen (Figure 3) was developed. By special modelling approaches, these material properties can be integrated into the structure simulation.

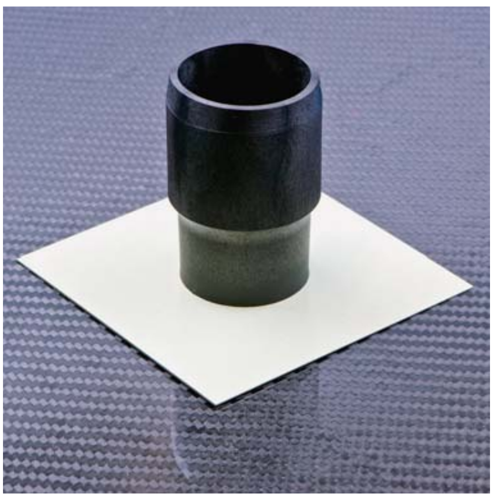

FIGURE 3 − Test specimen for the adhesive layer determination

After a validation of the established modelling approaches an optimised design of the front-end is virtually designed to detect the target weight saving with the same or even better mechanical properties. The precise interpretation of the cohesive structure of hybrid composites for new applications can be made ready for production, which further reduces the vehicle weight with the same performance.

Hybrid multi-component injection moulding

Within the described project, only the plastic component is injection moulded. The newly developed, so-called hybrid multi-component injection moulding (German: *Integriertes-Metall-Kunststoff-Spritzgießen*, IMKS) allows the manufacturing of plastics/metal-hybrids combining the injection moulding of plastics with the die casting of metals on one machine. The materials plastics and metal are combined in a specially designed multi-component injection mould. In the first step the plastic preform is moulded. In the second step, the injection of the liquid low melting tin based metal alloy enables the integration of full metal areas, preferably working as electrically conductive tracks. The additional metal injection unit developed by the *IKV* in cooperation with industrial partners is attached to the multi-component injection mould (Figure 4). The small unit allows die casting of low melting metal alloys. Integrated in the injection moulding process, the production of multifunctional parts for electric and electronic applications in high volumes becomes possible without any preceding or following process step.

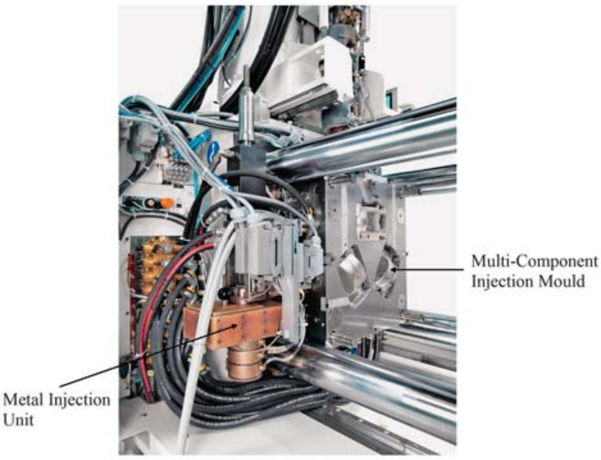

FIGURE 4 – Hybrid injection mould (HIMIM) with attached metal injection unit (Source: *KraussMaffei Technologies* GmbH)

HIMIM offers high reproducibility and short cycle times which qualifies the new technique for industrial production. As presented at the *Fakuma*-show 2012 in Friedrichshafen, Germany, the direct in-mould solder-like connection between conductor track and LED is possible. The demonstrator *desk light* (Figure 5) is produced in a compact production cell. Thereby a three dimensional conductor track with varying cross-sectional area was manufactured featuring high aspect ratios and the possibility to connect a LED inline to a power circuit.

Production efficiency with optimised mould technique

In the wide field of precision plastics parts made by injection moulding, such as for medical or optical applications, the mould technique has major influence on the resulting parts quality. Besides the recent development in process technologies, the development of the mould technology contributes significantly to advancement in the parts efficiency and quality (Figure 6).

FIGURE 5 – Demonstrator Desk Light" produced with HIMIM (Source: *Krallmann Kunststoffverarbeitung* GmbH)

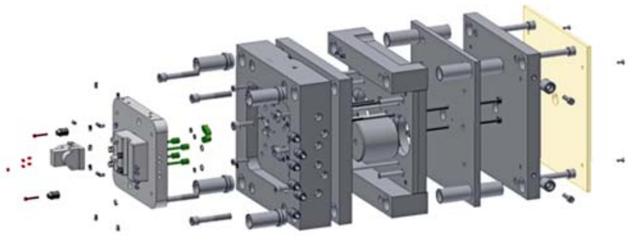

FIGURE 6 – Mould technology influencing parts quality

Mould technique for optical applications

The replication of complex optical components is a major topic in precision injection moulding in order to further enhance the optical properties of plastic lenses. For example, an innovative mould technology has been developed in the trans-regional collaborative research centre *SFB/TR4* that is capable of moving an optical mould insert in every cycle into a desired position. This movement is realised by integrated piezo-actuators (Figure 7). The micron-precise alignment of the optical surfaces allows minimising the centering error of every single lens before its production. Transfer of knowledge towards the production of free-form lenses and the use of this potential for the industrial production of optical components is subject of current research and development projects at the *IKV*.

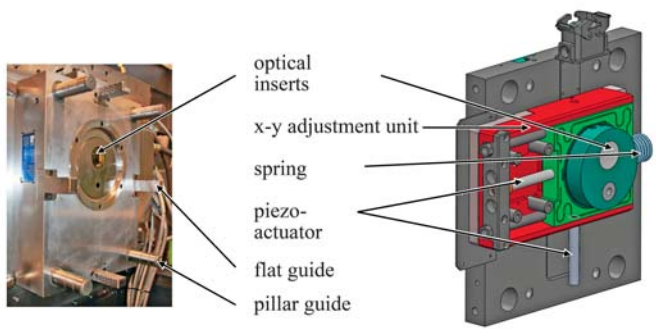

FIGURE 7 – Injection compression mould with integrated adjustment unit (*IKV*)

To increase the efficiency of the injection moulding technique for often thick-walled optical components, the multilayer injection moulding was introduced into the optical applications and is still being developed. The production of these thick-walled parts often requires long cycle times to achieve the necessary precision. By using a layered production of optical components the cycle time can be reduced by up to 30%. For this purpose special mould technology for multilayer injection moulding is needed. The main goals are to realise different layer thicknesses as well as to allow one- or two-sided overmoulding. Moreover, the pre-moulded part should not come into contact with the environment in order to avoid cooling and contaminations. According to the principle of the core-back mould-technology known from the multi-component-technique, the mould can be equipped with integrated hydraulic cores that enlarge the cavity after the pre-moulded part is manufactured to enable an overmoulding to the final thickness. The other possibility is to use index plates or rotary plates to change cavities for the pre-moulded part. In any case the precision of the used mould has to meet the challenges of optical production in the lower micron-range.

Temperature control of moulds for efficient productions

Especially for the high energy demanding process injection moulding, the focus shifts to the topic tempering, due to rising energy costs, higher demands of customers and new technological possibilities for the tempering of moulds.

Nowadays, injection moulds are characterised through rising number of cavities, more functional integration and more complex parts. This leads to higher demands for the tempering systems. Here, mainly three different technological trends can be spotted to counteract these tendencies. From inside the mould this is the technology of conformal cooling. Also, a better and more accurate thermal design of injection moulds, with the help of simulation methods, is growing. And finally, from the production side it is the use of different *variotherm* strategies.

Conformal cooling channels are normally realised through welding of several steel slices or with the use of additive manufacturing, e.g. selective laser melting. In doing so, a complex tempering channel layout can be realised, which actually follows the shape of the part. This reduces the mass, which has to be tempered. Less energy is needed for the process and shorter cycle times can be achieved as well. But also new ways for the mould design are being develped to meet the complex requirements of conformal channel layouts.

The simulation of the injection moulding process will become more and more a common part of the mould design process. Also, further improvements in simulation techniques will allow users to model different kinds of special processes in injection moulding. But also more accurate ways to build and analyse the tempering system are in development. At the moment there is a lot of effort being invested into the development of an automated tempering design.

Variothermal processes allow for a significant variation of the cavity wall temperature during one cycle. This combines the best of both worlds of high and low cavity wall temperatures. There are different processes in use like fluid-fluid systems, induction or the use of CO_2. A new and promising technique is the use of laser beam (Figure 8), which has been developed at the IKV. A system like this has the advantage that almost any mould can be used without adaption or reconstruction of the mould. Also, a programmable scanner unit offers the opportunity to realise nearly every desired course of process. This refers to the geometry, which can be heated as well as the heating time.

All the prior mentioned examples show that besides the special mould techniques for optical or medical applications, the tempering of injection moulds is still also a vivid field of research. An improved mould concept and tempering system has a viable part in sustainable enhancement of the injection moulding process and the parts quality.

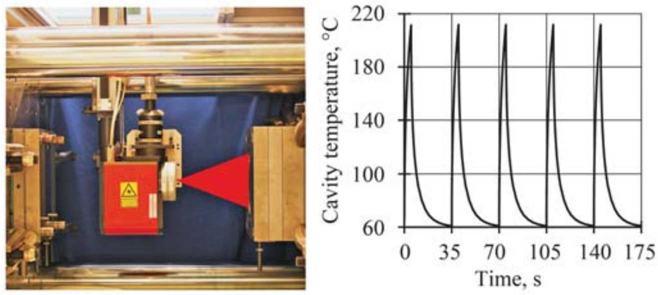

FIGURE 8 – Laser scanner at the IKV to heat up the cavity surface

Material efficiency

Despite numerous developments in the fields of mould and process technology, the conventional injection moulding process was not able to meet the rising demands in terms of continuously increasing the part complexity and functional integration. In this context, special injection moulding processes such as fluid-assisted injection moulding (FAIM) and thermoplastic foam injection moulding provide an alternative for the automated production of complex and highly integrated parts in a single process step. The objective of both processes is the reduction of material usage and the improvement of part properties by reducing e.g. warpage and mould shrinkage.

As a special injection moulding process, the thermoplastic foam injection moulding (FIM) has been employed for many decades. In this procedure, the plastics melt is provided with a blowing agent, which results in foam after the injection into the cavity of the mould. To give the plastic melt the space necessary for foaming, the cavity is initially filled partially and subsequently filled volumetrically through the expansion of the melt. The advantages of this procedure are in addition to weight reduction the avoidance of sink marks, a reduced warpage of the components after moulding and the potential of cycle time reductions.

ProFoam procedure

While in order to chemically foam thermoplastics a chemical blowing agent is added to the polymer melt, physical blowing agents (PBA) are fluids that experience a volume increase by expansion, or, if they can be solved in the polymer, by dissolving from the solution. Usually N_2 or CO_2 are used as physical blowing agents in the foam injection moulding process.

Technologies currently available for foam injection moulding with physical blowing agents require a high degree of system engineering and well-trained staff to run the processes.

Because of that a new foaming process for injection moulding was developed at the *IKV*. In this so-called *ProFoam* process, the plasticising unit of an injection moulding machine is pressurised with a blowing agent. To prevent the loss of blowing agent at the end of the screw, a seal is installed between the screw shaft and plasticising cylinder. The plasticising unit itself is sealed up with an airlock that is mounted between the barrel and material hopper (Figures 9 and 10).

The foaming process is controlled by only two process parameters, the type of blowing agent and its pressure, which makes the *ProFoam* process just as easy as the foaming processes with chemical blowing agents.

Furthermore, the aim of the current research project at the *IKV* is to develop an even more cost-efficient and machine-independent process without any gaskets for foam injection moulding using carbon dioxide in the solid state. The dry ice is dosed with a modified gravimetric dosing and mixing unit and is added to the polymer pellets before the mixture is forwarded to the plasticising unit. This flexibility makes it possible to realise smaller batches quickly to different machine capacity. Together with the short set-up time the cost of producing foamed thermoplastic components can be reduced significantly.

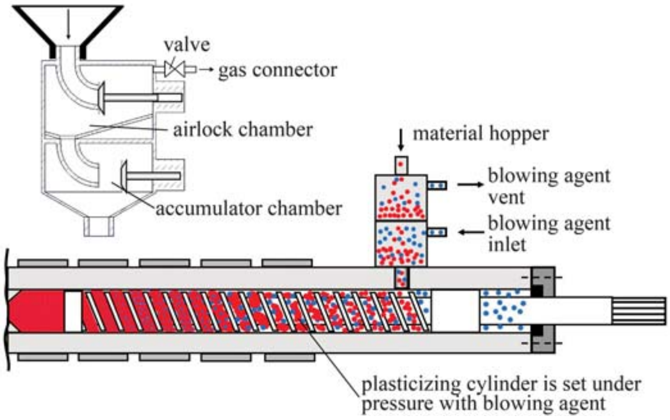

FIGURE 9 –The ProFoam process (*IKV*)

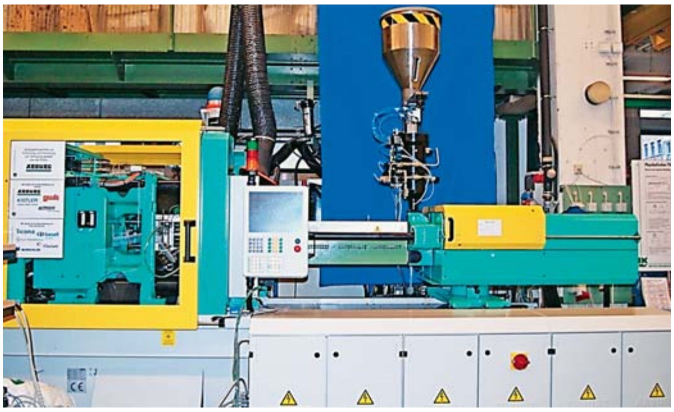

FIGURE 10 – Experimental setup of the ProFoam process

The fluid-assisted injection moulding does not use PBAs like the FIM to reduce the part weight and material usage, but forms hollow sections in the moulding by the injection of a fluid into the still molten core. The melt is displaced into additionally opened or not yet filled cavity areas and cooled during the fluid holding pressure phase. The water injection technique (WIT) is closely related to the well-established gas injection technique (GIT) and uses water instead of an inert gas to displace the molten material. The main advantage of the WIT compared to the GIT is the considerable reduction of the cycle time by effective water cooling on the inside.

Projectile injection technique (PIT)

A hitherto less considered process variant is the so-called projectile injection technique (PIT). With reference to the GIT and the WIT, a fluid is injected into the still molten core of the part within the PIT-process. However, for the actual melt displacement a projectile is used instead of the fluid itself. The process sequence is shown in Figure 11. The PIT represents an addition to the previously used procedures of the conventional FAIM. As practical investigations at the IKV show, it is possible to implement the benefits of the process in industrial applications. Research confirms the potential of PIT. The comparison of FAIM and PIT shows the possibilities of material savings and cycle time reduction. In addition to the significant reduction of the residual wall thickness (RWT), the use of PIT leads to a reduced eccentricity of the hollow space. Furthermore, the studies confirm the reproducible formation of the hollow space and the significant improvement in process stability.

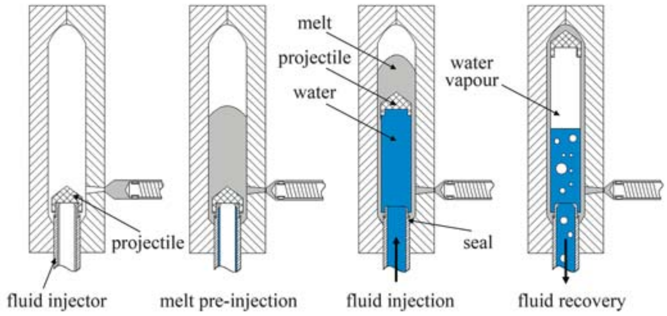

FIGURE 11 – Schematic drawing of the projectile injection process (*IKV*)

Other procedures

Until now inert gases like nitrogen for the gas-assisted injection moulding (GAIM) or water for the water injection technique (WIT) have been used as fluids almost exclusively. Both fluids differ significantly in their specific cooling effects. For large component sections, the desired heat transfer for economical production cannot be realised by GAIM. In contrast, depending on the processed material, the high cooling effect of WIT can lead to process-specific defects such as multi channels. The ongoing research projects at the *IKV* are therefore investigating how and to what extent the thermal properties of fluids – in particular the thermal conductivity and heat capacity – can be adjusted. The objective of the study is to use an atomised cooling spray for the fluid-assisted injection moulding, which allows the thermal properties to be varied in a wide range between the properties of gas and water. The thermal and rheological properties of the fluids can thereby be adjusted to the part geometry and material. The result is improved part quality and higher process stability due to another online adjustable parameter. For this purpose, an appropriate process technology in the form of a spray injector was designed and built. Its basic applicability was tested in feasibility studies. The comparison of a part made of polypropylene using gas, that is, the atomised cooling spray is shown in Figure 12. The foaming of the inner surface can be reduced due to the better cooling effect of the cooling spray. Cycle times and efficiency are thereby improved and help saving the pressurised inert gas.

FIGURE 12 – Comparison of gas and atomised spray cooling within the FAIM

Efficient part and process design using simulation techniques

For the efficient design of part and process for an injection moulding production, simulation tools are very important now. In the future they will predict the feasibility of the part regarding costs, stresses and strains, the producibility of the part in an injection moulding process and the high quality in an injection moulding process which is not sensitive to disturbance values. For future application of simulation, there are some new developments required regarding the simulation of special processes as foam injection moulding or fluid injection technique. Furthermore, important part characteristics as optical properties or the influence of microscopic processes on part behaviour cannot, for instance, be predicted. In addition, an important field for future part development is the efficient and reasonable use of simulation results for further steps during part and mould development until the start of production.

As described above, the so-called projectile injection technique represents an addition to the previously used technologies of FAIM. To enhance the use of the new technology in industrial applications, especially in small or middle-sized companies, simulation tools will be useful. In this context, research on PIT will be helpful to implement and improve the simulation tools. The objective of current research is the evaluation of the existing simulation tools that enable the simulation of gas- and water injection processes. The knowledge will be helpful within the implementation and verification process of new software tools regarding PIT.

A special injection moulding process like foam injection moulding offers many advantages to plastic processors. It is possible to achieve enhanced part properties as well as advantages in the production process. For a continuing process understanding in addition to the technological development of the process technology, the basis for a corresponding process simulation of foam injection moulding has to be developed. For this purpose, the interaction of the blowing agent and polymer is presently calculated in quite a complex manner in a two-phase model. In an alternative approach, a material card for blowing agent-loaded melts is now to be developed so that only the input variables are changed during the simulation, without needing any intervention in the actual programming. The data required for this are currently being determined through an online injection moulding rheometer and an online *pvT* (pressure-volume-temperature) cell at the IKV under real production conditions using an actual injection mould.

The injection moulded or injection-compression moulded optical parts have gained high market share in the last years in particular for automotive headlamps. In order to achieve parts with high precision, the process simulation enters the parts design phase additionally to the standard optical design. The aim is to simulate the flow-induced material behaviour that can be an optical issue, such as birefringence, retardation or polarisation. Simulation may help the user to optimise the process parameters or the part geometry, to affect important optical properties. In addition, today's simulations software can export the results like deformed part shape because of warpage or the resulting refractive index data for optical analysis into optical design software like *CodeV*. This integration allows designers to confirm or revise their optical designs.

It is characteristic of components made of thermoplastic materials that microscopic processes such as the entanglement or crystalline superstructures significantly influence macroscopic properties like shrinkage and warpage (Figure 13). Thus, precise prediction of these properties requires a multiscale and integrative simulation approach. Because of the increasing computing power and the possibility to calculate computational heavy problems these approaches get more and more important in research and application. In the context of the current cluster of excellence *Integrative Production Technology for High-Wage Countries* the IKV is developing an integrative simulation method for semi-crystalline materials across multiple scales. In future similar approaches will be developed to predict the complex material behaviour of thermoplastic materials on multiple scales.

The efficient and expedient application of the results of different simulation technologies is important for the part development process. At the moment, mostly results regarding part failure prediction for some defects or feasibility out of a virtual mould filling study are taken into account during the development process. In the future, different results have to be applied as the basis for further calculation. As shown in Figure 14, a method for the use of simulation results has been developed at *IKV*. By the use of statistical approaches as Design of Experiments in simulation, a mathematical model can be developed showing the dependencies between quality criteria and process parameter already in simulation. Thus, the process parameter set for a high quality part can already be predicted out of the injection moulding simulation. Considering possible disturbance variables already in simulation can show the way to an injection moulding process, which in reality is robust against these disturbances. The tolerances of the quality criteria can decrease and high-precision parts can be produced.

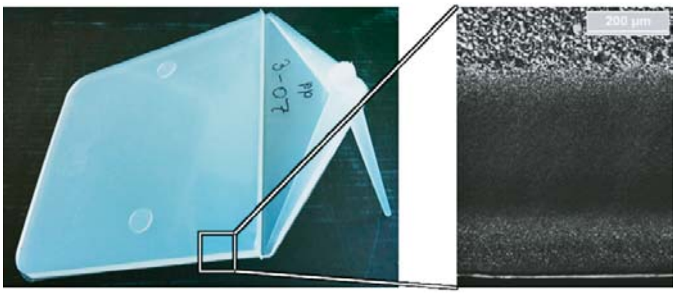

FIGURE 13 – Microstructure of an injection moulded plate

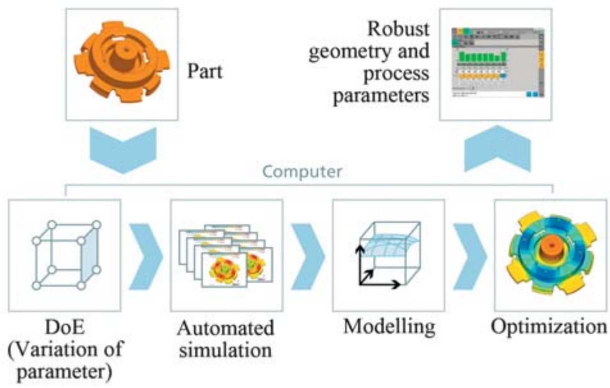

FIGURE 14 – Using Design of Experiments with simulation shows the feasibility to predict a robust geometry and an already defined process parameter set (*IKV*)

Outlook

To recapitulate, the depicted developments in different fields of injection moulding contribute to sustainable, economical and intelligent production in Europe.

For future successful applications of the injection moulding process as well as of all production technologies around plastics, robust processes are important to have high efficiency of production. Robustness has to be verified regarding the influence of all disturbing values as well as complex integration of all components of a production cell. All pieces of information should already be analysed together during the development of part and process using different simulation methods which have to be developed. In addition, simulation results should be validated with real data to improve simulation techniques for further applications. Thus, less raw material and lower energy will be needed and actual environment targets may be surpassed.

The vision of the *self-optimising-machine* represents the reduction of the adjustable parameters and thus the trend to simplify the machine setup. Such machines need to be increasingly autonomous. This requires increasing complexity of the decisions that are made by the machine and increasing communication of the machine with its environment, such as the resource planning or the communication with peripherals that are important for the quality of the product. This effects a change of the role of humans in production, who must control the increasing complexity of the machines.

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Dr. sc. Josip STOJŠIĆ

Josip Stojšić obranio je 25. rujna 2013. na *Strojarskom fakultetu* u Slavonskom Brodu (*Sveučilište Josipa Jurja Strossmayera*) doktorski rad pod naslovom *Utjecaj parametara smješavanja na svojstva nanokompozita od poliamida 12 ojačanog slojevitim glinama*, pred povjerenstvom u kojem su bili prof. dr. sc. Dražan Kozak, prof. dr. sc. Pero Raos, prof. dr. sc. Mladen Šercer, prof. dr. sc. Ivan Samardžić, izv. prof. dr. sc. Tomislav Galeta.

Josip Stojšić rođen je 1984. u Slavonskom Brodu. Nakon završetka osnovne škole polazio je srednju *Tehničku školu* u Županji, zanimanje strojarski tehničar. *Strojarski fakultet* u Slavonskom Brodu, smjer *Proizvodno strojarstvo*, VII. stupanj (diplomirani inženjer strojarstva) upisuje 2002. godine. Diplomira 2007. s temom iz područja preradbe polimernih materijala. Za vrijeme studija nagrađen je *Dekanovom* i *Rektorovom nagradom* za uspješno studiranje. Od listopada 2007. zaposlen je kao znanstveni novak u *Zavodu za proizvodno strojarstvo Strojarskog fakulteta* u Slavonskom Brodu na projektu *Napredni postupci izravne izradbe polimernih proizvoda* (voditelj: prof. dr. sc. Pero Raos). Koautor je 21 znanstvenog rada objavljenog u časopisima i zbornicima radova sa znanstveno-stručnih skupova na hrvatskom i engleskom jeziku, od kojih većina ima međunarodnu recenziju. Više puta boravio je na stručnom usavršavanju u inozemstvu, kao stipendist programa *Erasmus* na stručnom usavršavanju na *Faculty of Mechanical Engineering and Automation*, *Kecskemét College* (Mađarska), kao stipendist *Hrvatske zaklade za znanost*, te kao stipendist *Erasmus programa* za stručno usavršavanje nastavnoga osoblja boravi na *Tomas Bata University, Faculty of Technology*. U razdoblju od 2007. do 2012. godine sudjelovao je u izvođenju nastave na *Strojarskom fakultetu* i *Veleučilištu* u Slavonskom Brodu, a 2012. godine odlukom dekana nagrađen je zbog najbolje ostvarenog rezultata u studentskim anketama vrednovanja kvalitete studiranja.

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U doktorskom radu obrađeno je smješavanje i proizvodnja nanokompozita. Proizvodnja nanokompozita počela je početkom devedesetih godina i od tada nanotehnika je istraživačko područje koje se jako brzo širi i generira mnoge nove materijale poboljšanih svojstava. Nanokompoziti su višefazni materijali u kojima bar jedna komponenta ima jednu dimenziju manju od 100 nm, čime se postiže veća međufazna površina. Zbog karakterističnih svojstava nanokompoziti se sve više primjenjuju u tehnici i sigurno će zauzimati važan udio u proizvodnji materijala u budućnosti. Polimeri ojačani slojevitim silikatima vrlo su važna skupina nanokompozita, gdje je u polimernoj matrici raspršeno slojevito nanopunilo (najčešće je to modificirana prirodna glina). Na svojstva nanokompozita utječe tip polimerne matrice, tip i udio nanopunila u polimernoj matrici te niz preradbenih parametara kao što su temperatura taljevine, frekvencija vrtnje pužnog vijka, broj i oblik pužnih vijaka itd. Budući da su važnija istraživanja i primjena nanokompozita vezani za devedesete godine, još je nedovoljno istražen utjecaj preradbenih parametara na svojstva ovih materijala.

U sklopu doktorskog rada izrađeni su uzorci od nanokompozitnih smjesa PA12/nanoglina uz podešavanje različitih parametara (udio nanogline, frekvencija vrtnje pužnih vijaka i temperatura smješavanja). Zatim su analizirana mehanička i reološka svojstva dobivenih ispitnih tijela. Kao rezultat analize dobiveni su matematički modeli koji pokazuju funkcijsku ovisnost mehaničkih i reoloških svojstava o parametrima preradbe.

Ana PILIPOVIĆ