INTERNATIONAL DESIGN CONFERENCE - DESIGN 2006
Dubrovnik - Croatia, May 15 - 18, 2006.

DESIGN 2006

ICROS-THE SELECTIVE APPROACH TO HIGH-TECH POLYMER PRODUCT DESIGN- MODELLING AND EXPERIMENTAL VERIFICATION

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Keywords: simulation, polymers, ICROS, FEM, CAE

1. Introduction

In the product development process a major aim is to abridge the time for developing a new product. The conventional method in product design is to create a new structure, build a prototype and test its performance. In most of the development processes there are various evolution steps and lots of prototypes necessary until all requirements are fulfilled. In fact, with the help of **c**omputer-**a**ided **e**ngineering (CAE) and simulation tools, the development time decreases significantly and the number of prototypes and tests can be reduced. The use of FE techniques is state of the art and well known as part of the analysis phase of the design process. But the main problems today are the multitude of programs and utilities to work with and the right application chronology of the programmes.

Especially in polymer engineering, the question is: "How good is the performance of the chosen tool and what has to be done next in the design process?". Many different polymer simulation programs exist but they are complex in use because of the need for special nonlinear or anisotropic material subroutines to reproduce the polymeric material behaviour. In this paper, a procedure is described to reduce the evolution cycle time by integrating the use of commercial computer-aided engineering (CAE) software packages with injection moulding simulation software and commercial finite element software. With the intelligent combination of different software tools, the processing of polymer design could be simplified [Dolsak, Rieg, Novak, Hackenschmidt 2004]. This process is named ICROS from engineering by **i**ntelligent **cro**ss-linked **s**imulation. It is specially focussed on the optimized use of multiple simulation tools in industrial application.

In the following chapters, an overview of polymer product design is given. The finite element methodology and performance evaluation for polymeric materials are discussed. A case study involving a flexible elastomer polymer coupling is presented. The given example was engineered with the help of ICROS and the results were additionally verified with scores of lifecycle tests. The durability performance of the finished part was checked in plentiful trials.

2. Principles of product design with simulation programmes

2.1 The need for ICROS

The computational simulation becomes more and more efficient by improving performance and processing capabilities. But within the fullness of simulation programmes the question is: "How to decide which of the tools one has to use and in which order different computational simulations should be used?". It is a fact, that the order of simulation changes the results and the number of iterations, but there are no definitions for the exact proceedings. The reason for this lack of information is, that for every simulation and each material the right combination of simulation tools is different. This is the field of activities for the ICROS project. With the help of commercial simulation tools the utilisation of different simulation programmes is shown, depending on the type of simulation. ICROS is not simply just the use of common simulation programmes. It is the guideline for the intelligent utilisation and the visualisation of possible simulation tools. With the principles of ICROS the usage of simulation programmes is easier and common engineers are able to do some simulations quickly. In the continuation of this paper the use of ICROS is demonstrated on a polymer product design example.

2.2 An illustration of ICROS on designing with polymers

One problem in product design with polymers is the minor state of knowledge of the material behaviour. A fatal mistake is to use knowledge based on experiences with metallic materials. The computational simulation can produce relief with its capability to make procedures visible.

There are four main parameters that influence the performance of a polymer part:

- the chosen material
- the possible processing
- the application
- the design of the part

In the conventional approach, a material is first selected for the product. Normally, the choice of material already specifies the processing method. Afterwards, the product designer starts an iterative process between building a prototype, evaluating its performance and then modifying the design as needed. There are several inherent disadvantages of this method. First, the selected polymer may not be the most appropriate for the new product. Secondly, the advantages of the special polymer do not affect the design. And, most importantly, the cycle time to develop new products is inadequately long due to this “trial and error” procedure.

The most suitable process for polymer engineering is injection moulding. Consequently, conventional design process also involves also mould design and optimization using past experiences as well as “trial and error”. The main spotlight is usually focused on production requirements rather than mechanical product performance needs. Hence, polymer parts often are oversized.

The alternative approach for designing optimized parts with the injection moulding process is outlined here with ICROS. It replaces the conventional method by specifically linking several computer simulations, the design process is accelerated and leads to better products (Figure 1). The commonly used simulation tools for polymer engineering are mould flow and mechanical FE simulations. With ICROS, the usual order of simulations can be split off. The primary reason to carry out the ICROS simulations is getting more information about the behaviour of the chosen polymer. With knowledge of flow properties and material behaviour under stress, the adequate simulation methods can be used to select and optimize a design before building a prototype for testing.

The user of ICROS has to learn to combine different simulation tools. It is not important to know everything about each polymer. After every simulation step, the ICROS flow chart advises the next step and shows the possible opportunities to improve the preliminary model.

Frequently, manufacturers restrict their options to accustomed processes. This often hinders the development of a new product. ICROS overrides these mental barriers by integrating common engineers in the polymer design process. Mould flow analysis, for example, predicts the flow of polymeric materials through a mould. The information about injection time, flow rates, cooling time and so on gives the designer the ability to design a mould while knowing how the material will flow through the cavity. ICROS allows two methods of quickly designing: troubleshooting processing problems and developing new products.

For both troubleshooting and developing new products, the analysis procedure is very similar. The first step is to create a CAD model; then the user can choose between the simulation tools. With the mould flow simulation, the user is able to confirm proper filling, eliminate air traps, determine the optimum number of gates, their sizes and locations and optimize the process conditions. With the aid of FE analysis, the residual stresses in the component can be minimized. For reducing stresses in a part, a static linear analysis will work sufficiently, even if material behaviour is nonlinear. On the one hand, critical regions in the part can be identified in the product where failure is likely to occur under given conditions. On the other hand, a given design can be evaluated with regard to structural integrity.

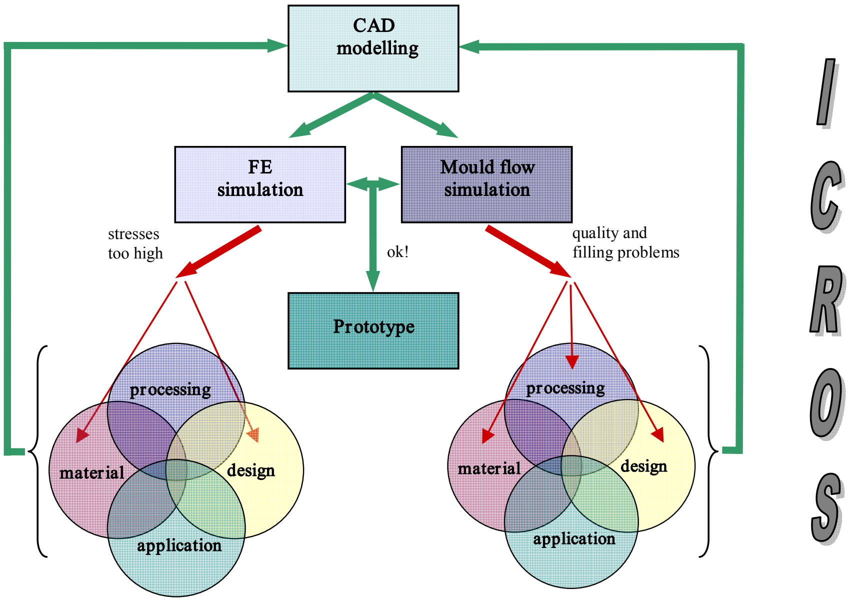
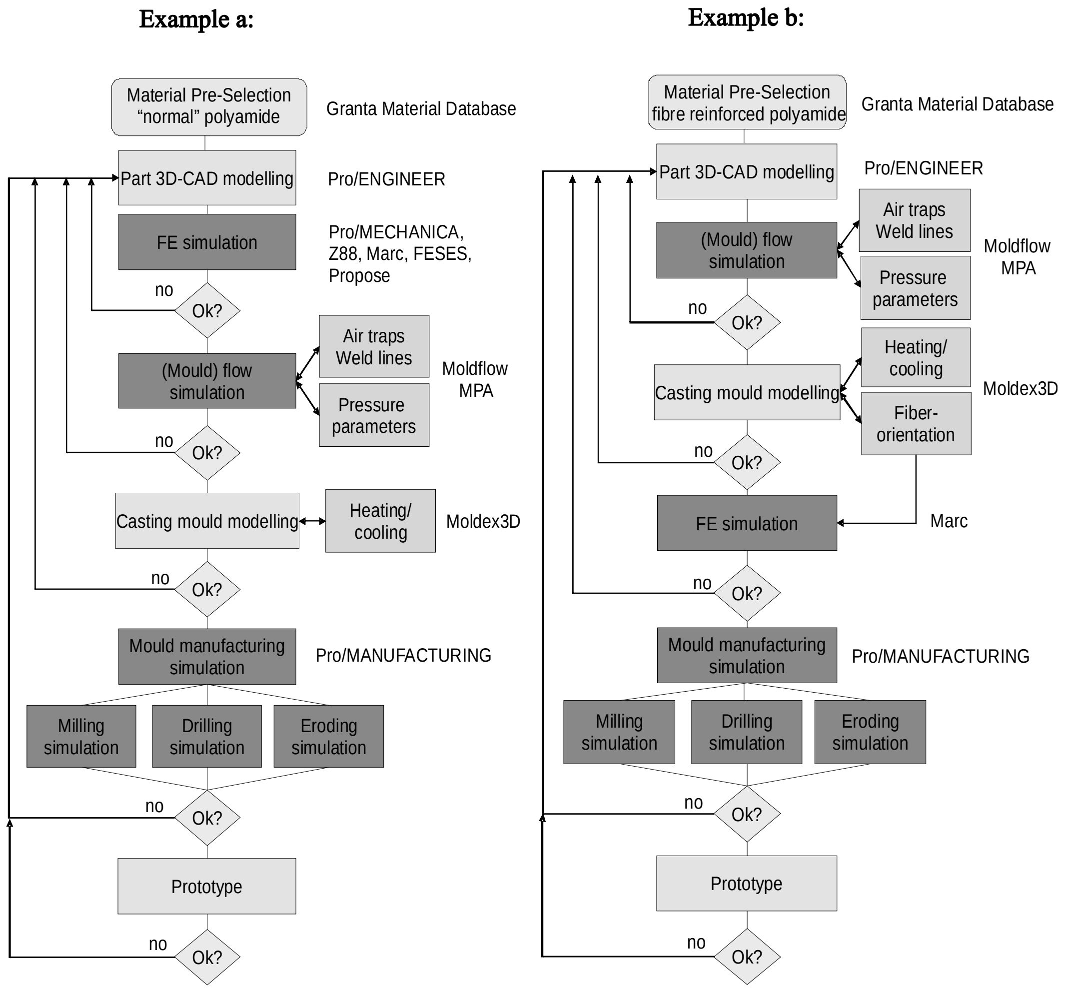


Figure 1. Cross linking of simulation programmes during the ICROS Process

As an example, two different approaches for polymer product development via ICROS are demonstrated:

- The classical injection moulded polymer part development can be optimized by using the following simulation tools (see Figure 2, left side): first, FEM programs (linear and/or nonlinear) to ensure the mechanical stability of the part, then mould simulation programs to optimize injection points and to identify weld lines and air traps under preselected pressure conditions, followed by mould optimization in terms of heating/cooling and machining with the help of several adequate simulation tools. For substituting metallic materials parts, this approach is the required method.
- Advanced materials like fibre-reinforced polymers need other devices and another simulation tool sequence (see Figure 2): Because the mechanical features of this material strongly depend on fibre orientation as a function of, for example, injection mould point, form and frequency, the mould simulation must be carried out at first using convenient program [Haag 2005]. This also means also checking and optimizing the filling degree and quality by varying the mould process parameters. In the next step, the FEM simulation can be done preferably using the results of the mould simulation as an input for the accurate mechanical attributes calculation of the fibre-reinforced polymer material. The following mould manufacturing simulation finishes the ICROS process.

ICROS can be used to iterate and vary designs until all requested parameters are satisfied. At this stage of design, a prototype needs to be built and tested. After the testing, the experimental data can be compared with the predictions.



Example a:

Example b:

Figure 2. Two examples of different polymer parts developments with ICROS

3. Case Study: Flexible Elastomer Polymer Coupling

3.1 Formulation of the problem

The part chosen for this case study is a flexible elastic coupling. These couplings are attenuating, electrically insulating, have zero backlash and compensate for misalignment. Normally these couplings are made of steel or aluminium alloys. The part must withstand a moment of torque of 60 Nm. The design steps in the design involved material selection, process selection, process simulation and optimization, residual stress determination with FE analysis, examination of the results of the simulations, lifetime and durability prediction and various prototype tests in dynamic use. The influence of weathering received attention with accelerated aging tests followed by prototype tests.
Figure 3 shows the original substituted part on the left, a CAD model of the final part after ICROS in the middle and the prototype of the new polymeric coupling on the right side.

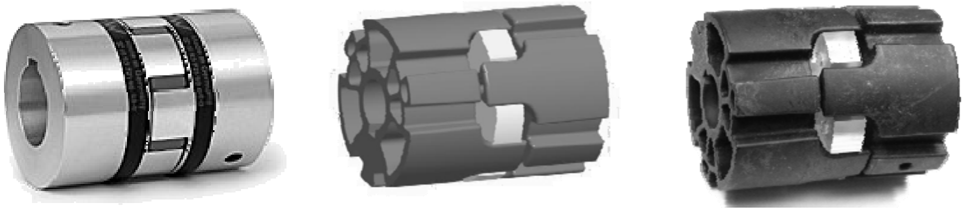


Figure 3. Evolution steps in the substitution of the common coupling

The following commercial software packages are used for engineering by ICROS (Table 1).

Table 1. Used software packages

Simulation tool	Commercial program
Geometry modelling	Pro/ENGINEER 2001, Wildfire 2.0
FE analysis	MSC.PATRAN/MSC.Marc, Pro/MECHANICA, Z88
Mould flow simulation	Moldflow MPA, MOLDEX3D
Milling simulation	Pro/MANUFACTURING

First, the material selection was made. For the case of operation, there were only two polymer families which hit the mark; the poly-ether-ether-ketones and the polyamides. Since the poly-ether-ether–ketones are very expensive, so a polyamide was chosen instead. Selected was a special long-fibre-reinforced material called FACTOR from EPIC Polymers.

3.2 FEM simulation of the residual stresses

Because of substituting a metal component, the first step in ICROS is analyzing the maximum stresses occurring in the part. This is important because the design in polymer engineering requires small wall thicknesses as well as the same ability in stress resistance [Stojek, Stommel, Korte 1998]. If the stresses are too high, an optimization of the structure would reduce them. But after this calculation, the stresses must have a minimum level; otherwise a substitution of metal can not be carried out.

First, a linear elastic material model was selected for the case study with a Poisson’s ratio of 0.34 and a Young’s Modulus of 17 GPa. Only triangular elements with quadratic approach were used [Rieg, Hackenschmidt 2003]. Several iterations in the design of this coupling were carried out following the steps of ICROS described in Figure 2. Merely some results of the final part iteration will be presented here. The worst-case boundary conditions are the complete moment of torque on the claws when the parallel key is attached. As seen in Figure 4, the equivalent residual stress (Von Misses) varies between 70 and 187 MPa. The maximum stress is located at the parallel key. This could be a problem in the part but the parallel key is essential for assembling. A solution would be a curvature of the parallel key.

As stated above, the stresses and the strains caused by the application were compared with critical values for the material [Stojek, Stommel, Korte 1998]. The special problem within this design is the application of polymers in dynamic cyclic strains. The material parameters normally decline with increasing dynamic use. This led to several iterations of the part and subsequent redesign of the features before arriving at the final acceptable design.

Table 2. Used FEA tools and maximum stress on the claws

FEA tool	Maximum stress (von Mises)
MSC.PATRAN/MSC.Marc	52.5
Pro/MECHANICA	54.9
Z88	52.3

As emphasized earlier, this was accomplished before the first prototype was ever built, thus lowering both time and cost in the product design phase of this project, all with the help of ICROS. For safety reasons, three different FEA tools were used. Table 2 shows the maximum occurred stress in the claws for comparing the results of different FEA tools. After the mould flow simulation, a model with fibre orientation was performed in Marc.

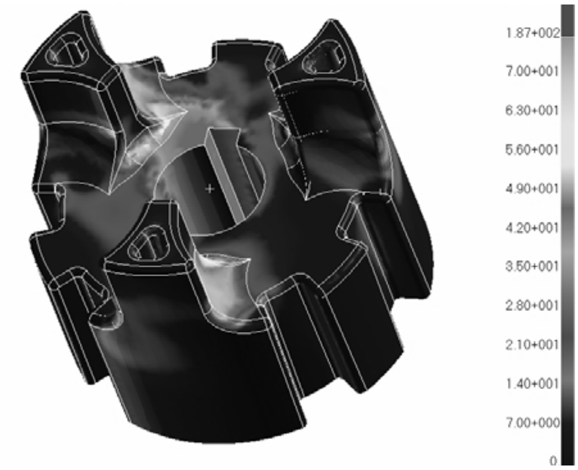


Figure 4. Maximal residual stress in the coupling in MSC.Marc

3.3 Mould flow simulation of the part

For optimizing the part, a simple 2 ½ D simulation is adequate. The gate locations, the weld lines and air traps can be reliably predicted. For fibre-reinforced materials, especially for long fibre reinforced materials a 3D simulation is required [Haag 2005]. Figure 5 on the left shows the fibre orientation on a sliced model of the coupling. The orientation changes inside the model because of the ribs and changing wall thickness. With the right picture, the engineer could estimate the injection time and the balance of the injection molding part. This is a check for the right meld entrance point.

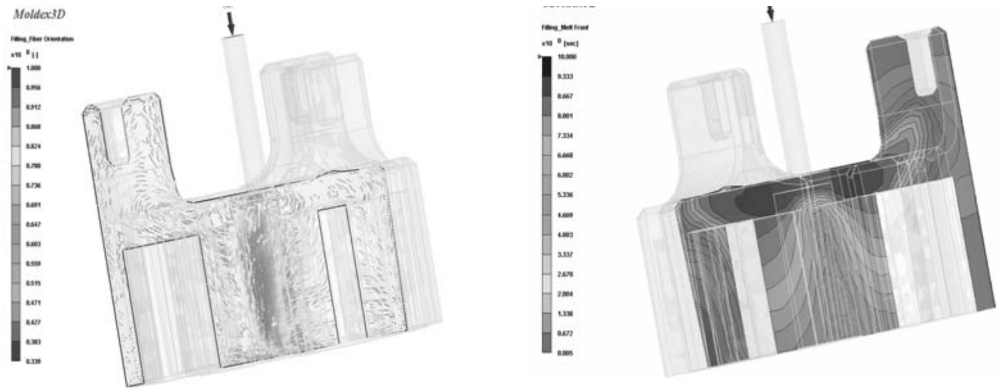


Figure 5. Fibre orientation and melt front prediction in MOLDEX 3D

3.4 Experimental verification

The prototypes were produced with an Arburg Allrounder 320 injection moulding machine. The parts were conditioned under room climate for further tests [DIN EN ISO 1110 1998]. To ascertain the middle fibre range, an ashing test was performed with some parts [DIN EN ISO 3451 1997]. A result of this test was a middle statistic fibre length of 7.5 mm. That is a very good result and this shows that the design of the casting mould is quite good. The material parameters normally decline with increasing age of the part. To eliminate the failure after years in use, it is usual to perform weathering tests [DIN EN ISO 4892 2001]. The couplings were weathered six months under a changing UV/condensation cycle. Dynamic and static tests were performed every four weeks. The couplings show no effects and their durability is maintained.

3.4.1 Engine test bench experiments

Static experiments

The parts were tested statically on an engine test bench. The moment of torque was raised constantly until rupture. The destruction happened at 190 Nm. Figure 6 shows the type of fracture. The parallel key is the beginning of the crack. The simulations clearly show the characteristic of the break. Serendipitously, the load in application is much lower.

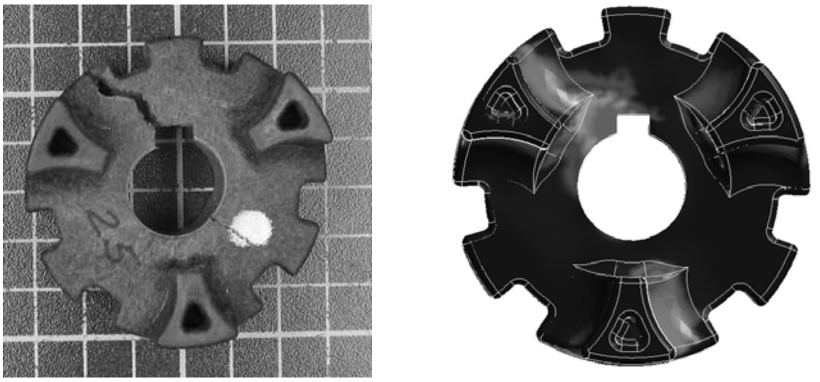


Figure 6. Experimental verification and simulation of the damage of the parallel key

Dynamic experiments

The dynamic fatigue strength test was performed at a distortion test drive with an engine speed of 3000 rpm. The test couplings were statically pre-stressed with 90 Nm. When the engine starts, the moment of torque climbs up to 125 Nm. The endurance of the tests is $4*10^7$ load cycles, which equates to approximately two weeks of permanent loading. More than twenty coupling pairs were tested and the results of these tests were always the same: The new polymer elastomer coupling withstood the loading.

4. Conclusion

The paper presents concepts for the simulation-based design of polymer parts. With the ICROS method, the design process could be sped up and simplified. This led to better products in a shorter development time. The showcase follows the guidelines of the engineering by intelligent cross-linked simulations and shows the success of the method. The developed prototype withstood all tests. The lifetime durability was tested, the influence of weathering was checked and cyclic loads were applied. The coupling broke at 190 Nm moment of torque. This is 315 % of the desired transmittable moment of torque. Additionally, the new polymeric coupling is more than 62% lighter than the aluminium coupling. In collaboration with a company it is considered to bring the new coupling to the market as soon as possible.

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