Project no. NMP2 – CT – 2003 – 505878

# PIAM

# Polymer Injection Advanced Moulding

Coordination Action
Thematic Priority NMP: Nanotechnologies and nanosciences, knowledge-based multi-functional materials and new production processes and devices

Publishable Activity Report

Period covered: from March 1, 2004 to February 29, 2008
Start date of project: March 1, 2004 - Duration: 4 years
Project coordinator name: Michel VINCENT
Project coordinator organisation name: ARMINES

Revision:

**Piam Coordination action**
# Publishable final activity report

# 1. Project execution

## 1. Introduction

The aim of the Coordination Action « Polymer Injection Advanced Moulding » was to gather European specialists involved in polymer Physics, experiments, injection molding technology and modeling from both the academic world and from industry.
The size of the consortium remained reasonable, even if management tasks were important:

- 14 academic laboratories from 7 European countries
- 6 industrial companies
- 2 technology transfer centre

A measure of the success of this Coordination Action is that four additional institutions applied to incorporate the consortium: one industrial partner was accepted and one rejected (for confidentiality reasons), and two research centers were accepted.
It is always dangerous to claim that "we gather the best European specialists". Working together, exchanging regularly certainly lead to important individual progresses in the knowledge and control of the complex injection molding process.

## 2. Contractors

| Partic. No. | Participant name | Participant short name |
|---|---|---|
| 1 | Ecole des Mines de Paris – Center for Material Forming - France | ARMINES CEMEF |
| 2 | Università di Salerno - Dipartimento di Ingegneria Chimica e Alimentare - Italy | DICA-UNISA |
| 3 | Arkema - France | ATOFINA |
| 4 | Dow Benelux B.V. - Belgium | DOW |
| 5 | Consorzio Interuniversitario Nazionale per la Scienza e la Tecnologia dei Materiali - Dipartimento di Ingegneria Chimica dei Processi e dei Materiali – University of Palermo - Italy | INSTMPA |
| 6 | Katholieke Universiteit Leuven - Laboratory of Applied Rheology and Polymer Technology - Belgium | K.U. Leuven |
| 7 | National Technical University of Athens - School of Mining and Metallurgical Engineering - Greece | NTUA |
| 8 | Ecole Polytechnique de l'Université de Nantes – Laboratoire de thermocinétique - France | Polytech Nantes |
| 9 | Institut fuer Kunststofftechnologie - Germany | IKT |
| 10 | Schneider Electric Industries SAS - France | SCHNEIDER ELECTRIC |
| 11 | Technische Universiteit Eindhoven – Materials Technology – The Netherlands | TU/e |
| 12 | University of Minho – Polymer Engineering Department – Portugal | UMinho |
| 13 | Università di Napoli Fedrico II – Diparatamento di Ingegneria Chimica - Italy | UNINA-DIC |
| 14 | Centre for Polymer Processing Simulation and Design School of Engineering, University of Wales Swansea – Great Britain | UWS |

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|---|---|---|
| 15 | Centre d'Animation Régional en Matériaux Avancés - France | CARMA |
| 16 | Innovation in Polymer Engineering - Portugal | PIEP |
| 17 | Transvalor SA – France | Transvalor |
| 18 | Ecole Centrale de Nantes – GEM – France | LMM-ECN |
| 19 | ENSAM – Laboratoire d'ingénierie macromoléculaire – France | LTVP |
| 20 | Iberomoldes – Portugal | IBER |
| 21 | Polish Academy of Sciences – Centre of Molecular and Macromolecular Studies – Poland | CMMS |
| 22 | Robert Bosch GmbH – Germany | Bosch |
| New members | Borealis – Austria | |
| | University of Padova – Dipartimento di Innovazione Meccanica e Gestionale – Italy | |
| | Sintef – Norway | |

## 3. Project objectives

The main objectives were the followings:

- To draw the state of the art on existing software packages: description of the physical laws, comparison of results on well defined parts.
- To specify new software packages capabilities according to the demand of the end-users (part and mould designers), and identification of blocking points (either numerical or physical). Test of the new software developments and comparison with the initial ones.
- Determination of material data: good practice guide can be established up for some data, but this is more difficult for advanced data. Guides to overcome this difficulty will be given, and advanced data will be provided.
- To identify the issues related to the use of thermoplastic software packages to other polymer systems (blends, composites…).
- To identify the issues related to process data acquisition, which are important for computation validation, and process understanding and control. A set of well defined comparison between experiments and computation will be provided.
- To identify the relation between injection molding, induced structure (orientation, crystallization), and final properties.
- To identify non-standard or emerging molding technologies, and list the needed developments (physical, numerical modeling).
- To obtain an overview of education activities dedicated to injection molding in Europe, and to organize an advanced course.
- To identify how technology transfer centers link SME's and research centers (circulation of information in both directions).
- To build research projects and to apply to national or European calls, taking into account the conclusions of the PIAM consortium about the research and technological domains which require further efforts.

## 3. Work performed, main results

A non exhaustive list of prominent developments and results is presented below. It does not follow exactly the sequence of workpackages.

1) Huge progresses have been made in the 3D modeling of the injection molding process:
- adaptive meshing driven by error estimate,
- code parallelization which allows to develop now computations with more than one million unknowns,
- space/time finite element methods which decrease significantly computation time.

2) A series of benchmarks with increasing complexities has been defined and different softwares have been tested. This benchmark will be used for several years to test the consistency of new developments in injection molding modeling. This is certainly one of the prominent results of this Coordination Action.

3) Advanced physical investigations of thermoplastic polymers and more complex systems (fiber reinforced, polymer blends) have been performed. Sometimes new experimental devices have been developed, which allow measuring new data:
- crystallization mechanisms and kinetics under severe conditions (high cooling rates, stress and pressure),
- PVT diagrams under the same severe conditions,
- Viscoelastic measurements in the liquid state

4) These enriched physical models and data have been progressively introduced in the 3D injection moulding softwares in order to master progressively the whole injection moulding cycle:
- coupling of filling and packing stages,
- introduction of viscoelastic constitutive equations in order to predict both the macromolecule orientation and the stress distribution at freezing time,
- prediction of fiber orientation during filling and packing,
- prediction of polymer crystallization.

5) Transparent moulds have been designed, built and tested in order to follow precisely the “dynamic“ of mould filling (more precisely than with the well known short shot approach); specific moulds have been built in order to investigate part warpage.

6) New injection moulding technologies (Gaz assisted, Water assisted, micromoulding) have been tested. Specific numerical models are under development

7) A one week PIAM Winter School has been organized January 2007 in Aussois (France). This was a great success :
- a series of lectures given by specialists;
- practical works both on physical instruments (optical microscopy, differential scanning calorimetry, rheology) and computers;
- open exchanges on the current problems in injection moulding.
  More than fifty people from industry and university were attending this Winter School.

## 4. Impact on industry and research

It is difficult to measure the industrial impact of a Coordination Action which aim is to gather experience of both academic and industrial partners, just four years after its beginning.

The potential impacts are numerous:

- Good practice in injection molding: what are the relevant parameters governing the process regularity and the part quality?
- The important material parameters and how to measure them in physical conditions near the process conditions;
- dissemination of softwares;
- development of new injection molding processes;
- ……

What is the situation in the PIAM Coordination Action?

1) There were 6 industrial partners at the beginning and 7 at the end involved in the PIAM Consortium: polymer producers, polymer converters, mould makers, software company. They were involved in the different Workpackages and participated to the nine successive meetings insuring the best possible diffusion in their companies.
2) The PIAM Winter School in Aussois (January 2007) was a unique opportunity to diffuse the best level of knowledge in Europe about injection moulding in a broader industrial community. Nine attendees came from industry, three from research centre and 46 from university. Thirteen countries were represented.
3) Two technology transfer Centers (one from France and one from Portugal) were also involved in the Consortium and they disseminated injection moulding knowledge in a wide polymer Processing SME community. In addition they built links with other technology transfer centers in their own countries and in other European countries and this results in several new European projects.
4) Two biannual meetings of the Consortium were attached to international conferences with a significant industrial attendance and this insured a wider dissemination throughout the world (see dissemination paragraph for further details)
5) Modeling softwares developed by PIAM partners are distributed in industry (within the Consortium but also outside) and they are intensively used to optimize mould design as well as processing parameters and to develop new polymers or polymer compounds for injection moulding. This has been consolidated by several benchmark tests of increasing complexity. They clearly point out the potentiality and the limitation of existing softwares.
6) New physical investigation methods have been developed within the consortium, especially for mastering the crystallization kinetic and the packing stage in non-isothermal mechanical conditions. These new methods are still at the laboratory level, but it is sure that some of them will be developed at industrial level.
7) New promising injection moulding processes are now under development (micro moulding, water assisted injection moulding…) and the specific contributions of PIAM research teams will contribute to secure them and to favor their use in polymer converter industry.

# 2. Dissemination and use

**1) Scientific and technical presentations**

The results obtained during the PIAM project were summarized in scientific papers, and presented at different international conferences, such as the Polymer Processing Society meetings, the Esaform meetings, the ANTEC conferences, International and European Rheology meetings. We have 102 papers and 135 conferences.

**2) Special sessions at international meetings**

The ESAFORM association (European Scientific Association for material FORMing) was an important vector of dissemination during the 4 years of the PIAM project. The goals of the ESAFORM Association are to stimulate and diffuse applied research in academic laboratories, public organizations and industrial companies, to spread scientific information on material forming, to link Industry and Public Research Laboratories, to teach material forming sciences in Europe, to promote the image of material forming.

A paper presents PIAM in the Esaform Bulletin, Vol. 5, N°1 (2005), and an electronic version is available on the Esaform website (http://www.esaform.org)

*8$^{th}$ Esaform conference on material forming (Cluj-Napoca, Romania, April 2005)*

The third meeting of the PIAM coordination action was organized end of April 2005 in Cluj-Napoca (Romania) jointly with the 8$^{th}$ Esaform conference. Several papers of the PIAM members were presented at this conference.

*11$^{th}$ Esaform conference on material forming. (Lyon, France, 23-25 april 2008)*

A special PIAM sub-session has been organized at the intersection of two mini-symposiums:
MS10: Structures and properties of polymers
MS11: Processing of polymers

A short introduction to the PIAM Coordination was presented by Michel Vincent followed by 11 papers.

**3) Students involved**

Education through research has been important, as most of the results were obtained by master students, PhD students, internship, and graduate students. Most of them will join industry and disseminate the knowledge.

| Participant | Student | Level | Title | Defense |
|---|---|---|---|---|
| Armines Cemef | J. Smirnova | PhD | Modélisation numérique et expérimentale de la cristallisation de polymères en injection | 22 September 2006 |
| | G. Beaume | PhD | Simulation of fiber orientation and residual stresses | |
| | W. Zeguine | PhD | Simulation of water assisted injection molding | |
| | A. Redjeb | PhD | Simulation of fiber orientation | December 4, 2007 |
| | M. Chaim | Internship | Observation of fiber motion | September 2007 |
| | M. Gicquel | Post-Master | Prédiction de la taille des morphologies cristallines dans les pièces injectées | September 2007 |
| INSTM PA | Zebene Kiflie Woldemariam | Post Doc | Collection of information on the solidification of amorphous polymers under conditions emulating processing. Collection of basic Information on the three polymers of choice: iPP, PA12 and PMMA | 4/2006 |

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|---|---|---|---|---|
| | Santo Pecoraro | graduate student | Solidification of complex systems: Influence of composition and processing parameters on the structure development under processing conditions of a blend of two linear polyesters | 5/2005 |
| | Di Salvo Fedele | fellowship | Set-up and improvement of a special mould for solidification under pressure | 4/2006 |
| | Antonio Stocco | graduate student | Solidification of complex systems: Influence of carbon black on the structure development under processing conditions | 3/2005 |
| | Davide Tranchida | graduate student | Determinazione delle Proprietà viscoelastiche su scala nanometrica con la nanoindentazione | 5/2007 |
| | Francesco Carfi | graduate student | Solidification of complex systems: Structure development during solidification under controlled cooling conditions of ternary polymer/solvent/non-solvent systems | 2/2006 |
| | Vincenzo Palermo | graduate student | Misura della temperatura di fusione dei polimeri in funzione della stabilità della fase solida cristallina | 3/2008 |
| | Vincenzo D'Ugo | graduate student | Solidification of complex systems: Comparison of the crystallization behaviour of a binary polyester blend (PET-PBT) with the behaviour of the components | 3/2008 |
| | Constantin Daniel | graduate student | Densification of iPP for low temperature ageing, dependence on initial structure | 7/2005 |
| KU Leuven | | | | |
| NTUA | S. Sofou | PhD | Calendering of viscoplastic materials | 21 March 2008 |
| | T. Zisis | Post-Doc | Injection molding of compressible materials | 28 Feb. 2008 |
| Polytech Nantes | | | | |
| Schneider Electric | Y. Szeflinski | Internship | Benchmarking des logiciels de simulation de l'injection: application à Moldflow 5.1 | September 2005 |
| | P. Barbosa | Internship | Simulation of the injection of reinforced thermoplastics | September 2006 |
| TU/e | Reinhard Forstner | PostDoc | | |
| | | PhD | | |
| | | Master | | |
| UMinho | Catarina Domingues | Graduate student | | |
| | Angel Stoyanov Yanev | PhD | Direct visualization and on-line monitoring in Injection Moulding | May 2008 |
| UNINA-DIC | R. Pasquino | PhD | Rheology of viscoelastic suspensions | October 2008 |
| ENSAM | Rennan Mendoza | PhD | Induced morphologies in injection molded polyolefine parts | May 30, 2005 |
| | Fahmi Bédoui | PhD | Elastic and viscoelastic modeling of the mechanical behavior of semicrystalline polymers by micromechanics homogenization approach | November 30, 2005 |
| | Delphine Dray | PhD | Thermoelastic properties prediction of an injection molded composite reinforced by short fibers) | March 10, 2006 |
| | Camilo Cruz | MSc | Elastic and viscoelastic predictions in polymer composites – an approximation to the nano-scale. | June 28, 2007 |
| CMMS | Jaroslaw MARCZYK | MSc | Mechanisms of plastic deformation of plasticized polylactide | spring 2008 |
| | Robert MASIREK | PhD | Influence of spatial confinements of crystallization of polymers | October 2007 |
| Bosch | Marion Houlière | internship | Fibre orientation measurement and simulation | June 2006 |
| | Valérie Hosdez | PhD | Deformation behaviour description for fibre reinforced thermoplastics | |

## 4) Exchanges, collaborations

PIAM was at the origin of several collaborations, sometimes between institutions which did not have relationships before.

1. Cemef - CMMS

- B.Monasse visited CMMS for one week in 2004.
- S.Boyer visited CMMS for two weeks in 2006.
- Rozanski (PhD student, one time), K. Sowa (PhD student, two times), E. Szkudlarek (PhD student, two times), R. Nowacki (PhD student, two times) visited CEMEF several times during PIAM each time for two weeks.

2. ENSAM - CMMS
- Co-supervision of the PhD of Margaret Walczak. She spent 6 months in ENSAM working on modelling of mechanical properties of amorphous phase in crystalline polymers.
- Joint supervision of Phd Thesis of Malgorzata Walzack with Prof Galeski on prediction of mechanical properties of semi-crystalline polymers: role and mechanical properties of the confined amorphous phase
- F. Bedoui (PhD student of ENSAM) visited CMMS for one month in 2006 working on characterization of injection moulded HDPE samples.
- A. Galeski (CMMS) visited ENSAM as invited professor three times: one month (2006), two months (2007) and one months (2008).
- A. Galeski, G. Regnier are co-authors of a chapter entitled “mechanical properties of solidified crystalline polymers, a chapter on "Nano- and micromechanics of crystalline polymers" in: "Micromechanics of polymer blends and composites” J. Karger-Kocsis, S. Fakirov (Eds.) (Hanser Publisher).
- G. Regnier (ENSAM) visited CMMS twice.

3. ENSAM - Cemef
Microconnect and Micropol projects funded by the French National Research Agency, on microinjection of polymers. 3 Phd thesis were, or will be, launched, one in joint supervision with CEMEF:
- olymer rheology under high shear rate (Cemef);
- induced microstructure and properties in microinjection molded parts (ENSAM);
- induced microstructure and properties in microinjection molded parts reinforced by nanofillers (joint supervision of Cemef and ENSAM).

4. Bosch
- Student project (Marion Houlière, now employee at Bosch in Drancy) between Bosch, CEMEF/Ecole des Mines de Paris and Transvalor.
- Measurements of pVT at high cooling rates for PA66 at DPI - TU/e
- Planned activity with ENSAM on Fibre reinforced materials (student project, starting 2008)
- Planned activity with CEMEF, continuation of work concerning fibre reinforced thermoplastic parts (simulation and characterization)

5. UMinho - Cemef
Collaboration was established between the work of Angel Yanev from UMinho (in the field of visualization) and Luisa Silva from CEMEF (in the field of Rem3D simulations)

6. Cemef / Schneider Electric:
Internship on visualization of particle motions in model fluids (M. Chaim, May-September 2007).

8. UNINA-DIC – KU Leuven

PhD student Rossana Pasquino from UNINA-DIC visited Professor Jan Vermant from KU Leuven for three months. The subject of the collaboration was the study of the alignment and migration of spherical particles in viscoelastic fluids under shear flow.

**5) Carma** had the following actions:

- 6th Innovative Materials and Processes show in La Valette (France) (September 2006)
  - 1st meeting of European Technology Transfer Centers
  - 2 posters presenting PIAM project
- 7th Materials and Processes show in La Valette (France) (27-28 September 2007)
  Official start date of the network with Technology Transfer Centers that would go towards eco-designed mutualized competencies in plastic industry and in composite materials fields.
- Info-CARMA n°35 (October/December 2005): PIAM project objectives announcement.
- Info-CARMA n°38 (October 2006): "le transfert de technologie, le maillon fort de l'innovation"
- Info-CARMA n°39 (November/December 2006): the PIAM project advancement was announced in CARMA's bulletin.
- Inter-Plast project: first project in continuity to PIAM in order to disseminate technology transfer in plastic industry and in eco-design.
  Kick-off meeting on September 28, 2006.
  Official start date on August 1, 2006.

**6) Training :**

- The Technology transfer centers have organized specific meetings devoted to dissemination of knowledge in injection moulding for SME**.** For example, Carma (France) organized a technical meeting devoted to "Les resines d'enrobage et le surmoulage en electronique et microelectronique" (Sophia-Antipolis, March 24, 2005)**.** KU Leuven organized in Leuven from September 12 till 16, 2005 a training on "Rheological Measurements: Applications to Polymers, Suspensions and Processing".

- The PIAM Winter School took place from 15 to 19 January 2007 in the center "Paul Langevin" which belongs to the French National Center for Research (CNRS) located in Aussois, France. Accommodation and conferences were at the same place, promoting interactions between participants. A web site was launched: http://piam.cemef.org/winterschool/winterschool.htm

  58 participants, including 12 ladies, came from 13 countries. 23 were Ph D students. 9 attendees came from industry, 3 from research centre and 46 from university.

  The program was composed of 18 lectures and 4 workshops, 1 "advanced session", 2 round tables.

  The assessment of the Winter school by the attendees was good. The organizers received several demands for a second session.

**7) Software dissemination**

A consortium has been built around the REM3D software, including Arkema, Schneider Electric and Transvalor, members of PIAM. Transvalor sells Rem3D to injection moulding

companies and especially SME, but also to universities. Some results of PIAM were readily incorporated in the software.

**8) Website**

The PIAM website has been launched during the first year: http://piam.cemef.org. This is an important tool for the network partners and for the dissemination.

**9) Patents**

An apparatus to measure the shrinkage and expansion behavior of a material (TU/e). A spin-off company, IME-Technologies, related to the Eindhoven University of Technology, will start the production of the PVT-apparatus that was used during the PIAM project.