Proceedings IRF2018: 6th International Conference Integrity-Reliability-Failure
Lisbon/Portugal 22-26 July 2018. Editors J.F. Silva Gomes and S.A. Meguid
Publl. INEGI/FEUP (2018); ISBN: 978-989-20-8313-1

PAPER REF: 7295

LINKING MOULD FILLING AND STRUCTURAL SIMULATIONS

Carlos Nuno Barbosa[1], Julio C. Viana[1], Markus Franzen[2], Thomas Baranowski[2], Ricardo Simoes[3(*)]

[1]University of Minho, Institute for Polymers and Composites IPC/I3N, 4800-058 Guimarães, Portugal
[2]Ford Werke GmbH, Research & Innovation Center Aachen, 52072 Aachen, Germany
[3]Polytechnic Institute of Cávado and Ave, IPCA Campus, 4750-810 Barcelos, Portugal
[(*)]*Email:* rsimoes@ipca.pt

ABSTRACT

Computer Aided Engineering (CAE) is common standard in the development process within the automotive industry. For thermoplastic components, for example, the manufacturing process is commonly simulated with injection moulding simulation software and passive safety with explicit crash software. Currently both disciplines are only linked within the simulation of fibre reinforced thermoplastics to take into account the fibre orientation from injection moulding simulation within crash simulation due to the significant influence of the fibre orientation on mechanical part properties. This work proposes a methodology that allows consideration of moulding conditions on the mechanical behaviour of unreinforced injection moulded components by coupling injection moulding simulation (Moldflow) and crash simulation (LS-DYNA®/RADIOSS®). A newly developed dedicated computer application allows to directly consider results from injection simulation within crash simulations. The manufacturing boundary conditions that most influence the mechanical behaviour are combined within the thermomechanical indices (TMI) methodology, and mapped onto each finite element within the crash simulation. Mathematical functions have been used to correlate the TMI to important mechanical properties of the moulded polymer. A user defined material model can read those indices and translate them to local mechanical properties.

Keywords: injection moulding, flow simulation, structural simulation, thermoplastics.

1. INTRODUCTION

Companies orbiting the automotive industry as OEMs (Original Equipment Manufacturers), 1st and 2nd tiers, raw-material suppliers, etc., are continuously challenged to develop and produce more reliable and lighter-weight components. This is mainly accomplished through product design innovations that encompasses high-performance materials. Over the last few decades, there has been a trend towards the use of advanced technopolymers. These materials have a pivotal impact on the weight reduction as well as on innovative design features of automotive components. Indeed, plastic materials are distinguished by the amazing physical adaptability and impressive breadth of technical/aesthetical performance, allowing product designers to create extraordinarily complex and highly fluid forms [1].

The development process of plastic automotive components is highly supported by sophisticated CAD (Computer-Aided Design) and CAE (Computer-Aided Engineering) software. These have extended the formal and functional possibilities of the engineering design and manufacturing processes. For instance, mold filling and crashworthiness simulations are fundamental computer-aided applications in the development of lighter and more reliable automotive injection moulded components. Nevertheless, there is room for improvements. Besides the increasing need for super computation power, computer-aided tools integration [2-4] and the complex modelling of thermoplastics' mechanical behaviour [5-7] are of crucial importance for better-quality simulation results.

Commonly, structure analyses of injection-moulded plastics parts are based on materials' isotropic characteristics. As known, their mechanical properties are extremely dependent on the process induced microstructures (e.g. molecular orientation and degree of crystallinity) resulting from the combination of the injection moulding conditions [8-11]. Therefore, this statement has oriented companies and academics to develop improved CAE techniques through the integration of moulding and structural simulations. Academics have been working on methodologies for improved prediction of the thermomechanical properties of injection moulded fibre-reinforced thermoplastics through the integration of fibre orientation and mechanical properties computation [12-17].

Car manufacturers are improving their intelligent plastic engineering design principles based on the intensifying use of such virtual development integrative methodologies. For instance, an applied research work has presented a method for transferring injection moulding outputs into structural FEA (finite element analysis) for a thermoplastic engine part [18]. The moulding-induced anisotropic material properties were readable in structure FEA by using the fibre orientation and mechanical properties of the material. Therefore, a more realistic behaviour of the part could be predicted. Nowadays, examples of standalone commercial software such as Converse [19] or Digimat [20] allow the orientation mapping and anisotropic material property data generation through fibres' orientation. Such data exchange interfaces tools are more useful when simulating fibre filled than non-filled materials.

Presently, there is a limited usage of coupling interfaces for unfilled semi-crystalline polymers. An attempted was made to combine injection moulding (Moldflow) and structural analysis (Abaqus) in order to improve the mechanical response prediction for unreinforced polymers [21]. The combined effect of crystalline growth and molecular orientation were considered the key features to couple both disciplines. A multilayered FEM (finite element model) was built and those microstructural features assigned for each through-thickness material layer. The authors reported a good agreement between the numerical and experimental results.

Besides the complex coupling process issues, a good description of the component's material behaviour in a wide range of loading conditions is determinant to achieve satisfactory simulation results. In the existing numerical tools for structural simulations (e.g. commercial crash software packages) the mechanical properties are described by numerical constitutive material models. A comparative review of material models for polymers (elastomers, foams and thermoplastics) with special focus on crashworthiness analysis is presented by Bois et al. [7]. An overview on existing material models for thermoplastics applicable on shell mesh elements in LS-Dyna is given by Huberth *et al*. [22]. Arriaga and co-authors [23] evaluated the validity of elasto-plastic strain rate sensitive constitutive models implemented in both Ansys and LS-Dyna commercial codes. Other relevant works have been improving the state-of-the-art on the constitutive material modelling for amorphous [24] and semi-crystalline [25-28] polymers.

Accurate modelling of thermoplastics structural behaviour is still a challenge due to several factors, enumerated elsewhere [6]. The complex material - yield or elasto-plastic and fracture - behaviour of thermoplastic materials has hitherto been described with limited accuracy, leading to obvious deviations between the physical and the simulated material behaviour. For this reason, the Ford Motor Company, has chosen an advanced material model developed by MATFEM [29] to enhance the crash simulation of thermoplastic materials. This material model, MF-GenYld+CrachFEM, which accounts for the major yield, hardening and failure issues of thermoplastics, is already validated for automotive applications [30-33]. Despite the good results achieved so far, there is a significant potential for improvement in crash simulations (e.g. efficient CAE tools integration).

This work proposes an approach so that data from injection moulding process simulation can be interpreted correctly by the commercial crash code LS-Dyna through the material model MF-GenYld+CrachFEM. The main objective is to evaluate the influence of the injection moulding conditions on the material properties (stiffness, meaning the Young's Modulus, strength, meaning the yield stress, and stress-strain behaviour, meaning fracture) at CAE level. This combines experimental and computational efforts to improve design and processing of thermoplastic components for impact load cases by predicting the mechanical properties through CAE tools integration. Practical experiences have shown the benefits of the integrative simulation process.

2. SIMULATION TECHNIQUES AND MAPPING TOOLS

2.1. Moldflow Simulations

The injection moulding process was replicated through the Autodesk Moldflow Insight (AMI) 2012 software. The program is able to report valuable results that are generally used to improve plastic part designs, injection mold designs and the manufacturing process.

The CAD model was discretized into a mid-plane finite element mesh type according to best practices [35]. Factors affecting AMI accuracy may include: solver technology; component modelling (mesh type and density of part, gate and feed system); material data; machine characteristics and process conditions.

The AMI midplane model used in this project has several simplifications. A 2.5D or 3D mesh type would lead to more accurate results. However, the computation time would exponentially increase and the link to the structural simulations would be unfeasible.

2.2. Structural FEA and Material Model

The LS-Dyna crash code is used for the analysis. Prior to any structural simulation it is necessary to perform a set of tasks and analysis, including:

- Creating the mid-mesh based on CAD data;
- Detailed consideration of local thicknesses (CAD2FE tool);
- Modelling the fixations;
- Creating the load case scenarios [boundary conditions for fixation and loads (degree of freedom, DOFs), contact modelling between parts if existing, test velocities.

In order to truthfully predict the mechanical performance of a component via simulations, FEA codes requires detailed information about the geometry, loads, boundary conditions, and of course the material. The material model must describe precisely the complete stress-strain behaviour curve of the polymer (elastic, plastic, hardening and fracture characteristics).

Most models are currently based on data from the tensile materials tests. The ISO 18872:2007 specifies procedures for determining the tensile properties of moulding plastics over a wide range of strain rates also appropriate to impact-loading situations [36]. Properties are determined through the use of mathematical functions to model the experimental results, considering rate-dependence of parameters; tensile properties at very high strain rates are then derived by calculation. The MF-GenYld+CrachFEM selected for this work is a user-defined material model developed by MATFEM [30-33].

2.3. Computational Approach for Properties Prediction

The AMI results have been combined in two semi-empirical mathematical equations (thermomechanical indices, TMI) to characterize the thermomechanical environment impose by moulding conditions. The most important process induced changes are based on the level of molecular orientation (thermo-stress index, TSI) and the degree of crystallinity (cooling index, CI) of the moulded samples [8, 9, 11].

The computation of the TMI has been performed with a computer application, denominated TMI-App, specifically developed for this project. The TMI-App was developed in native C language to parse AMI simulation outputs and store them in an embedded database. A frontend application has also been developed in C#, allowing faster results analysis and TMI calculation for every single moulding mesh element. Each mesh element contains the specific TMI info. A previous study has shown the development process of the TMI methodology and ensuing application, demonstrating the usefulness of this tool [9, 34].

A specific thickness is exported from the TMI-App to FEA packages (e.g. LS-Dyna) through MAPIT application. MAPIT is a Ford Motor Company in-house developed software, presented elsewhere [37]. In the scope of the present work, its function is to map the element properties from mold-filling-specified mesh to structure-specified mesh. The mapping tool matches the elements' geometric data and maps relevant information, even though the mesh characteristics are totally different, i.e. while the rheological mesh is given by triangle elements the structural mesh is represented by square elements. Consequently, every single structural mesh element contains the specific TMI info that decodes the process induced changes.

Figure 1 and Figure 2 show the element properties (nodes ID and coordinates, as well as elements ID and TMI info) mapping between mold-filling and structural meshes of a simple geometry for data exchange validation process. It must be noticed that, the best results can be obtained, if the geometrical difference between both meshes (rheological and structural) are small; large deviations in the mesh size discretization can lead to significant errors [16, 33].

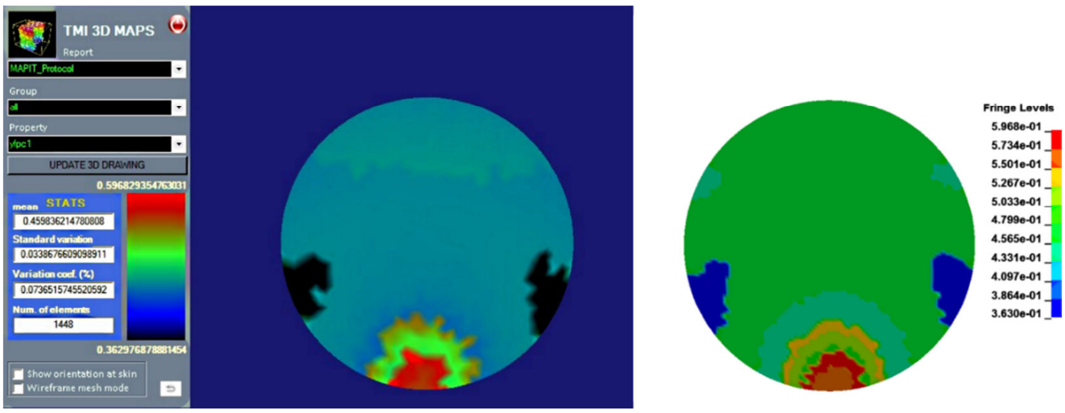

Fig. 1 - Cooling index as mapped by TMI-App (left image as per rheological mesh) and by MAPIT (right image as per structural mesh) for a simple disc geometry.

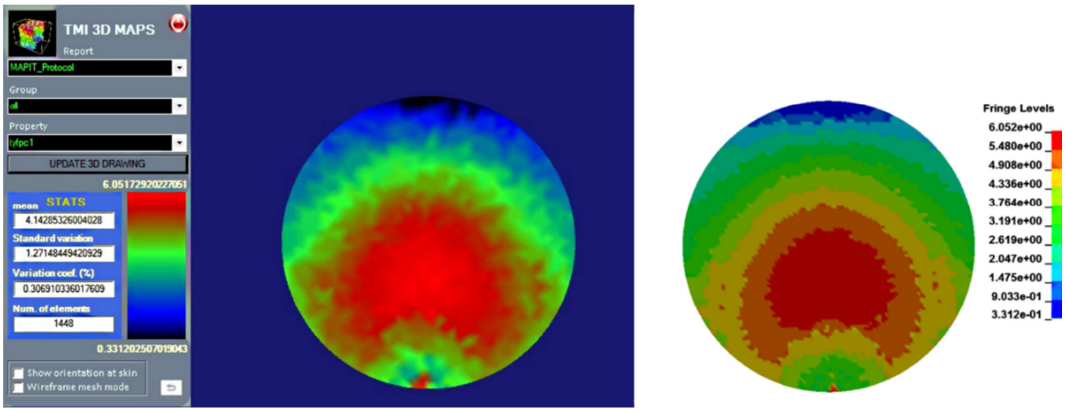

Fig. 2 - Thermo-stress index as mapped by TMI-App (left image as per rheological mesh) and by MAPIT (right image as per structural mesh).

3. INTEGRATIVE SIMULATION APPROACH

An integrative simulation chain has been established for assessing the deformation and failure behaviour of unreinforced injection moulded thermoplastics parts under mechanical load. For this purpose, dedicated (TMI and MAPIT) and commercial (AMI and LS-Dyna in combination with a user defined material model MF-GenYld+CrachFEM) computer applications have been applied.

The relevant AMI outputs are transferred to the TMI-App. This application generates a specific format mesh report file mapit.prot.txt which is synchronized with the MAPIT-App. Beforehand the FE LS-DYNA mesh model file fe-model.k is uploaded to the MAPIT-App. This application maps moldflow computed data onto crash mesh and generates the initial stress shell file inc_tmi-info.k.map that is required to run structural simulations. The crash finite element mesh contains, therefore, the thermomechanical environment imposed by the moulding conditions.

The TMI-App computes the CI and TSI for each processing simulation mesh element, and generates the tmi.txt report file. Three dimensional correlations between the computed TMI and properties measured experimentally (e.g. Young modulus, yield stress, fracture strain, etc.) can be determined through statistical design of experiment tools. The TMI methodology, here applied, basically finds straightforward mathematical relationships to model/predict the mechanical behaviour of moulded parts by considering the process induced thermomechanical environment. However, the basis to achieve reasonable predictive models is by performing a comprehensive characterization of the materials under different temperatures, strain rates and manufacturing conditions. The thermomechanical properties of the materials presented in this work were obtained through dynamic mechanical analyses and high-velocity tensile tests.

The mathematical model equations are then normalized, scaled and implemented in the user-defined-code file mfuser-tmi*.c and in the material card file. The normalization and scaling factors adjustment of the predictive models are executed by considering the reference material properties of a specific user-defined material card. The material card MF-GenYld + CrachFEM, already introduced, was used in this investigation. The reference material properties are achieved through a systematic procedure that combines laboratorial testing (e.g.

mechanical characterization of injection moulded samples) and mathematical fitting approach (e.g. force-displacement curves). The geometric features of the test samples as well as the boundary injection moulding conditions used for production must be used as AMI simulation inputs. As a result, the gap between material properties captured in the lab environment and those experienced in actual moulding conditions is empirically reduced.

The boundary injection moulding conditions of the studied thermoplastic induces a specific thermomechanical environment - characterized by the TMI - that leads to the reference material properties. These are the reference TMI. For improved understanding, the output of a structural simulation for a reference material grade without TMI data would result in an equivalent force-displacement response if the material card contains the reference TMI values. Any other combination of TMI leads to different mechanical response and the properties are scaled accordingly.

Finally, MF-GenYld+CrachFEM provides a shared object interface enabling the modification of the user defined material model. Within Linux, the makefile writes out the final shared object file mfuser-tmi.so and the crash simulation outputs are computed, reflecting the effects of the moulding conditions. The above described integrative user-defined simulation chain contributes to improved virtual product/process development.

4. INTEGRATIVE METHODOLOGY VALIDATION RESULTS

In order to validate the new developed functionality, i.e. include the injection moulding simulation results in the crash simulation material card through TMIs, at first a basic component (tensile specimen) simulation was carried out. With this approach, the capability of the developed simulation chain can be tested with reduced computation time. Moreover, functional issues can be easier identified than with complex simulation models. Secondly, experimental test results are compared to the simulated deformation behaviour of the toolboxes, following the same simulation chain approach. The analysis results have been proved valuable.

Simulations were performed in a tensile specimen model using different inputs. The boundary conditions and results are shown in Figure 3. At first, the simulation was run without any injection moulding history assigned to the material card (black curve) of the tensile specimen. Then, another simulation was carried out with the material card containing the reference thermomechanical history (red dashed line) that is equivalent to the first force-displacement curve. Other simulations were performed in order to evaluate the effect of different thermomechanical histories on the hardening response of the material. In this case, minimum (green curve), maximum (blue curve) and random (violet curve) TMIs values were used. The random TMI values are the result of thermomechanical history values (within minimum and maximum referenced TMIs) calculated from a specific injection moulding condition. As a result of these tensile tests it can be concluded that the method of taking into account the thermomechanical history within crash simulations is correctly working.

The next step will be to correlate the properties predicted through the proposed TMI-based approach with the results from experimental, extending the case-study to a real automotive component.

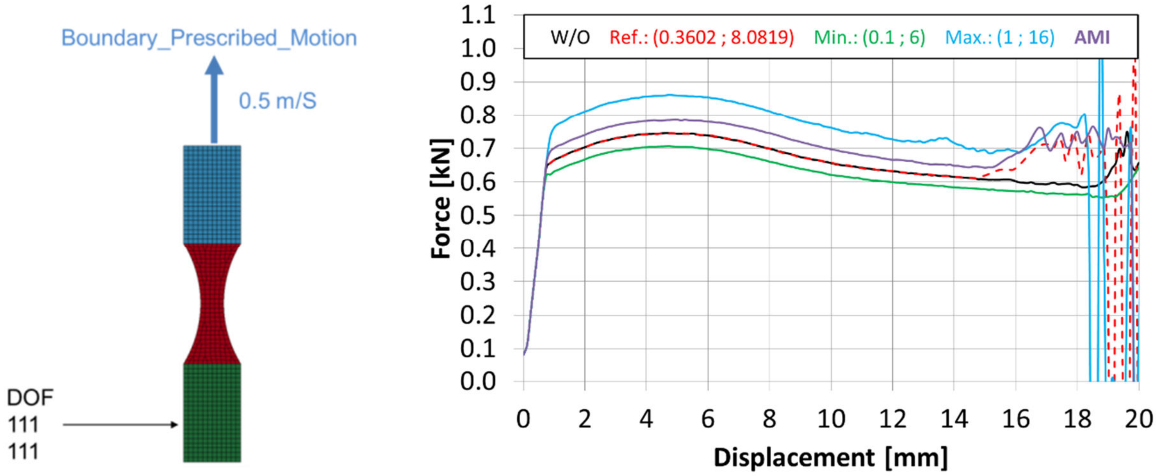

Fig. 3 - Boundary prescribed motion for tensile simulation (left), and comparative results for different inputs (right).

5. CONCLUDING REMARKS

Injection moulding simulations and finite element analysis have been applied to simulate the injection moulding process and to improve the crashworthiness of thermoplastic parts under specific conditions. In this work, a simulation chain is proposed to link moldflow and structural simulations in order to include the manufacturing process information into the material model.

The accuracy of the proposed methodology is dependent on several factors: from the Moldflow mesh model and the selection of processing settings, to the definition of the finite element model and the physical boundary conditions. The establishment of improved relationships between the developed microstructure (characterized by the TMI) and the mechanical response is essential to allow better predictions. The quality of the mathematical fitting (given by the coefficient of multiple correlation) of the TMI vs. mechanical properties must be statistically improved for more accurate predictions. This may be accomplished by redefining the TMI.

TMI are dependent on the injection moulding conditions used in simulation and the mechanical properties are measured in real injection moulded test components. There is always an error associated to the mechanical properties measurements and it must be highlight that differences always exist between moulding simulations and real production. The combination of these issues influences the accuracy of our predictions.

The simulation chain was successfully implemented. The scale factors were defined for the hardening (HRD) and elastic region (YM). Another approach may be followed to encompass a more complex strain-rate dependency of the materials on the mechanical response. This may improve the accuracy of the predictions. Other kind of tests, simpler tests (e.g. tensile on cut specimens from complex parts) should be performed in order to test the overall feasibility of this integrated methodology. We are currently finalizing experimental tests on box specimens in order to validate the methodology with a real case-study automotive component; these results will be subsequently reported.

ACKNOWLEDGMENTS

This work is funded by FEDER funds through the COMPETE 2020 program and National Funds through FCT under project UID/CTM/50025/2013, and grant SFRH/BD/51570/2011.

REFERENCES

[1] C. Fiell and P. Fiell. Plastic Dreams: Synthetic Visions in Design, Fiell Publishing Limited (2009).

[2] B. Louhichi, G.N. Abenhaim, and A.S. Tahan. Int. J. Adv. Manuf. Technol., 76, 391 (2015).

[3] V. Ferreira, L. P. Santos, M. Franzen, O.O. Ghouati, and R. Simoes. Advances in Engineering Software, 71, 52 (2014).

[4] H-S. Park and X-P. Dang. Computer-Aided Design, 42, 889 (2010).

[5] G. Gu, Y. Xia, C-H. Lin, S. Lin, Y. Meng, and Q. Zhou. Materials & Design, 44, 199 (2013).

[6] J.C. Viana, A.M. Cunha, and N. Billon. Polymer Engineering & Science, 47, 337 (2007).

[7] P.A. DuBois, S. Kolling, and M. Koesters, T. Frank. International Journal of Impact Engineering, 32, 725 (2006).

[8] C.N. Barbosa, R. Simoes, M. Franzen, T. Baranowski, and J.C. Viana. Polymer Engineering & Science DOI: 10.1002/pen.24650 (2017).

[9] C.N. Barbosa, F. Carvalho, J.C. Viana, M. Franzen, and R. Simoes. International Journal of Advanced Manufacturing Technology, 77, 873 (2015).

[10] J-W. Housmans, M. Gahleitner, G.W.M. Peters, and H.E.H. Meijer. Polymer, 50, 2304 (2009).

[11] J.C. Viana. Mechanical characterization of injection moulded plates, PhD Thesis, University of Minho (2002).

[12] Y. Xu, Q. Zhang, W. Zhang, and P. Zhang. International Journal of Advanced Manufacturing Technology,76, 2199 (2015).

[13] H. Miled, L. Silva, T. Coupez, and J.F. Agassant. International Polymer Processing, 27, 547 (2012).

[14] W. Michaeli, C. Hopmann, K. Bobzin, T. Arping, T. Baranowski, B. Heesel, G. Laschet, T. Schläfer, and M. Oete (2012). International Journal of Materials Research, 103, 120 (2012).

[15] A. Wüst, T. Hensel, and D. Jansen. ANSA & μETA International Conference, Halkidiki (2009).

[16] A.Y. Peng, E. Wu, and C.T. Huang. LS-Dyna European Users Conference, Strasbourg (2011).

[17] C. Kröner, H. Altenbach, and K. Naumenko. Mechanics of Composite Materials, 45, 249 (2009).

[18] T. Schmidt. SIMULIA Community Conference, Vienna (2013).

[19] www.partengineering.com/software/converse (accessed on October 01, 2017)

[20] www.e-xstream.com/products/digimat/about-digimat (accessed on October 01, 2017)

[21] E. Andreasson, L. Persson, H. Jacobsson, and J. Nordgren. SIMULIA Community Conference, Vienna (2013).

[22] F. Huberth, S. Hiermaier, and M. Neumann. LS-Dyna Anwenderforum, Bamberg (2005).

[23] A. Arriaga, R. Pagaldai, A.M. Zaldua, A. Chrysostomou, and M. O'Brien. Polymer Testing, 29, 170 (2010).

[24] H. Louche, F. Piette-Coudol, R. Arrieux, and J. Issartel. International Journal of Impact Engineering, 36, 847 (2009).

[25] F. Detrez, S. Cantournet, and R. Séguéla. Comptes Rendus Mécanique 338, 681 (2010).

[26] A.F. Epee, F. Lauro, B. Bennani, and B. Bourel. International Journal of Solids and Structures, 48, 1590 (2009).

[27] D.A. Şerban, L. Marşavina, and V.V. Silberschmidt. Computational Materials Science, 64, 116 (2012).

[28] A. Maurel-Pantel, E. Baquet, J. Bikard, J-L. Bouvard, and Noëlle Billon. International Journal of Plasticity, 67, 102 (2015).

[29] www.matfem.de/en (accessed on October 01, 2017)

[30] G. Oberhofer, M. Franzen, and H. Dell. Kunststoffe+Simulation, Fellbach/Stuttgart (2007).

[31] M. Franzen and H. Lanzerath. ATZautotechnology, 8, 40 (2008).

[32] G. Oberhofer, A. Bach, M. Franzen, H. Lanzerath. European LS-Dyna Conference (2009).

[33] H. Gese, G. Oberhofer, and H. Dell. LS-Dyna Anwenderforum, Frankenthal (2007).

[34] C.N. Barbosa, F. Carvalho, J.C. Viana, M. Franzen, T. Baranowski, and R. Simoes. International Journal of Materials and Product Technology, 52, 76 (2016).

[35] J. Shoemaker. Moldflow Design Guide: A Resource for Plastics Engineers, Hanser Gardner Pub. (2006).

[36] www.iso.org/standard/38914.html (accessed on September 28, 2017)

[37] A. Hänschke. The CAE Driven Safety Development Process of the New Ford Fiesta. European Hyperworks Technology Conference, (2009).