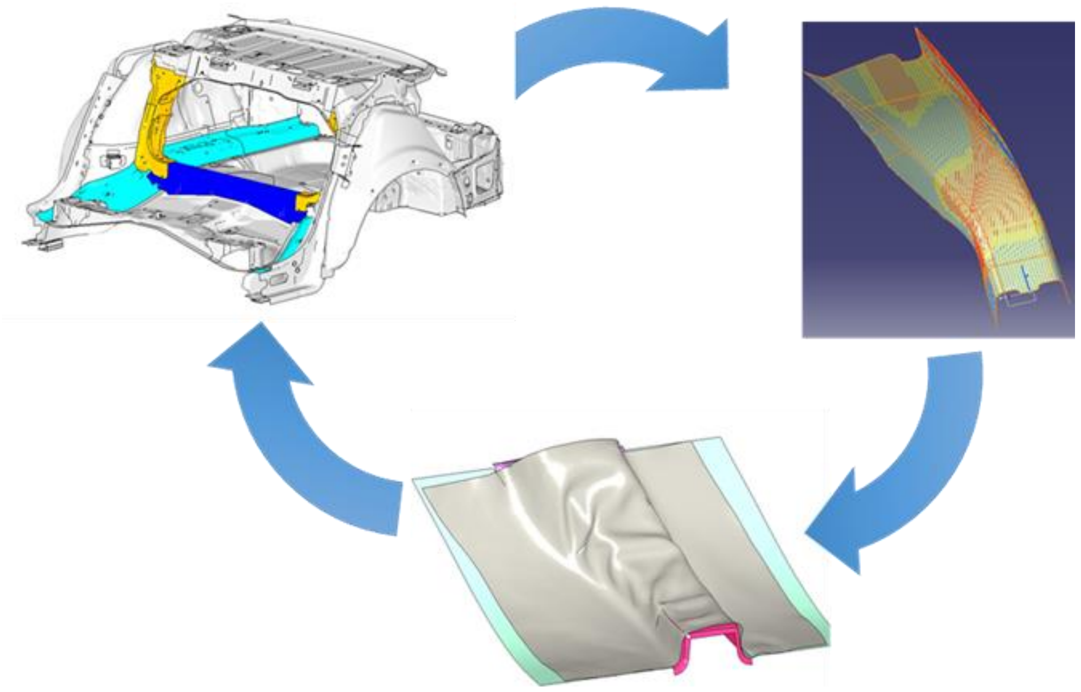
Process Simulation of Compression moulding – PROSICOMP



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Projekt inom Hållbar Produktion

FFI Fordonsstrategisk Forskning och Innovation

VINNOVA Energimyndigheten TRAFIKVERKET FKG VOLVO SCANIA VOLVO

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1 Summary

I Prosicomp-projektet som leds av svensk industri och akademi görs en kraftansamling att utveckla och möjliggöra användning av varmpressning (SMC-pressning) av kompositmaterial (en kombination av kontinuerliga och diskontinuerliga kolfiberkompositer). Processen är speciellt lämplig för strukturella komponenter som tillverkas i hög volym. Två doktorander har varit involverade i projektet med att förbättrade simuleringsmetoderna och resultatet har lett till högre noggrannheten förpressningssimuleringar av både SMC och prepreg.. Forskningen i Prosicomp har lett till att doktoranderna snart är klara med licentiatexamen. Ett antal mål för Prosicomp-projektet har uppnåtts:

- 3D-flödesimuleringar som fångar SMC-flöde i komplex geometri med luft som en tredje fas
- Mätning och modellering av intralaminärt skjuvbeteende i pressad snabbhärdande prepreg
- Materialkarakterisering av SMC
- Tillverkning och provning av valideringsdetalj
- Publikationer som ingår i licentiatexamen för två doktorander

De uppnådda forskningsmålen stöder utvecklingen mot att skapa fysikaliskt baserade simuleringsmodeller. Trots de förbättringar som utförts i projektet är simuleringsmetodernas för pressning av komposit långt ifrån lika effektiva och noggranna som metoder som används för simulering av plåtformning, där intensiv forskning har pågått i decennier. Det är därför viktigt att fortsätta det pågående arbetet med förbättrad noggrannhet och förbättrad användbarheten för de utvecklade metoderna. Fortsatt utvecklingsarbete är viktigt för att simuleringsmetoderna ska få industriell användning. I fortsättningsprojektet Prosicomp II är den viktigaste målsättningen att göra de nya metoderna tillräckligt noggranna så att de blir användbara som ett dagligt verktyg för beräkningsingenjörer och konstruktörer i industrin.

2 Executive summary in English

The Prosicomp project is a serious effort led by Swedish industry and academia with the objective of enabling the use of compression moulding of composite materials (more specifically a combination of continuous and dis-continuous carbon fibre composites). This is a process that is particularly suitable for manufacturing structural components at high volumes. Two PhD-students have been engaged in the project, and they have improved the accuracy of SMC and prepreg compression moulding, respectively. They are both on track to completing their licentiate degrees. A number of goals of the Prosicomp project have been achieved

- 3D flow simulations capturing carbon fibre SMC flow in complex geometry with air as a third phase
- Measurement and modelling of the intraply shear behaviour of pressed snap cure resin prepreg
- Material characterisation of SMC materials
- Development of simulation validation methods
- Manufacture and testing of validation parts
- Publications that will be part of the licentiate degrees for two doctoral students

The achieved research goals support the development of simulation models based on a solid background of material behaviour. However, despite the ongoing efforts, the maturity of the simulation methods is still far behind process simulation methods for metal manufacturing where intensive research has been going on for decades. It is therefore important to continue the ongoing work regarding improved accuracy as well as improving the usability of the methods developed. Continuing the development work is important in order to get the simulation methods into industrial use. In the continuation project Prosicomp II, the most important goal is to make the new methods accurate enough to be useful as a standard tool for computational engineers and designers in the industry.

3 Background

The automotive industry is currently facing significant challenges in order to meet future environmental legislations. The targets of 95 g CO_2/km for 2020 and 75 g CO_2/km for 2025 are major and immediate challenges. These targets mean either electrification or drastic weight reduction of the body-in-white of over 100 kg after 2020. Weight reduction is also important to electrification as this allows more weight for the batteries, increasing their range. The potential weight saving using current technology and extended use of ultra-high strength steel and aluminium is around 50 kg. Hence, a significant use of structural composites is the only way of reaching the weight reduction requirements, see Figure 1.

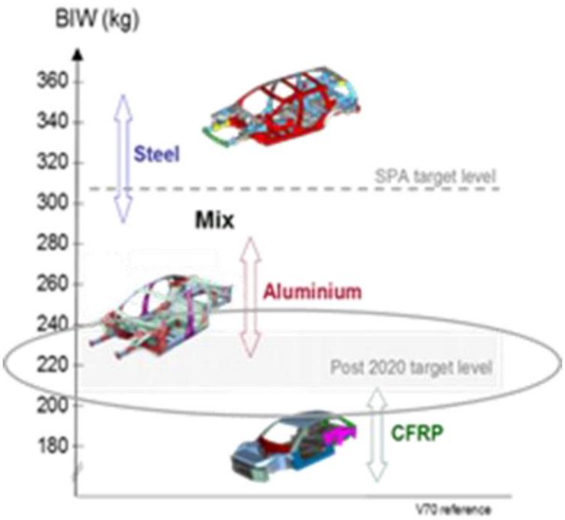

Figure 1 Illustration of weight saving potential using different

For this to be feasible for high volume car models the relatively high cost of the composite material needs to be counteracted by an efficient manufacturing method, low material waste and replacing several traditional metal parts with one composite part.

One manufacturing method that has potential for this is compression moulding of discontinuous fibres (Sheet moulding Compound (SMC), 25-50 mm fibres), continuous fibres (prepreg) and a mixture of these. One obstacle for applying these methods in high volume manufacturing is the lack of accurate process simulation tools which are essential in the automotive industry. With a development time of about 30 months for a new car model (aiming at 20 months in the near future) there is no time to use prototype tools for tuning the manufacturing process. The virtual tools used to optimize the manufacturing must be accurate enough to be able to build serial tools directly. The virtual tools for metal forming processes have been developed for several years in order to reach such accuracy. For compression moulding of composite materials such tools are still not detailed and accurate enough to avoid prototype tooling before serial production. Another area that is very important especially for OEMs are virtual tools for concept design, material selection and for doing the base documentation for ordering parts from a sub-contractor. Such tools need to be quick and less detailed than the tools for optimizing the actual manufacturing process. These tools are also important for subcontractors in the quotation process.

The aim of the Prosicomp project was to develop process simulation models and conceptual tools for compression moulding of both carbon fibre SMC (CF-SMC) and prepreg compression moulding (PCM). In the planned continuation project, the simulation of a combination of these methodologies will be developed. The development of the simulation methodologies will be conducted mainly by KTH and LTU respectively, in cooperation with the other partners of the

Project. The simulation models will also be validated by compression moulding experiments in an as realistic high-volume manufacturing environment as possible.
When manufacturing composites with compression moulding of SMC several issues need to be considered for optimal performance of the final part. Issues such as weld-lines, poor filling, incorrect fibre orientation, high void content and un-wanted shrinkage and deflections (i.e. spring back) may deteriorate the properties. To be able to minimize the influence from such defects, the filling of the mould during compression needs to be predicted and controlled. For relatively fast predictions the models may be based on continuity and the Folgar–Tucker model [1] or extensions of it [2] while for advanced methods fully three-dimensional flows and digital models may be applied as done in [3-4]. In [4] different models to predict the flow and heat transfer during moulding were evaluated and proper models to predict the pressure during the compression stage were found. Complementary to this are models for fibre orientation from [1-2], for instance, or approaches such as treating the fibre network as a deformable porous media [5]. In order to give relevant input data to the modelling, calibrate the simpler models and validate the models derived, experiments were to be performed in a well-controlled industrial press at SICOMP [6-7]. However, due to faulty and irreparable control systems, as a temporary solution, an SMC press at a local company in Kalix was used instead. Note that future press investigation will be carried out in the new 1200 ton press currently being installed at the sustainable composite manufacturing testbed in Piteå. The models obtained will be challenged with models used in commercial software like Moldflow [11] or 3D Timon and ways to couple the results to modelling of the performance of the part will be evaluated.

Compression moulding of continuous fibre materials with aligned fibres in well-defined fibre angles requires good knowledge of the forming process in order to produce flawless components without wrinkles of faults.

Several studies have been published on stamp forming of thermoplastic prepreg materials and focusing on the forming resistance, material shear and wrinkle development [12,13,14] as well as the mechanical performance of produced components [15]. Most of these studies are considering forming of single layers visualized on forming of a half sphere [16]. In combination with these forming experiments, the maximum intra-laminar shear of the material is commonly defined. In practice, multilayer forming is used, meaning that the forming behaviour is also highly influenced by the inter-ply shear resistance [17,18], since the different layers need to slip on top of each other during forming in order to avoid wrinkles. Another important material characteristic determining forming outcome of a material system is the out-of-plane bending stiffness [19,20,21].

The simplest forming models use kinematic draping where the only deformation mode is intra-laminar shear [22]. This holds fairly well for simple cases where this deformation mode dominates. To perform more detailed simulation analyses, continuous material models describing the intra-ply, inter-ply and out-of-plane deformation behaviour of the material are required. Two different software dedicated for detailed forming analysis are currently available on the market [23,24].

KTH has during the last 10 years worked with forming of multilayer, UD thermoset prepreg using vacuum forming towards a single sided mould; a technique commonly referred to as Hot Drape Forming (HDF) [25,26]. Methods for characterizing different material systems in terms of intra-ply shear and inter laminar shear has been developed [18,27] in order to find suitable material models [28] for detailed FE simulations aiming to explain e.g. how the stacking sequence [29,30,31,32] and draping sequence influences the wrinkle development during forming [33]. Material deformation during HDF is very similar to during compression moulding, but since the latter uses much higher forming pressures and speeds, material models needs to be extended covering a larger process window which potentially will magnify other material phenomena than known today.

In the field of compression moulding there are, within Sweden, a number of projects going on and some projects which had be just finalized as Prosicomp started. In these, parts of the consortium were participating. These projects (e.g. SALLSA, PRODKOMP1 (FFI), Triple Use, ROBUST and PRODKOMP2 (LIGHTer)) focused mainly on developing and learning the manufacturing process from an empirical point of view. The knowledge from these projects helped raise the correct questions and highlighted important issues when it comes to developing virtual tools for process simulation of compression moulding. The outcome from this project will also strengthen and increase the impact of the other projects since accurate simulation models is a requirement to achieve the rapid development of new car models within the automotive industry.

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4 Aims, Research Questions and Methods

Prosicomp aimed to developing the area of process simulation for compression moulding of composite materials. Compression moulding is a manufacturing methodology with high potential to manufacture composite structures of low weight and high mechanical performance in an efficient way (short cycle time, high degree of automation) and with very small amounts of waste material. As opposed to other composite manufacturing methods it is also important to note that investments in metal forming presses already made by the automotive industry could be reused instead of investing in a new infrastructure. Compression moulding has been around for decades but recent developments in material has made compression moulding of carbon fibre composites possible which also enables the use in structural components (e.g. body-in-white). The process for using these materials are being developed in several research projects both within and outside of Sweden but the tools for simulating the process are still not accurate enough for a large-scale production. The time it takes to develop a new car (~30 months) requires accurate simulation tools since the traditional composite way of making prototype tooling and adjusting after prototype manufacturing will simply take too long time.

The project aimed also to increase the research and innovation capacity in Sweden by taking two new PhD-students to their licentiate with competence in design, modelling, composite materials and manufacturing processes. It will also increase the knowledge in these areas at the involved companies and strengthen their already strong research organizations in a new area.

All project partners have competence in their areas that is at the highest international level. Since all partners work together, learn from each other and use their competences to develop a new

application in an area that is very important for the future, the research environment has been strengthened at company level for all participants. It has also strengthened the networking among the partners which will also benefit research and development outside this project. Since Toray has a strong position in their area internationally and even more so in Japan, this project gives the Swedish participants a fruitful opportunity to interact more with that region. The project also promoted the cooperation between two large Swedish OEMs (SAAB and VCC). Gestamp Hardtech is today a large subcontractor to the automotive industry in press hardened boron steel, and they are now aiming for new product areas which involve composites. This project thus strengthens their position in the industry and it also strengthens the Swedish R&D department within the Gestamp group which is beneficial for keeping qualified job opportunities in Sweden. Through this project the participating Swedish companies will, as already mentioned, gain a competitive advantage which will result in more work within the Swedish industry. This will therefore benefit all levels in the value chain (SMEs, subcontractors and OEMs).
Since both automotive and aeronautic industries are represented in the project, the project improves cooperation between these industries. Since Sicomp, Toray and the universities have experience in working together with both types of industries, the project already started with a good understanding for the needs, similarities and differences in the participating industries which ensured a well-planned and smooth-running project.

Prosicomp also worked towards the objectives of the program “Sustainable production” (“Hållbar produktion”) in several competence areas. Some examples are forming, material models, minimization of waste products and specific manufacturing methods for certain materials. Also as a more general note, most of the program and competence areas are dependent of accurate process simulations which today don’t exist for compression moulding of composite materials. According to the roadmap for “FFI Sustainable production” the purpose of the program is to enable manufacturing of new vehicle solutions and stronger global competitiveness while allowing lower environmental effects and higher vehicle safety. The roadmap identifies two main tracks for obtaining this; weight reduction and a higher degree of electrification.

This project followed the track of weight reduction since the development of process simulation tools as well as virtual tools for the early stages of industrial projects are essential for the implementation of compression moulding of composites in the automotive industry. The use of composite materials will in turn reduce the overall weight of the vehicles.

The second main track of the roadmap, “higher degree of electrification”, is not addressed directly but a weight reduction of the body-in-white would enable larger batteries and hence contribute to a higher degree of electrification.

Since the consortium represents the entire value chain, the development of knowledge is easier and new partnerships were developed. This also increases the probability that the results are implemented industrially, generating new partnerships for future research. Participating companies also have good opportunities to commercialize the results of this project.

5 Goal

The goals of the first Prosicomp project were to:

- Develop process simulation models and conceptual tools for compression moulding of carbon fibre SMC (CF-SMC)
- Develop process simulation models and conceptual tools for prepreg compression moulding (PCM)
- Manufacturing trials for validation in a process that is realistic to the automotive industry
- Review of methods for quality control

- Plan for continuation project
- Two Licentiate theses

6 Results and goal completion

The Prosicomp project was delayed by 8 months and the end date moved from August 2019 to April 2020. This was due to the fact that the project required the recruitment of 2 PhD students and the main research work was to be done by them and supported by the other partners, both industrial and academic. The recruitment and registration process took several months.

For the SMC modelling, different approaches were investigated before settling on using the work done by Kluge et al (1). This is summarised in the literature review done by Gustaf Alnersson, which was presented by him at the FPCM conference (2) and recently submitted to the journal Processes (3). At the same conference, Aitomäki also presented different commercially available methods that were tested on simple geometries (4). The preliminary tests showed that 3D Timon can show where filling issues can arise. Some new implementations in LS-Dyna for thermoplastic based fibres composites were also applied to SMC material, showing promising results but currently lacking stability in the solutions (5). However, it showed that some degree of tool design assessment can be done through these new implementations.

The advanced modelling work has been published at a conference and is currently extended with a simple model for the fibre orientation. This work uses a 3D model for the flow and energy balance and a proper viscosity model for the fluid. It shows the effect of the temperature of the tool on the flow front and how in certain geometries the flow can pass sharp corners resulting in a complex flow front direction at these points and this is likely to have an important effect on the fibre direction at these locations. The model has since been developed to add a model for the fibre orientation based on the work by Advani and Tucker (6) to the now 3D flow. Work on the validation of this, as well as adjustment to the code are being made and should be ready for publishing in March/April. With these two publications and a peer reviewed conference proceeding, Gustaf Alnersson is in a position to take his licentiate in Autumn 2020. The plan has been slightly delayed due to short time working at Gestamp and the impact of the change in working conditions due to the COVID-19.

RISE has been working on validation methods and has come up with a method of assessing the flow front by stopping the press process before completion and scanning the resultant components. This makes use of the fact that the SMC is a rapid curing system with high fibre content hence the flow is unlikely to move unless pressed further allowing the flow front to be captured without much distortion. The results also showed the variation that exists between components with complex geometries. The method has been published in a technical report (7). The resulting component are also being cut up to analyse the fibre orientation as a further method of validation and will be used to validate the 3D particulate flow model developed by Gustaf Alnersson and LTU. The validation method has been applied to manufacturing trials based on a process and component that are realistic and relevant to the automotive industry. The tool that has been designed and used for these trials has a rib structure that can be removed, and the tool can be modified to test prepreg components.

The current state of the art prepreg forming models are investigated and summarised in the literature review submitted by Kumaraswamy as a deliverable in the project (8). The existing models are capable of capturing the dominant deformation mechanisms in a single ply. During multi-layer forming of prepregs, Sjölander (9) has shown that interply friction has an impact on the forming induced defects. The state-of-the-art interply friction modelling technique and its significance in predicting defects is demonstrated on an automotive component and presented at Svenska Mekanikdagarna 2019(10). The cost and weight effectiveness of combining SMC and continuous fibre prepregs are also highlighted.

Generally, automotive components consist of multiple layers of prepregs with different architectures i.e. Unidirectional tapes and woven fabrics. The first paper summarises the in-plane formability of fast cure UD tape and a plain weave prepreg. A comparison in the intraply shear mechanism in these two architectures is done. The desired temperature window for processing the prepregs is identified. The results show a basis for using a multi-scale modelling approach for virtual testing for formability of composite prepregs of different architectures. The extended intraply shear tests showed the effect of ply/ply friction on the in-plane formability of the plies. The inability of the current friction models to capture the load response of stacked prepregs during pure in-plane shear shows the requirement to have improved methods to model the friction accurately. This work is described in Kumaraswamy et al's first publication (submitted). The second publication will focus purely on interply friction and the techniques to model the same.

Work on prepreg has also been carried out by Per Hallander from SAAB who investigated pressing prepregs with fluid cell press. This work, in collaboration with KTH, supported the Prosicomp project and led to a publication (11) and a conference article (12).

A draft review of methods for quality control has been done and described in a technical report for the project. The review shows that whilst advancements are being made with CRT for assessing component quality, it is not as suitable for composites as for other materials due to their low density and the nature of the type of void or crack found in composites. Shearography based systems and methods based on induction for carbon fibre composites are a more obvious choice as well as ultrasound systems when used together with high precision location devices or setups.

One aspect that has proved challenging is the material characterisation of the rapid curing SMC. The approach to overcome this is to use inverse modelling from simulations from LSDyna and 3D Timon. However, developing the fully functioning models for both these systems is required. Hence only a draft with preliminary results has been produced so far that has been shared with the other partners.w An updated version and publication of this work will be done in the follow up project, Prosicomp II.

The table below summarises the status so far with regards to goal completion

Develop process simulation models and conceptual tools for compression moulding of carbon fibre SMC (CF-SMC)	3D models has been developed that can be used with complex geometries and includes air. This has now been extended to include particulates, allowing fibre orientation and thus the mechanical properties of the material to be predicted.
Develop process simulation models and conceptual tools for prepreg compression moulding (PCM)	The mechanisms governing the behaviour during forming of multiply stacks of prepregs have been identified. A model accounting for several of these mechanisms is under development and is awaiting validation.
Manufacturing trials for validation in a process that is realistic to the automotive industry	These have been done. Development material from Toray with high fibre content and rapid cure time as well as being styrene free has been tested and shown to fill complex geometries successfully. Validation methods for the simulations based on these trials have been development.
Review of methods for quality control	In draft form.

Plan for continuation project	Project proposed, planned and started.
Two Licentiate theses	Gustaf Alnersson is expected to publish his licentiate in Autumn 2020 with two journal papers (1 in draft form) and 1 conference proceeding. Siddharth Kumaraswamy's first paper is submitted. Work with the second paper is ongoing. Siddharth is pausing his PhD studies and the decision to continue the studies will be taken during the continuation project. Meanwhile, he will be involved in the work forward and engage with and support KTH in the project.

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7 Dissemination and publication

7.1 Dissemination of knowledge and results

How will or are the project results used and disseminated?	Mark with X	Comments
Increase knowledge in the field	X	
Passed on to other advanced technological development projects	X	The work is intended to be used as a basis for a direct continuation project, Prosicomp II

Will be passed on to product development projects	X	The results from the project have already been partly used in product development studies.
Introduced in the market		
Used in investigations / regulations / permit cases / political decisions		

7.2 Publications

Alnersson, G, Ljung, A-L, Lundström, T. S. Numerical Study of the 3d-flow characteristics during compression moulding of SMC. In: TWENTY-SECOND INTERNATIONAL CONFERENCE ON COMPOSITE MATERIALS (ICCM22). 2019

Alnersson, G, Tahir, M. W., Ljung, A-L, Lundström, T. S., Review of the Numerical Modelling of Compression Moulding of Sheet Moulding Compound, Submitted to *Processes*

Aitomäki Y, Berglund D. A comparison of the approaches to process modelling of sheet molding compound. In: 14th International Conference on Flow Processing in Composite Materials (FPCM-14). 2018.

Aitomäki Y, Ahlqvist F, Westerlund R. CR19-010 Verification method development for SMC simulations: Test using 3D Timon on a beam with rib. 2019.

Aitomäki Y. Rapid cure advanced sheet moulding compounds:Characterisation for process simulations and flow orientation. In: Produktionskluster konferens. 2019.

Hallander P., Grankäll T., Åkermo M. Fast forming of aircraft composite parts. In: AEROSPACE TECHNOLOGY CONGRESS, FT2019 October 8-9, 2019 . Stockholm; 2019.

Hallander P, Sjölander J, Petersson M, Andersson T, Åkermo M. Fast forming of multistacked UD prepreg using a high-pressure process. Polym Compos. 2019 Sep 22;40(9):3550–61.

Kumaraswamy S., Gutkin R., Åkermo M, In-plane formability of fast cure prepregs. 2019, To be submitted.

Kumaraswamy S., Gutkin R., van der Putten Z. and Åkermo M., Design and process analysis of composite reinforcement for automotive Body in White. Svenska Mekanikdagarna, 2019, KTH Royal Institute of Technology; 2019.

Kumaraswamy S., Integrated design and process analysis of composite body structures. VIPP Conference 2019, Gothenburg 2019.

Kumaraswamy S., Integrated process and design analysis of composites – Literature review, VCC Internal report, Gothenburg 2019.

Kumaraswamy S., Research question and modelling approach, VCC Internal report, Gothenburg, 2019.

8 Conclusion and further research

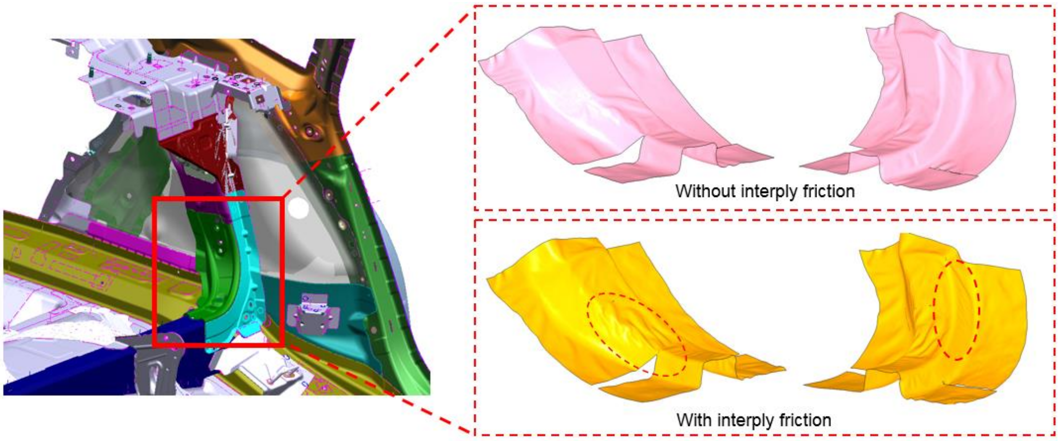
The Prosicomp project is a serious effort led by Swedish industry and academia with the objective of enabling the use of compression moulding of composite materials (more specifically a combination of continuous and discontinuous carbon fibre composites). This is a process that is particularly suitable for manufacturing structural components at high volumes. Prior to the project it was concluded that process simulation methods for such manufacturing were too immature to be applied in industrial product development. The two PhD-students engaged in the project are improving the accuracy of SMC and prepreg compression moulding respectively. Despite the ongoing efforts, the maturity of the simulation methods is still far behind process simulation methods for metal manufacturing where intensive research has been going on for decades. It is therefore important to continue the ongoing work regarding improved accuracy as well as improving the usability of the methods developed. This is an important task in order for the methods to be industrially implementable and not just of academic interest. In the upcoming project Prosicomp II, making the new methods usable in the industry is one of the major activities.

Important steps have been taken in this project through the development of models that can account for the behaviour of ply-to-ply interactions in the forming of multi-ply compression moulded prepreg stacks. The project has identified the mechanisms that govern the behaviour in forming of fast cure prepreg materials. The importance of accurately describing the interply anisotropic friction behaviour has been highlighted as critical. Existing numerical models of interply friction are unable to accurately capture the sliding behaviour in multi-layer composites. This has been proven using experimental tests and correlation.

As a next step the models will be further developed with the addition of anisotropic friction models describing the sliding conditions between plies. This will be directly implemented into state-of-the-art commercial software used in the automotive industry.

From a commercial product perspective, the combination of modern advanced SMC systems with fast cure prepreg materials is highly interesting and more relevant for the automotive industry than ever. The research continuing the Prosicomp results need to address this topic and develop models that allow simulation of the combination of SMC-prepregs.

Prepreg forming model used in process simulation of a car C-ring component at Volvo Cars.



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