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# A quantitative comparison of experimental and numerical orientation and mechanical results in weldlines of short fibre reinforced thermoplastics

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**ABSTRACT:** Complex injection moulded parts often present some structural defects, like weldlines or meldlines. For short glass fibre reinforced thermoplastics, these defects strongly affect the mechanical properties of the parts. This project is a collaboration between two laboratories (CROMeP : Material Research Centre of Ecole des Mines d'Albi, PRO<sup>2</sup>COM-LGTM : Toulouse Mechanical Laboratory) and three companies (Technofan, Microturbo, Liebherr Aerospace). We calculate, using Moldflow® MPI 2.0 software, the fibre orientations in the weldline region. This allows us to evaluate the mechanical properties of the part. This study is realised using an ISO specimen geometry, with a volume deviation channel. Then, calculated orientations and mechanical results are compared to experimental data (based on SEM observations and mechanical testing) using a Krigging interpolation method.

**Keywords:** injection moulding, fibre, weldline, deviation, krigging, Moldflow®, mechanical behaviour

## 1 INTRODUCTION

Equipment designers want to substitute conventional metallic alloys (steel, titanium, aluminium) for non-structural aeroplane parts. As a consequence, there is currently considerable interest in short fibre reinforced thermoplastic composites. These materials are easily processed and they also offer advantages of low cost and mass or special characteristics (chemical and fire resistance), very useful in the aeronautic field. The injection molding process allows to create very complex shapes without post machining and can be justified, even with relatively short series. Unfortunately, studies over many years (1, 2, 3) have shown quite complicated fibre orientations which depend on a lot of parameters, and on the cavity geometry. Meldlines are created when at least two flow fronts join each other with non opposite path (4). This is a common phenomenon appearing during the mold filling stage, and leading to particular fibre orientation distribution.

In this paper, we propose an original method to detect quantitative fibre orientation comparisons. Experimental measurements are based on SEM observations. Injection moulding simulations are realised using Moldflow® MPI 2.0 software. The way we use to quantify the orientation distribution of a given area uses a 2D Krigging interpolation method. We study the effect of the flow deviation through a weldline as an application of this method. This leads to an evaluation of the limitations of Moldflow®, and it gives us a better understanding of the deviation effect throughout thickness, including the mechanical response.

## 2 EXPERIMENTAL DETAILS

### 2.1 Injection moulding of the specimen

The moulded parts are ISO specimens for tensile test. They are manufactured on a DK-Codim 175 tons injection moulding machine. The material is a 30% weight short glass fiber reinforced

polyetherimide (grade Ultem® 2300-1000 natural, supplied by General Electric Plastics). The injection moulding machine has a complete instrumentation system. We can measure and have a real time acquisition of temperatures and pressures in the mould cavity, and of all process parameters from the injection unit. The parts are middle-gated ISO specimens. This allows us to calculate weldline factors (ratio: welded out of non-welded mechanical property) with specimens moulded in exactly identical conditions. The mould cavity has a deviation canal, which can be stopped up at different positions (see Fig. 1).

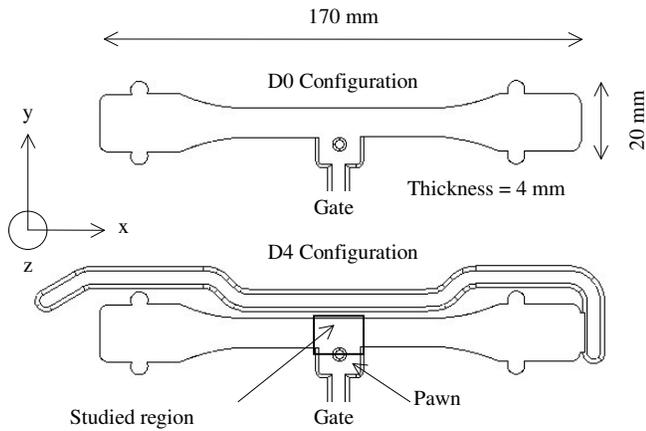


Fig. 1. ISO specimen and deviation configuration

The deviation canal is filled when the reference ISO cavity (D0) is full. The effect is a flow through the meldline, and the aim is to increase mechanical properties of the meldline (5).

## 2.2 Samples preparation and image analysis

The 4 mm thick specimens are cut in the meldline region in order to have views in the (x ; y) plane. All samples are polished with a 1 µm disc at three different positions throughout thickness. The skin layer is analysed with a 0.1 mm depth polishing operation. The intermediate and the core layers are respectively measured with 1 mm and 2 mm polishing operations. This choice of thickness division is done assuming a five layers fiber orientation distribution (1). Two skin layers (random orientation), two intermediate layers (orientation parallel to flow direction), and one core layer (orientation perpendicular to flow direction). At the end of the analysis operations (SEM observation and image analysis), all geometrical parameters are measured on the good particles (cut fibres), in order to calculate the orientation of each associated fiber.

The Advani tensor components " $a_{ij}$ " (6) are finally calculated. A correction function uses the average diameter and the length of the fibres. These dimensions are measured using a calcination method on 1000 fibres. Our experiments show an average diameter of 12 µm and an average length of 200 µm for the Ultem® 2300-1000 (7). An average for the picture (790 µm × 900 µm) is calculated for each Advani component (see equation 1), and the values are applied to the gravity centre of the image.

$$\underline{a} = \begin{bmatrix} \sin^2 \theta \cos^2 \varphi & \sin^2 \theta \cos \varphi \sin \varphi & \sin \theta \cos \theta \sin \varphi \\ \sin^2 \theta \cos \varphi \sin \varphi & \sin^2 \theta \cos^2 \varphi & \sin \theta \cos \theta \sin \varphi \\ \sin \theta \cos \theta \sin \varphi & \sin \theta \cos \theta \sin \varphi & \cos^2 \theta \end{bmatrix} \quad (1)$$

Where,  $\theta$  is the angle between y axis and fiber projection in (x ; y) plane, and  $\varphi$  is the angle between z axis and fiber.

## 2.3 Fibre orientation representation

Fibre orientation cartographies cover a range of images (experimental cartographies) or a range of mesh elements (calculated cartographies). As we want to have a quantitative comparison between experimental and calculated cartographies, we use a 2D Krigging interpolation method (8) in order to represent the fiber orientation statement in a given region of the part. Each SEM image and mesh element is associated with its gravity centre. This means that the studied region corresponds to a discontinuous area. Then, it must be transformed in a continuous area using an interpolation method: the dual 2D Krigging (8).

## 2.4 Mechanical testing

In order to have a mechanical evaluation of the deviation effect, the ISO specimen are tested using a dynamometer (Instron® 4467), and under directives fixed by the norm NFT51-034. The speed is constant and its value is 1 mm/min. Temperature and hygrometry are at the atmosphere level. The deformation is measured using an Instron® extensometer of 25 mm length. The different configurations of specimen (D0 to D4) are tested (10 specimen for each configuration). The rectangular gates are cut, tangentially to the pawn print, using a precision tool in order to obtain a good smoothness of the surface.

### 3 CALCULATION DETAILS

#### 3.1 Injection moulding simulation

Numerical simulation of the injection process allows to calculate the fibre orientation distribution. Using commercial non-3D software (Moldflow® MPI 2.0), strong assumptions are still necessary to solve these equations numerically, and to reduce calculation time. These assumptions are not done for 3D software (9), but this is not the subject of this study which uses a commercial software.

Close to the gate, there is a 3D flow of melt entering the mold. At the flow front, the melt follows a flow path comparable to a fountain flow. This motion is also a 3D movement. A lubrication region appears between gate and flow front. It is characterised by laminar flow.

#### 3.2 Mechanical calculations

Fibre orientation results files from Moldflow® are used as input for a self-developed software called "MTD" (10). This software carries out the mechanical properties estimation along the structural finite elements model of the part. It uses the fibre orientation distribution and a Mori-Tanaka homogenisation method (11). As MTD is not format-dependant for output data, results can be used with several mechanical CAE software (ANSYS, I-DEAS, NASTRAN, SAMCEF, etc.). Thus, we are able to realise mechanical simulations using fibre orientation distribution throughout the volume of the injection moulded part.

## 4 RESULTS AND DISCUSSION

#### 4.1 Fibre orientation measurements

Fibre orientation measurements are realised on  $10 \times 13 \text{ mm}^2$  regions for three different layers throughout thickness (skin, intermediate and core layers, assuming thickness symmetry). Each region represents approximately 300 SEM images. The first Advani tensor component  $a_{11}$  is calculated. It is a good evaluation of the specimen mechanical behaviour in the longitudinal direction. We notice some important surface fluctuations for all experimental cartographies. This is due to the

measurement method which is based on an assembly of SEM images. Moreover, by construction, the Krigging interpolation method fits all data points. Then, all measurement dispersion is represented on the interpolated cartography.

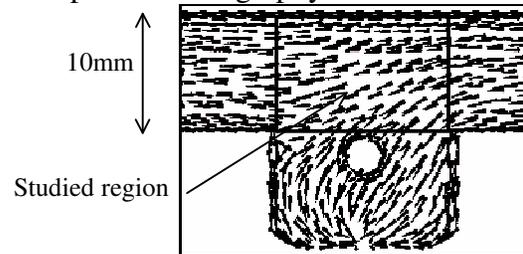


Fig. 2. Fibre orientation at core in pawn region for D4

The deviation rate does not have any significant effect on the skin layer. The fibre reorientation phenomenon is mainly located in the core (see Fig.2) and in the intermediate layers, because the polymer temperature remains much higher than in the skin layers. The intermediate layer of the welded specimen is less affected by the deviation flow than the core layer. In both layers, a reorientation path appears. The symmetry of defect disappears and more fibres are aligned in the longitudinal direction. The five-layers distribution was not observed for both D0 and D4 specimen.

#### 4.2 Mechanical testing

The fibres reorientation phenomenon is located in a part of both intermediate and core layers of the thickness. This explains the limited effect we notice on the mechanical properties of the specimen. The experimental weldline factor calculated on the longitudinal elastic modulus goes from 87% for the D0 configuration, to 97% for the D4 configuration.

#### 4.3 Fibre orientation calculations

Calculation results show a strong orientation in the longitudinal direction for both intermediate and core layers. Despite the existence of a skin layer, the other part of the thickness is quite homogenous. Moldflow® simulation does not show a five-layers orientation distribution. According to these calculations, the non-deviated specimen is highly oriented in the longitudinal direction. Moreover, the reorientation phenomenon is located to the very beginning of the weldline, and it appears for all the three layers we considered. Mechanical calculations are realised using MTD from Moldflow® fibre orientation results.

#### 4.4 Quantitative fibre orientation comparisons

There is a significant difference between both experimental and calculation results (see Fig.3). Across the studied region, the absolute difference on  $a_{11}$  equals 0.11 in the skin layer, 0.34 in the intermediate layer, and 0.38 in the core layer. Our simulations lead to a rather good prediction of the orientation distribution (about 10% confidence). It is to be noticed that the particular case we study in this paper does not respect the assumption of the thin flow channel thickness. As a consequence, the assumptions of the Hele-Shaw equation are not fully validated. We also notice that the studied region is very close to the gate. As the alimentation channels are 1D elements linked to the ISO cavity with a single node, important errors can exist in the entrance region.

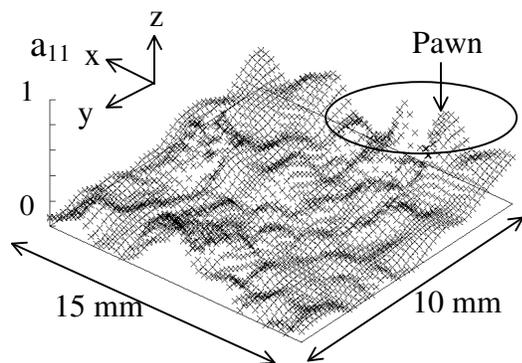


Fig. 3. Comparison between experimental and numerical fibre orientation results for D0 configuration (skin layer)

#### 4.5 Quantitative mechanical properties comparisons

The weldline factor calculated on the longitudinal elastic modulus goes from 95% for the D0 configuration, to 100% for the D4 configuration. Compared to experimental results, this mechanical property is very high. The gap equals 9% for the D0 configuration, and 3% for D4. This is much less than the fibre orientation gap, because of the "volume integration effect" of the elastic modulus.

## 5 CONCLUSIONS

The Krigging interpolation method is an original way to have quantitative comparisons by transforming a discontinuous data in a continuous surface. As an application of this method, we wanted to test the capabilities of Moldflow® MPI 2.0 software in the particular case of a deviated

meldline. This comparison region is characterised by a very complicated flow which does not perfectly respect all Hele-Shaw assumptions. We find a particular orientation distribution which is not constituted of a five-layers structure. Both core and intermediate layers are influenced by the deviation flow. The core layer is more affected than the intermediate one because of a higher temperature. We are able to have a quantitative difference between experimental and calculated data. This is an important tool for another project consisting in prediction of elastic mechanical properties of injection moulded parts including meldlines. Moreover, this method can be extended to 3D cases, using 3D Krigging interpolation.

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