# CHARACTERIZATION OF TOOL-PART-INTERACTION AND INTERLAMINAR FRICTION FOR MANUFACTURING PROCESS SIMULATION

Tobias A. Weber[1], Jane J. Tellis[1] and Miro Duhovic[2]

[1]Airbus Helicopters Deutschland GmbH, Industriestr. 4, 86607 Donauwörth, Germany
Email: tobias.t.weber@airbus.com, Web Page: http://www.airbushelicopters.com
[2]Institut für Verbundwerkstoffe GmbH, Erwin-Schrödinger-Straße 58, 67663 Kaiserslautern, Germany
Email: miro.duhovic@ivw.uni-kl.de, Web Page: http://www.ivw.uni-kl.de

**Keywords:** tool-part-interaction, interlaminar friction, fabric, manufacturing process simulation

**Abstract**
Tool-part-interaction and interlaminar friction influence quality parameters like fiber waviness, final part thickness, porosity, and also warpage created during autoclave manufacturing [1]. To predict these quality parameters by means of manufacturing process simulation, it is necessary to introduce interlaminar friction and tool-part-interaction into the simulation. Different testing methods are available to characterize both types of friction. This paper explains and compares two possible testing methods and discusses the outcome of the tests performed. Different factors influencing the friction are identified and their interactions are determined.

## 1. Introduction

Tool-part-interaction and interlaminar friction influence process induced deformations (PID) and fiber wrinkling [1-3]. Using the finite element method a simulation of heat transfer, curing, compaction, and stress development during manufacturing can be performed [1-2, 4]. If the necessary friction characterization has been done, tool-part-interaction and interlaminar friction might also be included [1-2]. An understanding of the friction phenomena and their influencing factors can help to develop a more efficient simulation methodology. The ASTM Standard D 1894-90 describes friction tests for composites using a test sled with dead weight [5]. Murtagh et al. [6] conducted similar tests. In addition, the so-called pull-out or pull-through tests are very common to determine interlaminar friction as well as tool-part-interaction. Ersoy et al. [7] and Larberg & Akermo [8] use different versions of those testing methods. A servo-hydraulic testing rig and a couple of heating plates are necessary to perform the tests. The normal forces are generated either by a hydraulic mechanism or simple springs.
This paper explains two testing methods that were derived from the approaches of the ASTM Standard D 1894-90 [5] and Ersoy et al. [7]. Both methods are compared and their advantages and disadvantages summarized. Furthermore, the results of both methods are analyzed with special focus on the influencing factors and their interaction.

Excerpt from ISBN 978-3-00-053387-7

## 2. Testing Methods

### 2.1. Scratch 4 Surface Tester

The SMS Scratch 4 Surface Machine™ was originally designed to test the resistance of hard surface coatings against cutting and scratching. It consists of a base plate for clamping down specimens and the testing unit that moves horizontally at a predefined speed. The testing unit itself applies a predefined normal force that is recorded in addition to the tangential force measurement. To enable friction measurements for prepreg material, the scratching needle is substituted with a test sled. The test sled can either represent a tooling coated with release agent or it can be designed to hold one or more prepreg layers. A heating plate is added to the base plate of the Scratch 4 Surface Machine to heat up the specimens. One or more layers of prepreg are clamped on top of the heating plate as shown in Figure 1. The set-up is similar to the ASTM Standard D 1894-90 [5] with the advantage that the normal force is measured directly. A constant testing area is used to simplify the determination of the coulomb friction coefficient. Two thermocouples are used to control the temperature of specimen and test sled which are both heated via conduction using the heating plate.

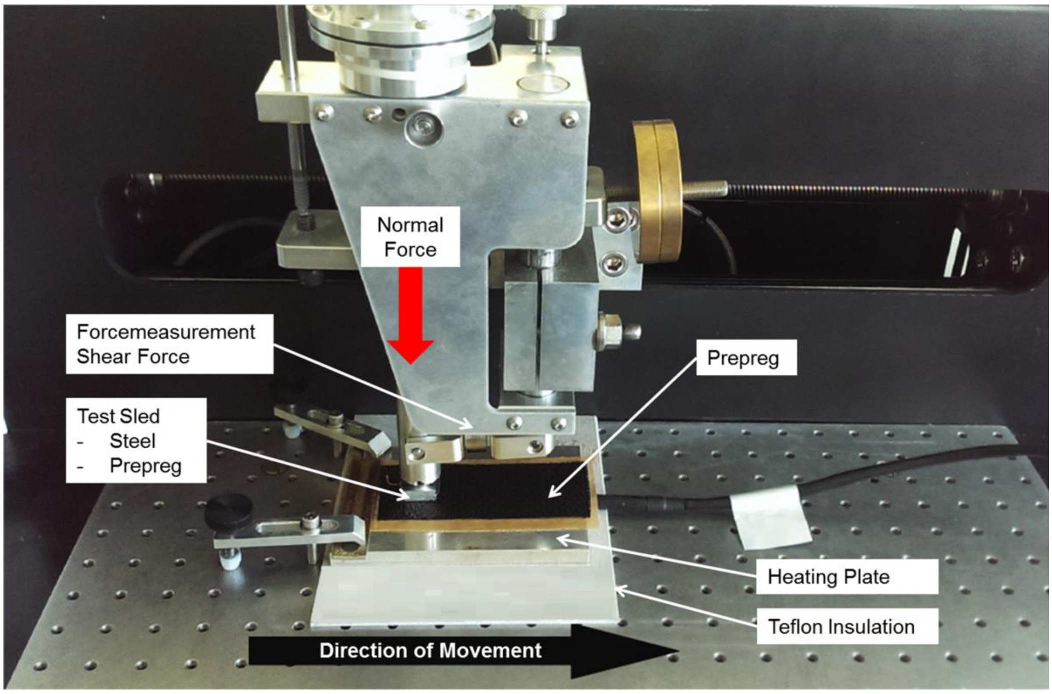



**Figure 1.** Scratch 4 Surface Machine

### 2.2. Pull-through Tests

The pull-through test is performed by pulling several prepreg plies or a metal strip out of a laminate to measure the resistance generated. A servo-electrical test rig in combination with a temperature chamber and a clamping device developed at Airbus Helicopters is used. The clamping device shown in Figure 1 was developed as a simplified version of the device shown by Ersoy et al. [7]. Instead of mounting heating plates directly to the clamping device a temperature chamber is used. This reduces the complexity of the clamping mechanism.

A disadvantage of this approach is the fact that the normal or clamping force, which is applied by four springs, might be affected by the thermal expansion of the device in the temperature chamber. To keep that negative temperature influence low, the maximum testing temperature is limited to 90°C and the

Excerpt from ISBN 978-3-00-053387-7

device is completely manufactured from steel instead of aluminum to keep the thermal expansion low. The normal force is adjusted using the length of the bushings placed around the screws. They function as a stop during assembly of the device together with the specimen and ensure that the same normal force is used for all tests. Much higher normal forces can be achieved than with the Scratch 4 Surface Machine. The testing area remains constant but is bigger than with the Scratch 4 Surface Machine, thereby reducing the impact of local variations in the fiber architecture on the measurement results.

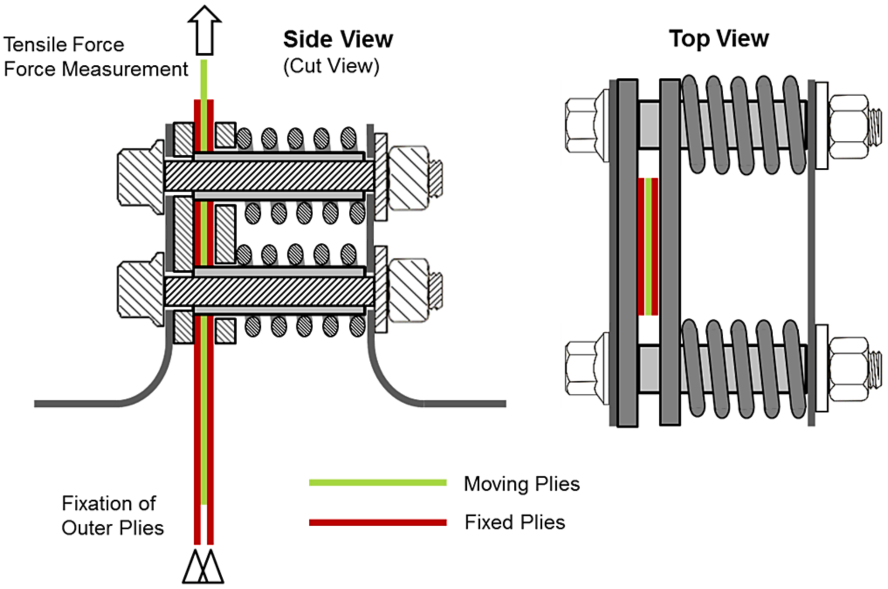



**Figure 2.** Clamping device for pull-thorugh tests

Advantages and disadvantages of both testing methods are summarized in Table 1.

**Table 1.** Comparison of both testing methods.

| | Scratch 4 Surface Tester | Pull-through Test |
|---|---|---|
| Normal Force | 1 N to 100 N | 200 N to 1000 N |
| Temperature | 130°C to 180°C | 20°C to 90°C |
| Velocity | 0.5 mm/min and above | depending on test rig |
| Testing Area | up to 625 mm² | up to 5600 mm² |
| Advantages | constant testing area<br>normal force measurement<br>pre-curing possible | constant testing area<br>high normal forces possible<br>small velocities possible |
| Disadvantages | high min. velocity<br>small normal forces<br>measurement limited to 8 min. | only for low temperatures<br>no measurement of normal force |

Excerpt from ISBN 978-3-00-053387-7

## 3. Test Results

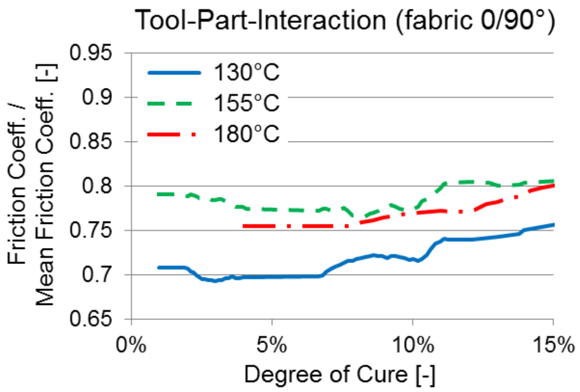
Hexcel HexPly M18/1™ unidirectional and fabric prepreg were used. The settings are summarized in Table 2.

**Table 2.** Settings for friction measurement

| | Scratch 4 Surface Tester | Pull-through Test |
|---|---|---|
| Normal Force | 10 N | 500 N |
| Testing Area | 625 mm² | 2500 mm² |
| Temperatures | 130°C, 140°C, 155°C, 180°C | 50°C, 60°C, 70°C, 85°C |
| Velocity | 0.5 mm/min | 0.5 mm/min |
| Orientations | fabric 0/90° to fabric 0/90°<br>fabric 0/90° to UD 0°<br>UD 0° to UD 0°<br>fabric 0/90° to tooling | fabric 0/90° to fabric 0/90°<br>fabric 0/90° to tooling |

### 3.1. Temperature and Degree of Cure Dependence

The tool-part-interaction reveals temperature dependence between 130°C and 155°C, whereas the difference between 155°C and 180°C is rather small and statistically not significant (Figure 3). It is rather unexpected that increasing temperature leads to an increasing friction coefficient. If hydrodynamic friction is assumed, increasing temperature should decrease the viscosity of the resin and thereby also decrease the friction coefficient. Increasing friction might be caused by an increasing fiber to tooling contact. The decreasing resin viscosity at higher temperatures and the continuous normal force will press some resin out of the contact area allowing more fibers to get into contact with the tooling. The friction coefficient slightly increases towards the gel point (about 40% degree of cure) and decreases again in the rubbery phase (Figure 3, right). An explanation can be found in Kaushik [9]. The increase beyond 60% degree of cure is a result of the resin becoming glassy and the friction changing to boundary friction behavior.



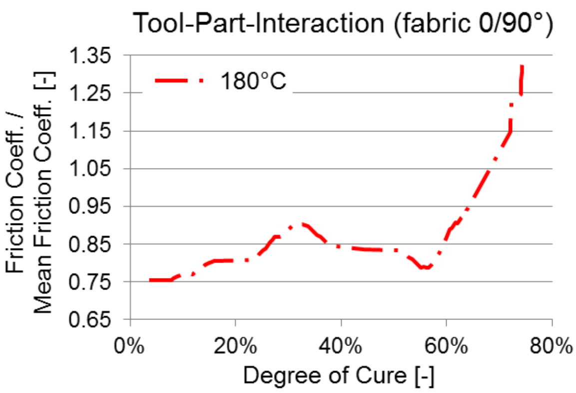




**Figure 3.** Temperature and degree of cure dependence of tool-part-interaction

For interlaminar friction, the temperature dependence is influenced by the material combination (fabric-fabric, fabric-UD, UD-UD). Figure 4 shows that the combination of two fabric layers has



Excerpt from ISBN 978-3-00-053387-7

almost no temperature dependence. The combination of fabric and UD on the other hand shows a significant dependence, which can also be proven statistically. These differences cannot be explained by looking into the behavior of the resin alone. It is the opinion of the authors that the fiber architecture of the prepreg and the degree of compaction interact with the temperature (Section 3.2). A degree of cure dependence could not be identified with statistical relevance, except for the strong increase when gelation occurs.

### 3.2. Dependence on Fiber Architecture and Degree of Compaction

The fiber architecture has a significant influence on the interlaminar friction and interacts with other influencing factors such as temperature and degree of cure. Figure 4 demonstrates that a fabric to fabric combination experiences almost no temperature dependence whereas fabric to UD shows significant temperature dependence. This temperature dependence is normally caused by the resin which changes its viscosity when altering the temperature. Therefore, every material combination that shows such dependence has most likely a resin dominated friction behavior, whereas fabric against fabric is dominated by the fiber to fiber contact.

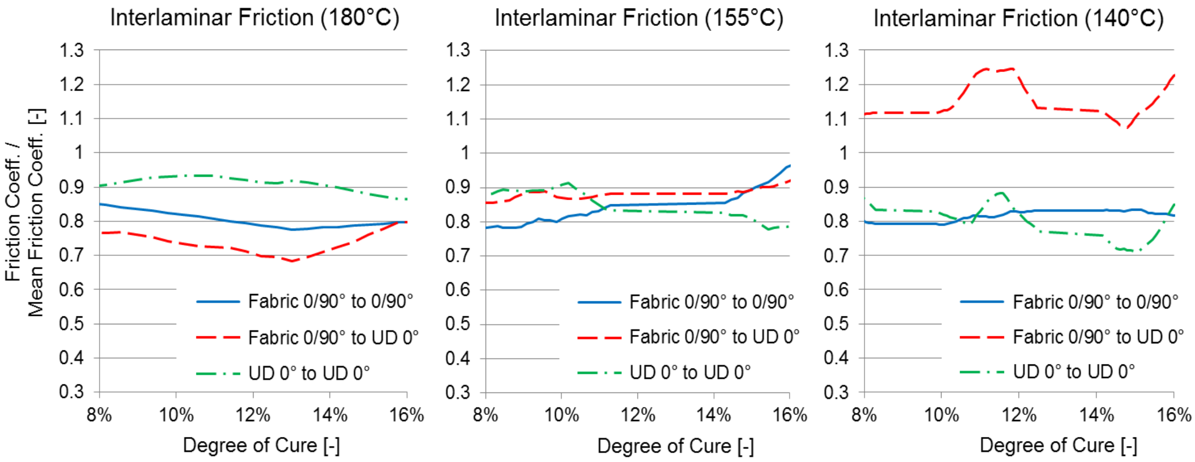



**Figure 4.** Temperature dependence of normalized friction values for interlaminar friction

Clifford et al. [10] summarized this behavior in a friction law for thermoplastic composite materials. It combines hydrodynamic with coulomb friction. Depending on the area of fiber to fiber or fiber to tooling contact the friction is dominated either by hydrodynamic or coulomb friction.

$$\tau = \eta \, \dot{\gamma} + \phi \, \mu_c \, P_N \tag{1}$$

$\tau$ is the acting shear stress between adjacent plies, $\eta$ the viscosity of the resin, $\dot{\gamma}$ is the shear rate, $\mu_c$ is the coulomb friction coefficient, $P_N$ the normal pressure, and $\phi$ the ratio of fiber contact area to total contact area. It is the opinion of the authors that this equation can also be used for thermosetting composites and explains the behavior shown in Figure 4. Using a combination of two 0/90° fabric layers, the fiber to fiber contact area is rather high ($\phi > 0.5$) leading to a coulomb dominated friction behavior that is temperature independent (compare Figure 5). Combining fabric with UD reduces the fiber to fiber contact area, because one of the plies does not have undulations (Figure 5, center right). The change in viscosity of the resin therefore has a bigger effect on the fabric-UD combination than on the fabric-fabric combination. From 140°C to 155°C resin viscosity decreases, having two counteracting effects. Reduction of viscosity reduces the hydrodynamic friction but also allows more resin to bleed out of the contact area, which increases the fiber to fiber contact area. Comparing 140°C to 155°C, we see a reduction of the friction coefficient of about 0.22. From 155°C to 180°C the mean decrease is only 0.14, although the change in temperature is greater than before. This is due to the already explained increase in fiber contact area which counteracts the reduction in friction on account of viscosity reduction.


**Figure 5.** Influence of fiber architecture on the interaction with neighboring plies

This theory is supported by the results of the pull-through measurements at lower temperatures (Figure 6). As a result of the higher normal forces applied in the pull-through tests, the resin can be squeezed out of the contact area allowing a greater fiber to fiber contact, especially for fabric material with undulations (Figure 5 center left). At low temperatures (50 to 70°C) the high resin viscosity reduces the flow velocity of the resin, thereby keeping a certain lubrication film intact. At higher temperatures (85°C and above) the resin can be squeezed out of the contact area allowing a greater fiber contact. The behavior in Figure 6 can therefore be explained by the interaction of reduced resin viscosity with increased degree of compaction. Between 50°C and 70°C the reduction in resin viscosity partly counteracts the increasing friction due to increasing compaction. The higher the temperature, the more resin can be squeezed out, reducing the lubrication film and increasing the intertwining of the fiber undulations. The increasing waviness of the measured curves is another hint toward that theory. At low temperatures the friction coefficient remains almost constant over time (Figure 6), which suggests a smooth hydrodynamic friction behavior. At higher temperatures and therefore higher degree of compaction, waviness is observed. This could be the result of fiber undulations interacting with each other as described on the right side of Figure 6. Undulations hitting each other increase the local normal forces, which results in an increase in tangential forces as well. After the undulations have passed each other, normal and friction forces decrease again (Figure 6).

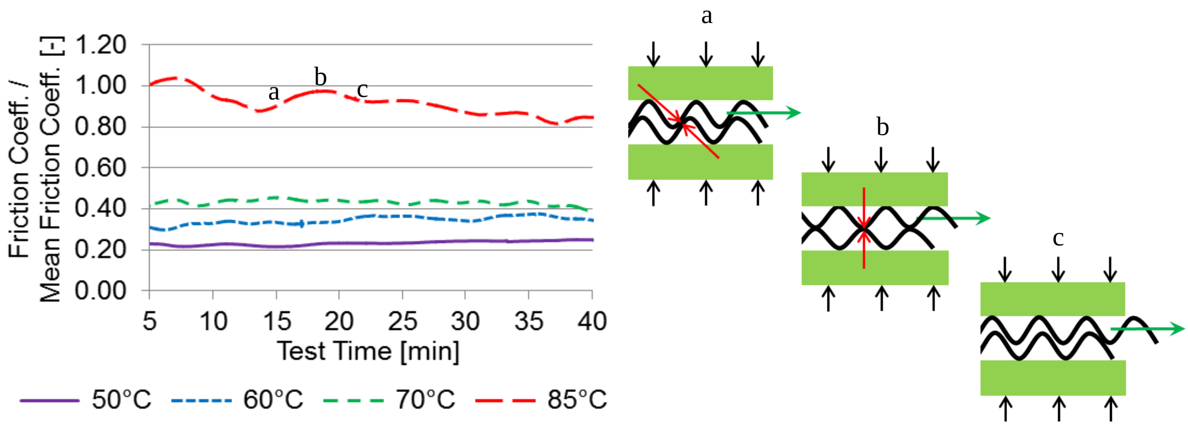



**Figure 6.** Influence of the degree of compaction on the firction coefficient for fabric-fabric-interaction

For the UD to UD combination almost no temperature dependence is observed. The reason is again the large fiber to fiber contact area that is caused by intertwining of the fibers of neighboring layers (Figure 5 right). The slight increase between 140°C and 180°C is most likely a result of the increased degree of compaction at higher temperatures and lower resin viscosity.

Excerpt from ISBN 978-3-00-053387-7

The tool-part-interaction tests (Figure 3) show an increase in friction coefficient from 130°C to 155°C, which is brought about by the increased resin bleed out at higher temperatures and the resulting increase in fiber contact area. A further in-creasing the temperature produces no significant change which is most likely caused by the interaction of decreasing viscosity with increasing fiber contact area. The combination of fabric to UD showed a similar interaction. The decrease in friction coefficient between 155°C and 180°C was caused by the increasing fiber to fiber contact area. Compared to the tool-part-interaction the decrease is not reduced to zero because both constituents are impregnated with resin, which allows a thicker lubrication film to remain even at 180°C.

## 4. Conclusions

Both measurement techniques can be used efficiently for friction measurements, but especially their combination revealed deep insights into the effects of the fiber architecture on the friction coefficient. The fiber architecture not only influences the friction coefficient itself but interacts with other influencing factors such as temperature and degree of cure.

## Acknowledgments

The work reported here is part of an ongoing PhD research project supported by Airbus Helicopters and the Institut für Verbundwerkstoffe GmbH.

## References

[1] G. Twigg, A. Poursartip, G. Fernlund. Tool-Part Interaction in Composites Processing. Part II: Numerical Modelling. *Composites Part A*, 35:135-141, 2004.

[2] A. A. Johnston. An Integrated Model of the Development of Process-Induced Deformations in Autoclave Processing of Composite Structures. *Vancouver, UBC, Dissertation*, 1997.

[3] K. Potter, M. Campbell, C. Langer, M. Wisnom. The Generation of Geometrical Deformations Due to Tool/Part Interaction in the Manufacture of Composite Components. *Composites Part A*, 36:301-308, 2005.

[4] Lightfoot, J. S.: Mechanisms of Defect Formation in Carbon Fibre Composites. *University of Bristol, Dissertation*, 2013.

[5] ASTM Standard D 1894-90. Standard Test Method for Static and Kinetic Coefficients of Friction of Plastic Film and Sheeting. *American Society for Testing Materials*, Philadelphia.

[6] A. M. Murtagh, J. J. Lennon, P. J. Mallon. Surface friction effects related to pressforming of continuous fibre thermoplastic composites. *Composites Manufacturing*, 6:169-175, 1995.

[7] N. Ersoy, K. Potter, M. Wisnom, M. Clegg. An Experimental Method to Study the Frictional Processes During Composites Manufacturing. *Composites Part A*, 36:1536-1544, 2005.

[8] Y. R. Larberg and A. Akermo. On the Interply Friction of Different Generations of Carbon/Epoxy Prepreg Systems. *Composites Part A*, 42:1067-1074, 2011.

[9] V. Kaushik. Experimental Study of Tool -Part Interaction during Autoclave Processing of Aerospace Thermoset Composite Structures. *Canada, University of Manitoba, Master Thesis*, 2008.

[10] M. J. Clifford, A. C. Long, P. deLuca. Forming of Engineering Prepregs and Reinforced Thermoplastics. *TMS Annual Meeting and Exhibition, 2nd Global Symposium on Innovations in Materials, Processing & Manufacturing: Composite Processing, New Orleans, LA*, 2001.

*Excerpt from ISBN 978-3-00-053387-7*