DETERMINATION OF INTERACTIONS BETWEEN BAR SPREADING PROCESS PARAMETERS AND SPREADING QUALITY FOR THE DEVELOPMENT OF AN AUTOMATED QUALITY CONTROL OF SPREAD HIGH MODULUS FIBER TOWS

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Keywords: tow spreading, spreading quality, automated quality control, control model, carbon fiber

Abstract

The width as well as the quality of produced spread tows is not constant. In order to control the spreading width and the quality of the spread fiber tow during production, an active control of the spreading process has to be obtained. For the generation of a control model the influences of the spreading bar process parameters on the width and the quality of the spread tow were identified numerically by analyzing factorial spreading experiments. The main influences are the pre-tension force of the initial tow and the wrapping angle of the spreading bars. The width and all quality parameters of the spread tow are influenced by these parameters. The spreading velocity has a minor influence and is only influencing the tow tension and the filament breakage after spreading. Furthermore, regression models with good predictabilities were generated as a basis for the development of a control model for the bar spreading process.

1. Introduction

The spreading of high modulus fiber tows is a necessary process step in many manufacturing process chains for parts made from fiber reinforced plastics. The spreading process parallelizes the filaments, decreases the areal weight of the carbon fibers and increases the mechanical properties. [1] Several methods to spread carbon fibers have been developed [2-4]. Commonly implemented in industrial applications is the bar spreading process. A carbon fiber is pulled over several spreader bars by an upwinding unit. The contact between the fiber and the bars leads to a widening of the tow [5, 6]. However, the width as well as the quality of the spread tow is not constant during the spreading process due to variations in the initial tow. As a result, the quality is not reproducible. Therefore, an automated control of the bar spreading process is being developed by the Institut für Textiltechnik (ITA) of RWTH Aachen University and the Institute Cluster IMA/ZLW & IfU of RWTH Aachen University. The spreading process will be controlled by the adjustment of the relative velocity between the tow and the spreading bar and the adjustment of the bar wrapping angle around the spreading bar. The relative velocity is adjusted by changing the rotational speed of the bars and the wrapping angle is adjusted by changing the vertical position of two spreading bar. The width and quality of the spread tow is detected by a camera system, force measuring sensors and a fiber breakage sensor. The real-

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

time control of the specific spreading process parameters will be performed by a control system (Fig. 1).

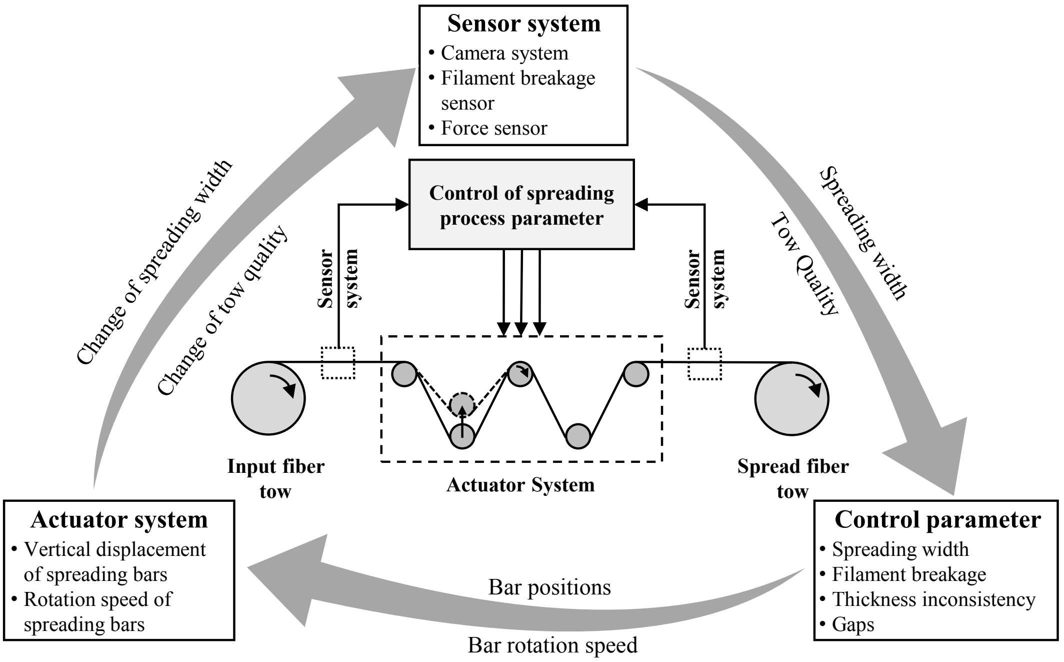

Figure 1. Controlling circuit of bar spreading process

This control system will be based on a control model that is derived from mathematical relations of the influencing effects of the bar spreading process parameters *spreading velocity*, *wrapping angle* of the spreading bar and the *pre-tension force of the initial tow* on the width and quality of the spread tow. The mathematical relations were identified by performing and analyzing spreading tests and are presented in this paper.

2. Methods

The spreading tests were performed with the spreading test stand at ITA. The following sections describe the setup of the test stand, the used measurement devices and the factorial design of the spreading tests as well as the analysis methods.

2.1. Spreading test stand

The spreading test stand at ITA is structured like an industrial spreading machine. It consists of three units. The units are the unwinding, the spreading and the winding unit. At the interface of the unwinding and spreading unit the initial tow has a defined and adjustable tension and a constant position and speed. This enables to analyze the spreading process at the spreading unit with constant parameters. In the spreading unit of the test stand the spreading module and the measurement modules are placed. At the winding unit the spread tow is winded on a flanged bobbin. [7] The setup of the spreading test stand is shown in Fig. 2.

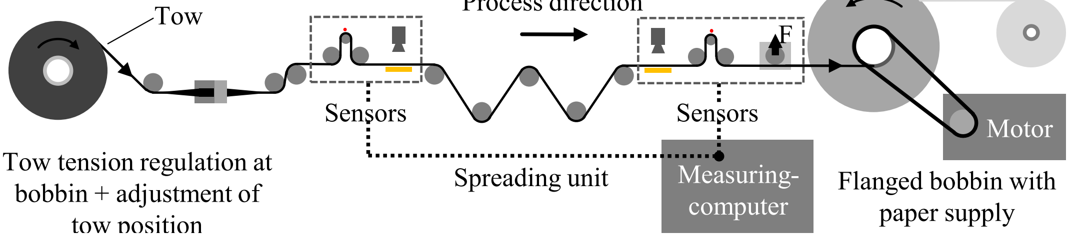

Figure 2. Setup of spreading test stand

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2.2. Measurement devices

For the quality measurement of the spreading process three different measurement devices were used. The measurement of the tow width and the thickness inconsistency of the spread tow were obtained by utilizing a XG 8000 camera system by KEYENCE Deutschland GmbH, Neu-Isenburg, Germany. The camera system consists of a CCD camera with 640x480 pixels for measuring the initial tow and a 2K-line camera for measuring the spread tow. A transmitted light underneath the fiber was captured by the cameras above. The width of the tow was measured continuously (Fig. 3a) by detecting the side-edges of the tow and measuring the distance between these edges. The thickness inconsistency of the spread tow was determined by measuring the intensity of let-through light over the width of the spread tow. If the intensity of the let-through light is higher, less light is absorbed by the tow so the thickness of the spread tow is lower. If the intensity is lower more light is absorbed which means that the thickness is higher (Fig. 3b). The calculation of the standard deviation of the measured intensities over the width of the spread tow makes it possible to set a value for the thickness inconsistency of the spread tow.

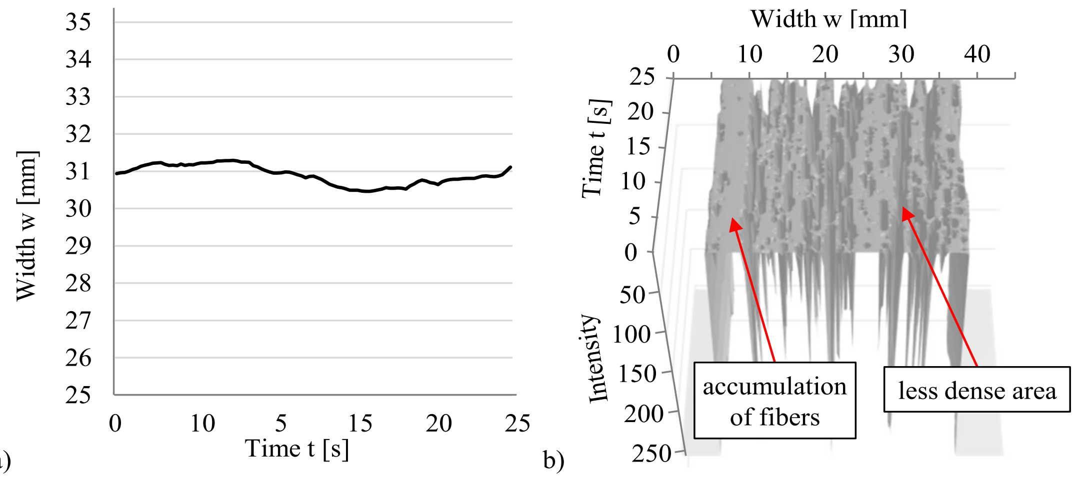

Figure 3. a) Exemplary progression of width b) thickness inconsistency over time

The tow tension after spreading was measured by guiding the tow over a roller with two attached weight measuring cells by Bosche GmbH & Co. KG, Damme, Germany. The two force measuring cells detected the elongation in the sensors that resulted from pulling the fiber across the bars. The elongation was correlated to predetermined weights. The resulting force was calculated using these correlated masses, the wrapping angle and a correlation formula inherent to the measuring cells. Finally, the fiber tension was calculated by dividing the resulting fiber force by the tow cross section.
The fiber breakage was detected by a laser measuring unit. For this purpose, the fiber was drawn with a wrapping angle of 180° over a bar with a smaller diameter than the spreader bars'. This caused the broken filaments to stick out and deflect a laser beam. The resulting shadowing was detected by an IB-01 laser sensor from KEYENCE Deutschland GmbH, Neu-Isenburg, Germany. The amount of fiber breakage was determined by counting the amount of times the broken fibers went through the laser.

2.3. Design of experiments

For the presented study carbon fiber heavy tows with 50,000 filaments were used. The spreading test setup consists of 5 spreading bars with a diameter of 30 mm. The first and the last spreading bar are wrapped with half of the defined spreading angle and the spreading bars 2, 3, 4 are wrapped with the full defined wrapping angle. All experiments were conducted using a 3-level full factor design of experiments for the analysis of the main effects and the interactions. Each test point was measured 5 times with a measuring length of 50 m. The factors of the experiments were the spreading velocity (*velocity*), the pre-tension force of the initial tow (*force*) and the wrapping angle of the spreading bar (*angle*). Table 1 shows the values of each test level.

Table 1. Levels of factors in the design of experiments

Level \ Factor	1 *Velocity* (m/min)	2 *Force* (cN)	3 *Angle* (°)
0	5	200	114
1	15	1100	143.5
2	25	2000	173

The analyzed quality parameters were the spreading width, the variation of the spreading width, the thickness inconstancy of the spread tow, the fiber breakage after spreading and the tow tension after spreading. For the analysis the spreading width, the thickness inconstancy of the spread tow and the tow tension were averaged over the time. The value for the variation of tow width is the calculated standard deviation of the width over time. In order to get a velocity-independent value for fiber breakage the specific value of broken fibers per meter were calculated.
The nomenclature used in the diagrams in chapter 3 is based on these levels, 0 being the lowest, 1 an intermediate level and 2 the highest. The position of the number indicates the varied factor. The first digit indicates the variation of the rotational velocity, the second the variation of the applied force and the third the wrapping angle. In the following diagrams the abbreviation *vel* abridges velocity, *for* abridges force and *ang* abridges angle.

3. Results

In the following chapter the results of the spreading test are shown. For every spreading quality parameter the test result of every factor combination as well as the main effects and interactions between effects are presented.

3.1. Tow width after spreading

The fiber width before the spreading process is constant at about 19 mm. There are no significant effects on the width before. The width after spreading is highly depending on the test factors (Fig. 4a) and has a small standard deviation (error bars). When examining the increase of width over the course of experiments a subdivision in blocks of three as well as blocks of nine is apparent. The force was altered every three realizations, the angle every nine. The calculated main influencing factors on the parameter width are the pre-tension force as well as the wrapping angle of the spreading bar. Both, the force and the wrapping angle also interact positively on the widening of the tow. In Fig. 4b the total effects and the 95 % confidence interval (error bars) are shown.

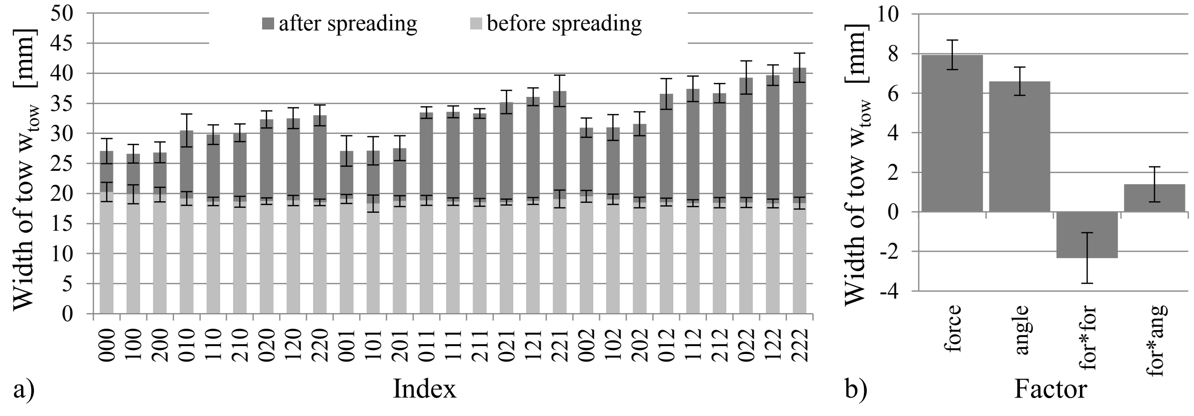

Figure 4. Width before and after spreading a) results of testing b) effects

3.2. Variation of tow width after spreading

The variation of the width before and after spreading is varying strongly for each combination of factors and a high standard deviation of every factor combination is shown (Fig. 5a). The numerical analysis of the influence shows, that only two factors are influencing the variation of the width significantly. Those are the force and the wrapping angle (Fig. 5b).

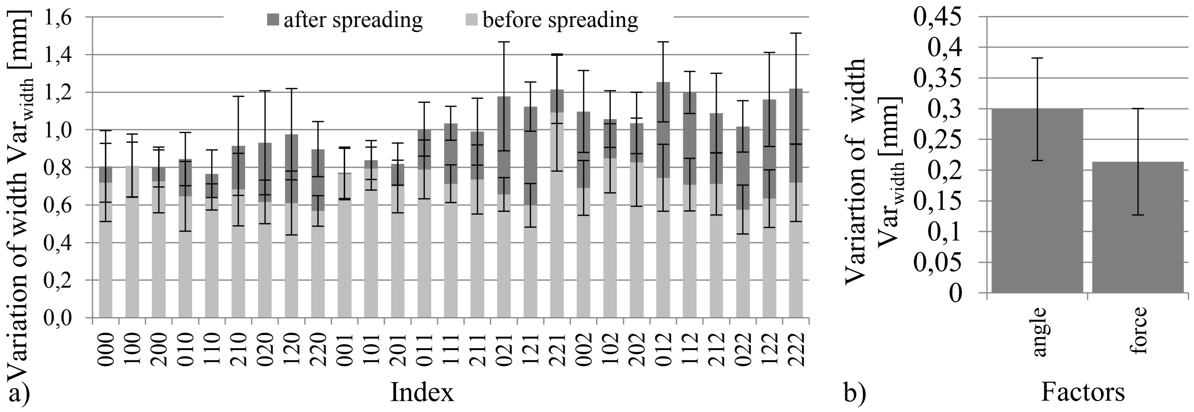

Figure 5. Variation of width before and after spreading a) results of testing b) effects

3.3. Thickness inconsistency after spreading

The presence of gaps or areas with amassed fibers is only significantly influenced by the process parameters force and angle. The results show a subdivision in blocks of three (Fig. 6a). When changing the factor level of the force from low to high, the variation of light intensity over the width of the spread tow is increased. When the wrapping angle is enlarged, the value for the thickness inconsistency grows. The interaction of pre-tension force and wrapping angle is also influencing the thickness inconsistency significantly (Fig. 6b).

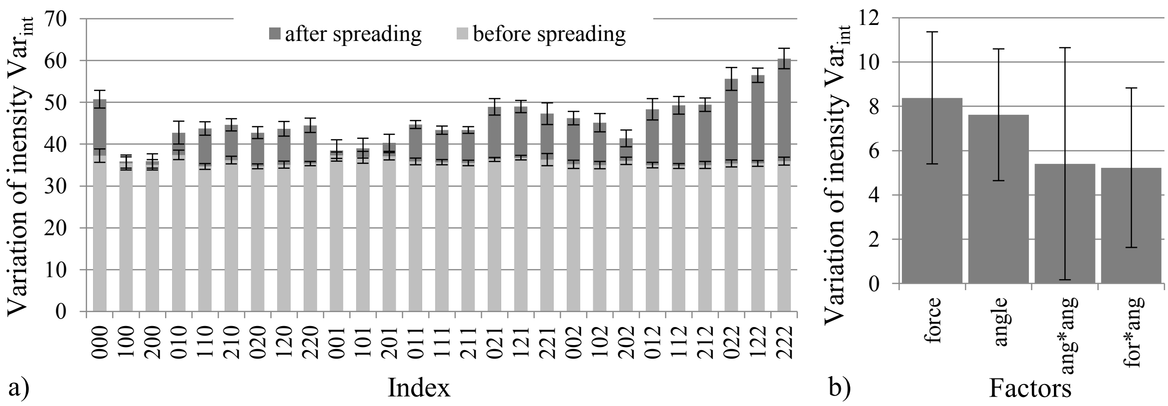

Figure 6. Thickness inconsistency before and after spreading a) results of testing b) effects

3.4. Filament breakage after spreading

The test results of the filament breakage after spreading show three blocks of each nine experiments with a stair-like rise of the number of broken filament per meter (n_{FB}/m) (Fig. 7b). This relates to the significant influence of the force and wrapping angle. Furthermore, the interaction of the force and the wrapping angle has a significant effect on the increase of the amount of broken filaments (Fig. 7b).

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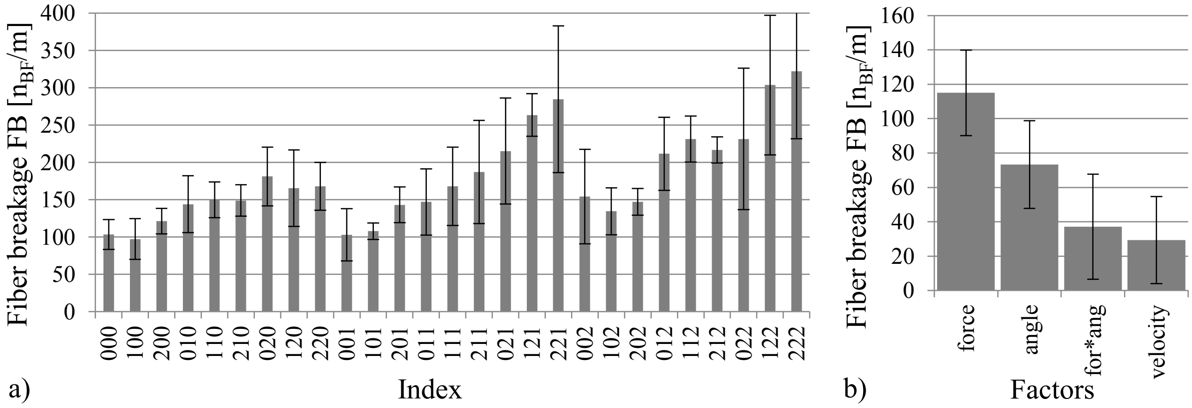

Figure 7. Fiber breakage after spreading a) results of testing b) effects

3.5. Tow tension after spreading

When plotting the results of the tow tension after spreading, the influences can also easily be displayed (Fig. 8a). The parameter pre-tension force, with the highest impact on fiber tension, is varied every three realizations. The stair-like shape of the bars indicates this relation. Moreover, three blocks of each nine experiments can be observed. This relates to the behavior when changing the angle. Despite this clear influence the numerical analysis show that all factors have an influence on the tow tension. The factors force, angle and velocity lead to a significant rise of tow tension. Furthermore, all factors interact positively, with the interaction between the force and the angle being the highest, the interaction between the velocity and the angle an intermediate value and the interaction between the velocity and force the lowest. The 95 % confidence intervals of all effects are small. (Fig. 8b)

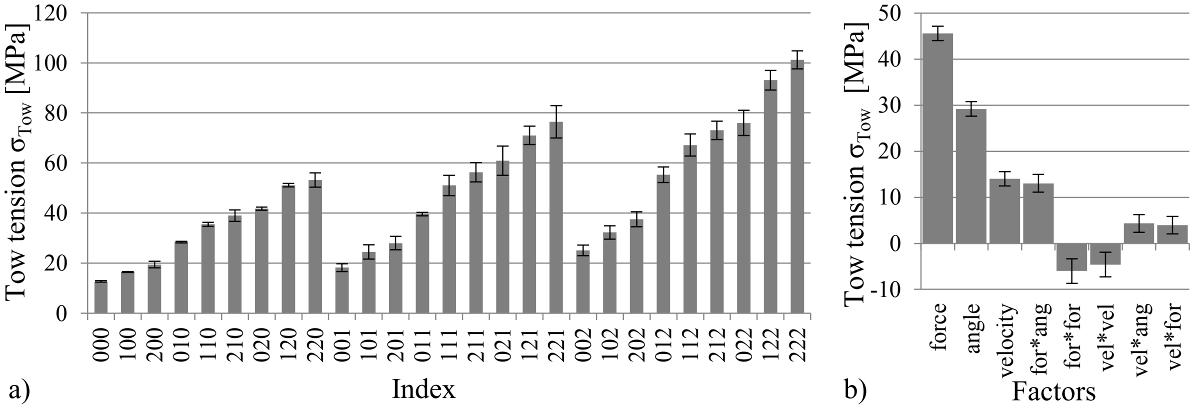

Figure 8. Tow tension after spreading a) results of testing b) effects

4. Discussion

For the development of a spreading control model, a mathematical relation needs to be determined for the influence of the spreading process parameters on the width and quality of the spread tow. For this purpose, the results of the 3-level factorial design were used to fit linear regression models for the spreading width and each spreading quality parameter. The models were fit using the multiple linear regression attempts. In this section the regression model for each spreading quality parameter is presented and discussed.

4.1. Tow width after spreading

The analyses of the influences of the spreading process parameters on the tow width after spreading show clear effects of the pre-tension force and the wrapping angle around the spreading bar as well as their interaction. The measured effects are significantly higher than their 95 % confidence interval. This results in a good regression model with a R^2 of 0.855. The regression model is shown in the following equation (Eq. 1).

$$y_{Width} = 33.593 + 3.20357 * x_{For} + 2.81638 * x_{Ang} - 0.78084 * x_{For}^2 + 0.482941 * x_{For} x_{Ang} \quad (1)$$

In the equation y_{width} is the predicted width and x_i is the normalized value (between -1 and 1) of the spreading machine parameters. Normalized values mean that the lowest value of the parameter (e.g. $force_{min}$=200 cN) is represented by -1, the highest value of the parameter (e.g. $force_{max}$=2000 cN) is represented by 1. The normalized values in between are proportional to the minimum and maximum values (e.g. $force_{middle}$ of 1100 cN equals 0).

4.2. Variation of tow width after spreading

The variation of tow width is only significantly influenced by the wrapping angle and the pre-tension force. Compared to their 95 % confidence interval both effects are small. As a result the regression model of the influences of the spreading parameters on the variation of spreading width has only a R^2 of 0.347. The measured values cannot properly be described with the generated regression model (Eq. 2).

$$y_{Variation\_width} = 1.00388 + 0.0871113 * x_{For} + 0.126662 * x_{Ang} \quad (2)$$

A reason for the low fit of the model could be an influence of the machine vibration on the measurement cameras. As a result the variation of the width can possibly not be measured with a high robustness. In order to solve this problem the camera is subsequent excluded from the spreading test stand onto an extern camera mount.

4.3. Thickness inconsistency after spreading

The thickness inconsistency is significantly influenced by the pre-tension force, wrapping angle and their interaction, but the effects of the thickness inconsistency show high values of 95 % confidence intervals which represents a high variation of the results. This variation leads to a low quality of the regression model (Eq. 3) with a R^2= of 0.412.

$$y_{Thick\_inconsistency} = 44.0539 + 3.55558 * x_{For} + 3.32945 * x_{Ang} + 1.85483 * x_{Ang}^2 + 1.79203 * x_{For} x_{Ang} \quad (3)$$

It can be assumed that the thickness inconsistency is highly influenced by the material properties before the spreading process (e.g. filament entanglement, sizing distribution). Therefore, the machine parameters only have a lower influence on the thickness inconsistency after spreading and not a high quality of the regression model can be achieved.

4.4. Filament breakage after spreading

The filament breakage is significantly influenced by the pre-tension force, wrapping angle and their interaction. Furthermore, the velocity of the spreading process has a significant influence on the amount of filament breakage. Nevertheless, the results show high variations which result in high values of 95 % confidence intervals of the effects. The generated regression model for the prediction of the filament breakage (Eq. 4) has as a moderate R^2 of 0.604.

$$y_{Fil\_breakage} = 181.981 + 48.5358 * x_{For} + 29.9845 * x_{Ang} + 12.0088 * x_{Vel} + 12.705 * x_{For} x_{Ang} \quad (4)$$

The robustness of the measurement of the filament breakage has to be improved to get an even better fit of the regression model. Therefore, the filament breakage sensor is going to be revised.

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4.5. Tow tension after spreading

The tow tension after spreading has the highest amount of influencing effects and the smallest 95 % confidence interval of every effect. The value of the tow tension after spreading can therefore be predicted with the highest accuracy. The R^2 of the regression model (Eq. 5) is 0.984.

$$y_{Tension} = 51.568 + 19.2601 * x_{For} + 11.6767 * x_{Ang} + 5.83656 * x_{Vel} - 2.06766 * x_{For}^2 - 1.61746 * x_{Vel}^2 + 4.32258 * x_{For} x_{Ang} + 1.41876 * x_{Vel} x_{Ang} + 1.29526 * x_{Vel} x_{For} \quad (5)$$

5. Conclusions

The highest influences on the spreading width and quality are the pre-tension force and the wrapping angle of the tow around the spreading bar. The width and all spreading quality parameters are significantly influenced by these parameters. Therefore, the parameters can directly be used to control the spreading process. The velocity of the spreading process is only just significantly influencing the filament breakage and the tow tension. A regulation of the rotation speeds of the spreading bar can be used to decrease the filament breakage without influencing the spreading width and the other quality parameters.
The presented regression models of the spreading width and the tow tension have a very good fit. Also, the prediction model of the filament breakage has a moderate fit. These models can be used to develop a model for the control of the spreading process. The regression model for the thickness inconsistency and variation of width after spreading show a low prediction quality and are not yet suitable for the control of the spreading process. The results of the study will be subsequently used for setting up a control model for the spreading process and the construction of an automated control unit.

Acknowledgments

This IGF-project “Auto-Tow“ 18713 N of the Forschungsvereinigung Institut für Unternehmenskybernetik e.V. - IFU an der RWTH Aachen, Dennewartstraße 27, 52068 Aachen is funded via the AiF by the Federal Ministry for Economic Affairs and Energy (BMWi) according to a decision of the German Federal Parliament. We would like to thank all project partners and companies listed on the official project homepage (http://auto-tow.de) for their support and financial aid.

Supported by:
Federal Ministry for Economic Affairs and Energy
on the basis of a decision by the German Bundestag

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