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Interpreting process data of wet pressing process. Part 2: Verification with real values

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Abstract

For the analysis of the wet pressing process, which was presented in the first part of this paper, a theoretical approach was chosen. This enabled the pre-definition of three quality-related priorities which now will be considered in detail in the second part. For further analysis, real process data, recorded in an early phase of the process implementation, are used. The challenge is that in this process status, the availability of data is limited or the data sets are incomplete. Supported by the theoretical approach, an easier interpretation of the process data, and in case of ambiguous issues, an accelerated decision making is expected. The objective is to show that this combination is suitable for the process analysis in an early production phase.

Keywords

Wet pressing, process monitoring, layered structures, non-destructive evaluation

Introduction

The wet pressing process is an innovative method for the manufacturing of composite materials. The semi-finished fibre material is impregnated with resin and compressed in a heated two-part tool to the required fibre volume fraction afterwards. In the first part of this paper, it was determined that there are no cost saving analysing methods such as the simulation approaches known from common manufacturing processes as the Resin-Transfer-Moulding (RTM).^{1–4} That is why in the first step a theoretical approach was chosen to get an overview about relevant influences, affecting the part quality and the formation of defects or features (Figure 1).

As a result of the theoretical approach, three key aspects have been identified to build the basis for the selection of data recorded during the production process. By comparing the results of the first step with real process data, the theoretical approach can be verified. In that case, a particular challenge is the state of measurement technique in early process phases. In case of inconclusive correlations between the process parameters, the theoretical approach also can be used as a complementary evaluation tool. The recorded amount of data is small and the data sets can be incomplete, so

it is difficult to evaluate them. In that case, the analysis by data mining is not appropriate and should be implemented on the basis of the theoretical approach.

The evaluation of process data can have different objectives. So, the process stability can be assessed by recorded process data. Therefore, different evaluation tools such as control charts or the determination of process capability indices have been developed which allow a statement about the process capability in dependence of the measurement scattering (C_p) and location in the tolerance range (C_{pk}). In addition to statistic evaluation methods, there are analytical approaches such as data mining which enable the implementation of process-integrated quality control systems by using control loops.⁵

This type of evaluation is suitable for running systems which provide a sufficient amount of data. For new processes, in contrast much less or only incomplete data is recorded. In addition, new process settings are

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Figure 1. Procedure of process analysis.

tested during the start-up phase which makes it impossible to use control charts in a conventional way. The calculation of process indices is also not practicable due to multiple process changes. The same applies for data mining. Because of the incomplete data records, the choice of modelling approaches is difficult as they show deviating results.

Therefore, simpler evaluation options have to be used which deliver results despite lower data volume.

Data preparation

The basis of data analysis is to transform the data into terms in order to simplify the analysis. This includes, e.g., merging process data, which is recorded and stored separately. In that case, a concrete component labeling, recorded in each production area and assigned to the measured values, is essential to match the data. A very good data compilation consists of a set of process data and the related quality data. This combination enables the deduction of correlations between parameters and component quality. Aside the process and quality data, an optimal data set contains measurement data as well as information about the raw material and ambient conditions which are filtered and prepared to generate a uniform data appearance (Figure 2).

After combining the data, a sequential number which counts upward with each press stroke is introduced to facilitate the work with the data. Especially in early process phases, the data implementation is not fully automated, so values are added manually. In that case, special attention is required. For example, different spellings of one word or a short cut can affect errors in data evaluation. Therefore, it is necessary to standardise the spellings and data formats. This can be implemented by an input mask to avoid wrong entries or subsequently adapted in the context of data processing.

Also critical are incomplete records. If sufficient data are available, data sets with missing values are removed completely. With a lower number of data, this quickly leads to the fact that no representative data remains. So

in the first step, a filler application can be used to add missing data which is constant for a longer production period and can be clearly assigned like the batch number of the resin system. For the next step, it is suitable to filter the data selective according to the parameter which needs to be evaluated. A further subdivision is based on the type of component if several components are produced with one press. Another factor is the setup time of the tools which can influence the process behaviour and needs to be marked clearly in data. The same applies to deliberate variation of process parameters which also should be highlight. After data preparation, the evaluation can be started.

Parameter and quality analysis

Compared to the theoretical process, which offers the possibility of analysing a wide range of parameters, there are only a limited number of process parameters since for some data it is very difficult or almost impossible to record. For each component, about 800 data sets with different levels of completeness have been recorded in one of the early process phases. In this paper, the most critical factors identified during the theoretical analysis and recorded during the production process are interpreted.

For the analysis of the process parameters, visual methods have been used as these are clear and easy to evaluate for a small number of records. The simplest version is the combination of a sequential number on the X-axis and the process parameter on Y-axis. When the sequential number is automatically assigned during production process and more than one type of part is produced on the press, tool changes can be recognised by gaps in the data recording. An alternative shows the timestamp. The combination of date and time represents the exact production time which can lead to extremely stretched diagrams when the time range between two charges is very long. That is why in this paper the sequential number is used in the parameter diagrams.

In the following figures, the quality of the final component is evaluated and displayed by the colour of the

Figure 2. Overview data preparation.

marks. Black dots stand for parts which are listed as waste parts with “not in order” (n.i.O.) and the white dots represent the working parts which are “in order” (i.O.).

For the parameters concerning the resin system, the amount of resin, the raw material temperature and the infiltration time is recorded. First, two separate diagrams of the resin weight and infiltration time are viewed (Figure 3).

Figure 3 shows that in the first interval, a low amount of resin is used and combined with a short infiltration time. After a production interruption, the resin’s weight is clearly increased. In comparison, the infiltration time is slightly raised. In this area, a lot of n.i.O parts are produced. Only when the infiltration time further increases, the percentage of waste parts is reduced. When the resin’s weight is raised one more time, the infiltration time is not adjusted. In Figure 4, the two factors are compared.

The figure shows that there is a bunch of i.O. parts in the area of low infiltration time and low resin weight and another at long infiltration time and high resin amount. Compared to the parts produced with a shorter infiltration time and higher resin amount, the percentage of good parts is clearly higher. So if there is a low proportion of infiltration time and resin weight, more n.i.O. parts occur.

Looking at the temperatures of resin and curing agent (Figure 5), a slightly increase of the resin temperature and decrease with a following increase of the curing agent temperature is visible. During the conversion, primarily a higher reject rate can be seen.

A further option is to oppose infiltration time and the temperatures of the resin system. In this case, the resin temperature is chosen as it has the larger volume fraction compared to the curing agent (Figure 6).

It can be seen that the resin temperature shows considerably greater variations in a set process range. Influences on the component quality cannot be derived from this diagram.

The resin system is further influenced by a set of parameters concerning the press and the functionality of the tool. Parameters recorded are the maximum mould pressure and the temperatures of bottom and top tool. To compare tool and resin temperature, the data of the bottom tool and resin are used, since the impregnated semi-finished fibre material first gets in contact with the bottom tool before the press is closing (Figure 7).

It can be seen that inside the process range, more n.i.O. parts are produced the higher the resin and tool temperature is. Another important process parameter is the maximum mould pressure (Figure 8).

Figure 8 shows that parallel to the reduction of the infiltration time (Figure 3), the mould pressure reduced. It can be seen that the combination of lower pressure and higher infiltration time provides the lowest percentage of waste parts. Since there are no data available, the pressing profile cannot be evaluated. Another factor which influences the drapability of the material is the quality of the semi-finished fibre product. As a part of this evaluation, the delivery and processing date was recorded to analyse the influence of the storing period (Figure 9).

Figure 3. Diagram of resin weight (a) and infiltration time (b).

Figure 4. Diagram infiltration time versus resin weight.

Figure 5. Diagram of resin (a) and curing agent (b) temperature.

Figure 6. Diagram infiltration time versus resin temperature.

Figure 7. Diagram resin versus bottom mould temperature.

Figure 8. Diagram mould pressure.

Since the distance between the data points is very small, a fluctuation mask is used to loosen up the data and simplify the evaluation. In the depicted example, a split stack is used, so there is a diagram for the lower (a) and upper (b) stack. Based on the figures, it is initially apparent that for storing periods, which last longer than five days, more waste parts occur. In this case, both semi-finished must be considered. For the combination of two stacks which have been stored for a short time, a low rate of n.i.O. parts can be expected. As soon as one of it has been stored longer, the percentage of waste parts increases. When two stacks with a long storing period are combined, the probability to get i.O. parts is very low.

The critical factors, which were found in the QFD, have been confirmed by the graphical parameter evaluation. However, it poses a great challenge to assign

exactly which parameter has the biggest influence on the formation of features. In addition, the interactions between the parameters play a major role. Therefore, it is relevant to analyse on which way process parameters cause features.

Feature analysis

For the analysis of the feature formation, the same three-parameter clusters are used as for the parameter evaluation. In that case, not the component quality is shown, but the type of resulting features and their occurrence. Therefore, each feature has another marker shape and the size is a measure for the occurrence of the feature (Table 1).

In the feature analysis, the focus is on identifying the process areas in which features prevalent arise. For the

Figure 9. Diagram storing period lower (a) and upper (b) stack (jittered).

resin system, first the infiltration time versus the resin weight is evaluated (Figure 10).

In the diagram of the infiltration time versus the resin weight, it can be seen that with low resin amount and infiltration time, dry spots preferably arise. With increasing the resin weight, dry spots vanish but defects in pure resin geometries appear. When infiltration time also is increased, the cross folds which appear at lower infiltration time give way to wavy areas which represent a lower grade of folds. However, entrapped air areas also occur more often.

For the temperatures of resin and curing agent, that type of interactions cannot be identified. As seen in Figure 11, the parameters show a linear relationship, but no bunches of specific features arise. All types of features appear in the entire parameter range.

Comparing the temperature of resin and bottom tool (Figure 12), it can be seen that at lower tool temperature, wavy areas occur and for higher temperatures

cross folds are more common. For the combination of high tool and moderate to high resin temperatures, dry spots can be expected.

In Figure 13 it can be seen that depending on the maximum mould pressure, dry spots occur primarily in the range of high pressure. The same applies to defects in the top resin layer. In that case, it should be contemplated if they primarily depend on the applied resin amount. Looking on sequential number 500, the decrease of mould pressure causes the forming of wavy areas instead of cross folds, which implies an improvement of part quality. In all pressure ranges, air inclusions can be found.

The last section aside the pressing process and resin properties is the quality of the semi-finished fibre parts (Figure 14). For lower and upper stack, it is conspicuous that with longer storing periods cross folds appear more often. New fibre material tends proportionately more to wavy areas. Defects in the outer resin layer

Table 1. Legend of features and their occurrence.

Features		Occurrence
Dry spots	•	Classification 1
Defects in outer resin film	●	Classification 2
Multiple entrapped air areas in laminate	●	Classification 3
Defects in pure resin geometries	●	Classification 4
Cross fold in visible fibre layer
Longitudinal fold in visible fibre layer
Waviness in fibre course
Air gaps, bubbles, delamination		

occur most frequently when two stacks, which have been stored for a long time, are combined. Air inclusions are visible in all ranges of the storing period.

Summarising the analysis of the features, trends of the feature forming in specific parameter ranges can be seen. In this analysis, it has to be taken in account that the influence of a strong deviation of the resin amount also can be seen the diagram of mould pressure. At this point, it is a challenge to identify the major cause of the specific feature. In data mining analysis, such relationships could be easily identified due to a significantly higher amount of data. Since these are not available in this state of process, the QFD provides the necessary information which lead to a satisfying result.

Merging of the results

The parameter clusters identified by the QFD analysed in the first part of the paper have been evaluated during the analysis of process data. The results are various correlations which are compared to the outcome of QFD. The information, developed by the team of experts, has been used to confirm the relationships identified during the graphical interpretation of diagrams. Similarly, explanations for the effects of process variation are found and completed by contexts concerning the process implementation and measurement. A combination of the results on the level of the three main clusters is useful. The impact on the component quality is defined by the classification of the features.

The resin system affects primary features related to the fibre infiltrations. These include dry spots, various types of air inclusions, and defects of the pure resin areas. In particular, the resin amount, which received the classifying 5, and the constant impregnation of the semi-finished fibre materials are essential criteria for the forming of such features. Looking on the detailed impregnation matrix, a constant impregnation is strongly influenced by the quality of semi-finished fibre parts, the temperature of the resin system, and the infiltration time. During feature evaluation using the real process data, it was found that with a low resin amount and infiltration time, the emission of dry spots increases. Furthermore, the temperatures of the raw materials show an influence on the part quality which also can be related to the data fluctuation.

Aside the resin properties according to QFD, the press parameters affect dry spots, air bubbles, and defects in pure resin geometries as well albeit to a lesser extent. This can be decisive for the evaluation of the features concerning the mould pressure. During the implementation of QFD, it was found that a higher pressure can effect a better impregnation of the fibres. In the graphical analysis of the defects for mould pressure, a bunch of dry spots in combination with high pressure is shown. This result can be weakened, because parallel there was only a smaller amount of resin available for these parts and according to QFD the resin weight has a stronger influence on the forming of dry spots. It was also proved that the mould temperatures have an influence on the forming of folds and wavy

Figure 10. Feature diagram infiltration time versus resin weight.

Figure 11. Feature diagram curing agent versus resin temperature.

Figure 12. Feature diagram resin versus bottom mould temperature.

Figure 13. Feature diagram mould pressure.

Figure 14. Feature diagram storing period lower (a) and upper (b) stack.

areas like predicted in QFD. For high temperatures of the bottom mould, more cross folds can be seen. For lower tool temperatures, these features are weakened to wavy areas. Like the pressing parameters according to the QFD, also the properties of the semi-finished fibre product have an impact on the drapability of the stack and consequently on the formation of wavy areas and folds. So it is conspicuous that with a longer storing period of the stacks features, depending on drapability, occur more frequently. Similarly, wavy areas are intensified to folds which lead to a rising scrap rate.

Using the QFD interactions between process parameters, component quality and feature forming can be identified. Furthermore, it helps in decision making in the case of inconclusive process data. So interactions between the clustered parameters and individual parameters can be included. An example is the reaction kinetics of the resin system, which is influenced by the temperature of the raw material, the infiltration time and also the tool temperature.

The implementation difficulty of the analysed process parameters shows that variations of resin temperature, infiltration time, and maximum mould pressure have the best feasibility. With little effort, the mould temperatures and resin amount can be changed. Therefore, it needs to be noted that these variations can affect the entire process, e. g. the cycle time.

In addition, the function of the used measurements can be discussed, since it can provide different results depending on the exact position of the sensors. An extreme example would be the measurement for tool temperature. A sensor inside the mould would deliver useful data. In contrast, a sensor outside the mould would provide unrealistic temperature information. With a proper documentation, the evaluation by a team of experts can also deliver approaches for a profound and systematic research of individual preselected parameters which allow a quantification of the interactions and relationship between the process parameters.

Summary of results

On the basis of these studies, it was found that the QFD enables a comprehensive analysis of the wet pressing process. Three parameter clusters have been identified – the resin system, pressing process and quality of fibre material – which have influence on the part quality and equally the forming of features. These were confirmed by analysing real process data. The variety of information, collected and analysed in QFD, provides a comprehensive understanding of the overall process. The gained experiences can be deepened in experiments to quantify the parameter

interactions. Furthermore, it is a solid basis for the design of new production facilities. The aim is to create a meaningful combination of measured values, which deliver significant results without overloading the system with unnecessary measurements, to enable a continuous long-term monitoring and stabilisation of the production process. In summary, the following findings have been made:

- QFD is suitable to identify critical process parameters,
- Results from QFD can simplify analyses of a low amount of process data or incomplete records,
- QFD enables a multidisciplinary and comprehensive process analyses in an early process phase using recorded data,
- Useful approaches for deepening analyses can be found and
- Due to new insights into the processes, new production lines can be improved systematically.

The versatile applicable results offer a great potential of process improvement. The focus therefore is always the improvement of component quality as well as time and cost reduction.

Declaration of Conflicting Interests

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