Influence of process parameters on residual stress in thermoplastic filament-wound parts

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Abstract: Owing to the existence of residual stresses, working stresses can have a smaller effect. The present paper reports on an investigation of the influence of process parameters on the induced residual stress in filament-wound test samples. It describes the necessary machinery and measuring devices for a repeatable process. The process parameters were identified and their influence on the implemented residual stress during the production of thermoplastic filament-wound parts was determined using a design of experiments approach with a fractional factorial concept. As a result of this sensitivity study on the established process, the winding angle, the annealing, the number of layers, the mandrel temperature and, to a slightly smaller extent, the tape tension were identified to have a significant influence. However, only the applied tape tension provides the possibility of controlling the residual stress independently from the parameters that are fixed by the mechanical design or simply the geometry of the part.

Keywords: filament winding, residual stress, thermoplastic matrix, design of experiments

NOTATION

a	radius of the sample ring
E_x	Young's modulus in the direction of the x axis for a single ply
E_1	Young's modulus in the fibre direction
E_2	Young's modulus perpendicular to the fibre direction
f_{e_1}	treatment degree of freedom
f_{e_2}	observation degree of freedom
f_j	treatment factor degree of freedom
F	tabulated value for the F-test
F_j	experimentally determined value for the F-test
G_{12}	shear modulus
h	wall thickness
j	treatment factor index
j_1	treatment factor index with level 1
j_2	treatment factor index with level 2
k	critical length parameter
ℓ	length of the sample ring
n	number of observations
n_{j_1}	number of observations with index j and level 1
n_{j_2}	number of observations with index j and level 2
$\hat{n}_1$	normal stress
$\hat{n}_2$	normal stress
p_j	dependency of residual stress on the treatment factor with index j
Q_{ij}	elements of the stiffness matrix ($i, j = 1, 2, 3$)
r_i	inner radius of the filament-wound part
r_o	outer radius of the filament-wound part
S_{e_1}	treatment combination sum of the squares of error
S_{e_2}	observation sum of the squares of error
S_j	sum of the squares of the variation for treatment factor index j
S_m	sum of the squares of the variation of the average of all observations
S_T	sum of the squares of the variation of the entire system
S_{T_1}	sum of the squares of the variation of all treatment factors
T_c	crystallization temperature
V_{e_2}	variance of the error e_2
V_j	variance of the treatment factor with index j
x_i	observation with index i
α	winding angle
γ_{xy}	shear strain (index x in the direction of the x axis, index y in the direction of the y axis)
γ_{12}	shear strain (index 1 in the fibre direction, index 2 perpendicular to 1)
ε_1	strain in the direction of the fibres
ε_2	strain perpendicular to the fibres
ν	Poisson's ratio

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ν_{12}	Poisson's ratio (index 1 in the fibre direction, index 2 perpendicular to 1)
σ_x	stress in the direction of the x axis
σ_y	stress in the direction of the y axis
σ_1	stress in the direction of the fibres
σ_2	stress perpendicular to the fibres
τ_{xy}	shear stress in the plane of the x and y axis
τ_{12}	shear stress in the plane of the fibres and perpendicular to it

1 INTRODUCTION

Filament winding is a widely used process for the production of fibre reinforced plastic parts with an axisymmetric shape. Among them, pressure vessels play an increasingly important role. The weight reduction for fibre reinforced vessels in combination with an increasing demand for compressed natural gas (CNG) vessels makes filament winding a still growing market. Today's applications are mainly manufactured with thermoset matrix systems. The machinery and the processing methods are more or less state of the art. For thermoplastic matrix systems this is not the case. The applications are rare and many manufacturers are afraid of installing a new technique and of the related risks. Thus, the potential of thermoplastic filament winding as processing without curing time, without stop and go processing for breaks, with no styrene emissions and with unrestricted stocking time for semi-finished materials has until now been unexploited.

A technique already applied in thermoset is the inducing of residual stress in the part partially to compensate for the stress from the work load. In principle this is also feasible for thermoplastic fibre reinforced parts. For thermoset/fibre combinations the matter of residual stresses has been investigated over quite a long period of time [**1–5**]. In the case of thermoplastic matrix materials, various models were developed to predict the inducing of residual stress during production [**6–9**], but less practical work can be found that deals with stress induction in the process itself. The present paper will show how these residual stresses can be generated, measured and evaluated in a practical and simple reproducible way.

2 WORK PRINCIPLE FOR USEFUL RESIDUAL STRESS

The idea is to create residual stresses that can be superimposed upon the stresses resulting from the work load. It seems to be a simple thing to do, but even in isotropic material in radial parts the stress distribution from internal pressure makes it rather difficult. This is even more the case for orthotropic materials such as the thermoplastic tapes in this paper.

Nevertheless, the relations between circumferential stress and axial stress are similar to all other applications. The circumferential stress is twice as high as the axial stress.

Figure 1 shows schematically the curvature of the circumferential stress resulting from internal pressure in an axisymmetric part over the wall thickness and a theoretical residual stress distribution (dotted line) that could be useful for an even stress distribution over the wall thickness. The addition of both stress profiles (dashed line) shows the improvement in material stress peaks. Normal residual stress distributions show the change from tensile to compressive stress more or less in the middle of the wall thickness, but it is easy to imagine that, with steeper curves for load stress, the residual stress distribution should change as well. A parabolic curve with a change in sign that can be 'placed' at any radius within the wall would guarantee optimal compensation because the appropriate profile of the residual stress depends on the load, the wall thickness and on the diameter and has to be determined individually for every application.

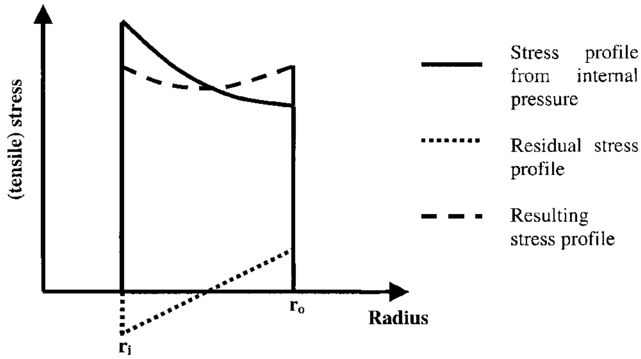

Fig. 1 Residual and load stress through the wall thickness

Regarding hoop winding, the composite material is nearly orthotropic. Hoop winding is therefore an easy and effective way of reinforcing existing vessels.

The direction of the fibres is then almost the same as for the circumferential stress. From the composite material point of view this is quite good because the stress is in line with the fibres that must bear the main load.

For the design of a new vessel, the liner can be reduced to the function of a permeability barrier. In this case the reinforcement bears also the axial load and can no longer consist of only hoop-wound layers. To avoid the axial winding and the difficulties that it brings in the dome section of vessels, it is then better to have a winding angle of $\pm 54.7^\circ$. This angle is found by classical laminate theory for balanced ply laminates and assumed plain stress. It is a function of the normal stress [**10**]

$$\tan \alpha = \sqrt{\frac{\hat{n}_2}{\hat{n}_1}} \tag{1}$$

For balanced ply laminates, the angle is positive for one ply and negative for the corresponding balancing ply. The stresses $\hat{n}_1$ and $\hat{n}_2$ are in the present case the axial and the hoop stresses in a vessel. From $\tan \alpha = \sqrt{2}$, α can be identified as $\pm 54.7^\circ$.

For such an angle the stress distribution in the composite material is no longer presentable in properties along and transverse to the fibre direction. The stress becomes a function of the Young's modulus following Hooke's law because the modulus in the circumferential direction again is a function of the winding angle. This could be seen in the following equations [**10**]. The equation normally used for the estimation of the Young's modulus of a single ply under an angle α (mathematically positive between the axis of the vessel and the fibre direction) is in the form

$$E_x = \frac{1}{\cos^4 \alpha / E_1 + (1/G_{12} - 2(\nu_{12}/E_1)) \times \sin^2 \alpha \cos^2 \alpha + \sin^4 \alpha / E_2} \tag{2}$$

and is derived from the stress–strain relation for known deformations ε

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} \frac{E_1}{1-\nu_{21}\nu_{12}} & \frac{\nu_{21}E_2}{1-\nu_{21}\nu_{12}} & 0 \\ \frac{\nu_{12}E_1}{1-\nu_{21}\nu_{12}} & \frac{E_2}{1-\nu_{21}\nu_{12}} & 0 \\ 0 & 0 & G_{21} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix} \tag{3}$$

which can be transformed into the x, y coordinate system as

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \cos^2 \alpha & \sin^2 \alpha & \sin 2\alpha \\ \sin^2 \alpha & \cos^2 \alpha & -\sin 2\alpha \\ -0.5 \sin 2\alpha & 0.5 \sin 2\alpha & \cos 2\alpha \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} \tag{4}$$

Transforming also the flexibility and the stiffness matrix, the elasticity matrix can be written in the form

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{21} & Q_{31} \\ Q_{12} & Q_{22} & Q_{32} \\ Q_{13} & Q_{32} & Q_{33} \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} \tag{5}$$

Using matrix (5) and considering Q_{11} as given by the equation

$$Q_{11} = \frac{\cos^4 \alpha}{E_1} + \frac{\sin^4 \alpha}{E_2} + \frac{1}{4}\left(\frac{1}{G_{21}} - 2\frac{\nu_{21}}{E_2}\right) \sin^2 2\alpha = \frac{1}{E_x} \tag{6}$$

The dependency in equation (2) is apparent. The other elements of the matrix will not be given here as they can easily be determined by means of the transformations shown above.

More detailed calculation methods require numerical methods. A method designed for the thermoplastic filament winding process corresponding to the study presented below is described in reference [**11**].

3 SENSITIVITY STUDY

3.1 Input parameters

The aim of the present sensitivity study is to show the influence of processing parameters on the measured residual stress with the constraint that they are controllable within the real existing process. Investigating all the possible influences would lead to a great number of experiments, so that first of all a selection of the major parameters was done. They are listed in Table 1.

However, even the remaining parameters cannot be treated in a full factorial experiment concept where all parameters are fixed while one is varied. The amount of material and time necessary to check all parameters individually to find the degree of influence they exert can significantly be reduced by changing to a fractional factorial concept. The design of experiments (DOE) described in references [**12**] to [**15**] is an appropriate technique to determine the influence of parameters by means of statistical analysis.

Preliminary research showed that one planned variation concerning the heat source had to be cancelled. The winding speed with infrared heaters was too low to produce test samples with ten layers within a reasonable time.

Figure 2 shows microscopic pictures taken from sample rings made with infrared heaters, carbon fibre reinforced Polyetheretherketone (CF/PEEK) and hoop winding (left-hand picture). The winding speed was increased with every back and forth movement, as indicated in the picture (which in the present paper is considered to be one layer for hoop winding). It is easy to see that with a speed of 3 m/min the quality of the consolidation becomes very poor, whereas with a flame as the heat source (right-hand picture) a winding speed of 6 m/min gives satisfactory quality. The maximum winding speed that has been successfully used with CF/PEEK material using flame heating at the Institut für Verbundwerkstoffe GmbH is 15 m/min. Nevertheless, the relatively slow winding speed of 5 m/min was chosen as this has proven to deliver stable and good consolidation quality in the past.

The investigation with the infrared heaters as installed in the winding trials could not be continued owing to the slow winding speeds. Only specialized winding machines with heaters over the whole circumference can provide enough energy to satisfy processing times.

Another parameter that was fixed in preliminary studies was the geometry of the test samples. Their diameter suits

Table 1 Possible influences on the residual stress

Temperature	Mandrel temperature
	Heat-up temperature
	Annealing temperature
Time	Heating time
	Cooling time
	Production time
Material	Tape material
	Mandrel material
	Liner material
Forces/tensions	Tape tension
	Consolidation force
Boundary Conditions	Tape width
	Geometry of sample part
	Winding angle
	Liner (yes/no)
	Heat source (flame/infrared)

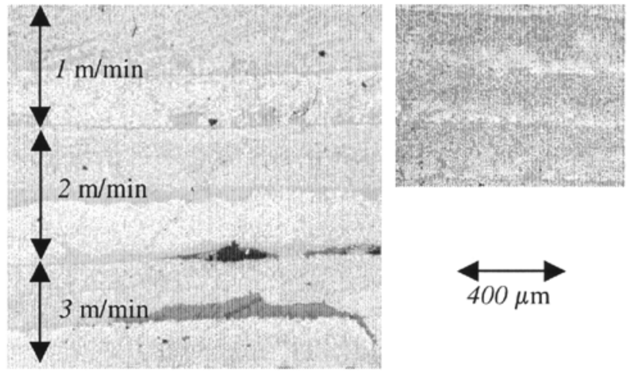

Fig. 2 Comparison of infrared heaters and different winding speeds (left-hand side) and flame with 6 m/min (right-hand side)

the standard test method for the apparent tensile strength of ring or tubular plastics by the split disc method [**16**]. According to reference [**17**], the length of the specimen is a function of its diameter and its wall thickness when boundary effects are to be minimized. Equation (7) gives the function of the critical parameters as follows

$$k^4 = \frac{3(1 - v^2)}{a^2 h^2} \tag{7}$$

where k is the critical parameter, v is Poisson's ratio, a is the radius and h is the wall thickness.

For short cylindrical shells the product of k and the length l of the sample part has to be $kl \geqslant 6$ to guarantee that the influence of the free boundaries is reduced. The test samples were designed according to equation (7). To obtain the minimal length l, k has to reach its maximum value. As the radius of the specimen is fixed according to reference [**16**], the influencing parameters are the wall thickness, which showed its maximum for GF/PP parts and hoop winding, and Poisson's ratio v, which, according to the laminate theory, showed its minimum for a winding angle of 60° (or alternatively 90°, see Table 2). This worst case was chosen as a reference for all samples, considering also the additional length needed to apply the strain gauges.

Table 2 Treatment factors and their levels for the experiments

	Parameter	Level 1	Level 2
A	Mandrel temperature	Not heated	$0.9T_c$
B	Annealing	RT	$0.9T_c$
C	Tape material	CF/PEEK	GF/PP
D	Liner	Yes	No
E	Winding angle deg	90	60
F	Tape tension (N)	5	70
G	Number of layers	5	10

Notes. T_c is the crystallisation temperature of the material, RT is room temperature, CF/PEEK is carbon fibre reinforced polyetheretherketone and GF/PP is glass fibre reinforced polypropylene.

3.2 Design of experiments

The design of experiments (DOE) is a method for reducing the number of tests. At the same time, all the test variants are designed to give information on one response of the system, in this case the amount of residual stress. Any other result of the variation of parameters has to be investigated separately. Once the main factors from the DOE are known, separate parameter studies can concentrate on the relevant parameters. It is necessary to define the desired response and the known and controllable influencing parameters. In the present case the response is the residual stress even if the measured response is the strain that was used to calculate the stress. For this response a zero hypothesis is formulated. In this case a parameter has no influence on the residual stress creation in the sample parts. The alternative hypothesis to the zero hypothesis is that it does have influence. The alternative hypothesis is then verified by using the so called F-test [**13**]. The F-test is based on the comparison of two variances. If the variance of the experiment is smaller than the variance of a threshold, the hypothesis is rejected. The threshold depends on the test plan and on the risk that the rejection might be unjustified. Usually, the risk is not more than 1 or 5 per cent. The corresponding thresholds are listed in tables in the given references.

Generally, DOE offers the possibility of examining parameters—so-called treatment factors with two or more levels. If more than two levels are chosen, then the number of treatment factors that can be examined is reduced respectively. Furthermore, the experimental technique is designed for $2^n - 1$ treatment factors owing to the statistics behind it [**15**]. For practical applications there are eight experiments to start with and seven treatment factors, and the next level would be 16 experiments with 15 treatment factors. In the present case the so-called L_8 table, which works with a setting of seven controllable variables in eight combinations, was chosen. The variables listed in Table 1 were reduced to seven. The heating time, like the production time, is mainly a function of the winding speed which was fixed as discussed above. The cooling time was not affected as the parts cooled down in ambient conditions until they reached room temperature. As only one temperature-controlled mandrel was built for the investigations, the mandrel material was not varied. The consolidation force was experimentally determined to prevent the matrix from being squeezed out of the part in preliminary work. Tape geometry had to be constant to satisfy the condition of having the same for all materials, and finally the heat source was always the gas flame for the reasons given above. The remaining seven treatment factors that were chosen to be varied and their combination are listed in Table 2. They are the parameters from Table 1 that can be varied in the existing process.

Table 3 gives the combinations of the treatment factors and their levels as a result of the experimental planning. It should be clear that in these experiments the liner will not only serve as the support for the forces resulting from the tape tension during production. The mandrel supporting

Table 3 Design of the experiments

Treatment combination	Mandrel temperature	Annealing	Tape material	Liner	Winding angle (deg)	Tape force (N)	Number of layers
1	Not heated	RT	CF/PEEK	No	60	5	5
2	Not heated	RT	CF/PEEK	Yes	90	70	10
3	Not heated	$0.9T_c$	GF/PP	No	60	5	10
4	Not heated	$0.9T_c$	GF/PP	Yes	90	70	5
5	$0.9T_c$	RT	GF/PP	No	60	5	10
6	$0.9T_c$	RT	GF/PP	Yes	90	70	5
7	$0.9T_c$	$0.9T_c$	CF/PEEK	No	60	5	5
8	$0.9T_c$	$0.9T_c$	CF/PEEK	Yes	90	70	10

the liner also guarantees temperature control (see Table 2, mandrel temperature) by thermal conduction. The effect of stresses between liner and composite material known as autofrettage was avoided in these experiments.

3.3 Control of process parameters

The process parameters that are not directly movements of the winding machine were all controlled and recorded with a personal computer that was acting as the controller of a field bus system. In this bus system the linked actuators and sensors are in all-digital communication via one cable. The controller as a part of the computer offers direct access to all data acquired or any action such as, for example, a temperature adjustment. The advantage compared with the normally used local control units is that all parameters are directly and logically linked to the movements of the winding machine. The field bus system is the key to the knowledge of the processing parameters during the production. It gives the opportunity to control the process parameters as a function of any other parameter by simple creation of or change in an algorithm on the control computer. The variability that the software solution offers in comparison with conventional hardware control makes research work easier and faster.

The control personal computer serves at the same time as the data recorder for all relevant process parameters. The data are directly available in a format that can be treated with any spread sheet program.

Thus, the H_2/O_2 flame becomes a reproducible heat source. Instead of the former hand-regulated control of the volume of the two components and the overall volume by the component volumes, it is possible to choose the ratio and the gas volume on the computer in norm-litres (ln) which corresponds to the volume of one litre of O_2 per litre of H_2 at 0 °C and 0.1013 N/mm^2 even if the actual conditions are different. The valves are adjusted self-dependently to changing ambient conditions, the flame is no longer dependent on the ambient temperature and the energy of the flame is known at any time during the process through the recorded data.

3.4 Testing of the ring samples

The residual circumferential stresses in the ring samples were evaluated by cutting out a piece and allowing the ring to deform. The deformation is measured with strain gauges applied on the opposite site of the cut. This method, already applied in reference [**18**], is accurate, fast and of high reproducibility and therefore a good choice for the testing of many sample parts, which is not the case for all other methods. For example, for the layer removal method, which has been proved suitable in reference [**19**], for the compliance method or for the photoelastic analysis described in reference [**20**], it is relatively complicated regarding the application of the sensors. The data are recorded on the computer from the beginning of the cutting procedure until the end of the relaxation. Any influence of the sawing and the clamping of the rings can therefore be easily detected and taken into account.

Figure 3 shows the test device designed for the measurement of the strains, the amplifier and the diamond sawing blade driven by compressed air.

Each treatment combination from the test plan (see Table 3) was produced in a quantity of three sample rings according to equation (2) and Table 3. These rings, made under identical conditions, were then cut. As it is not the aim to determine a scaled value for the residual stress, three parts are sufficient to show the influence of the parameters by means of the analysis of variance.

3.5 Analysis of variance

The analysis of variance and the mathematical background can be found in reference [**14**], or again in reference [**12**], and, as this is not a composite materials matter, they will be described only very briefly. The idea is to calculate the influence of the parameters mentioned in Table 2 on the residual stress as a percentage. To do so, the following steps are necessary. First of all, the sum of the squares of the variation of the average of all values, S_m, has to be determined

$$S_m = \frac{\sum x_i^2}{n} \tag{8}$$

and, with S_m, the sum of the squares of the variation of the entire system, S_T

$$S_T = \sum x_i^2 - S_m \tag{9}$$

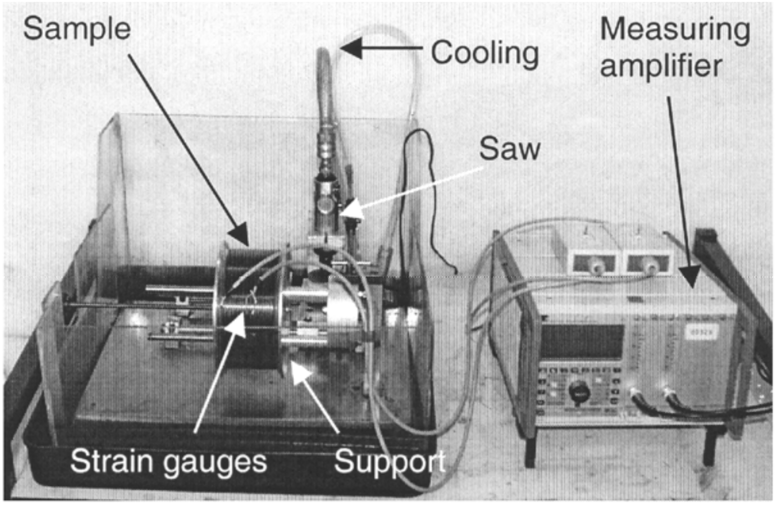

Fig. 3 Measuring device for residual strains

which makes it possible to calculate the sum of the squares for the treatment factor S_j with index j for the eight treatment factors of Table 3

$$S_j = \frac{(\sum j_1)^2}{n_{j_1}} + \frac{(\sum j_2)^2}{n_{j_2}} - S_{\mathrm{m}} \tag{10}$$

As all the columns in Table 3 are filled with treatment factors (and not interdependencies), the treatment combination sum of the squares of error S_{e_1} is zero and the overall sum of the squares of the seven treatment factors is

$$S_{\mathrm{T}_1} = \sum S_j \tag{11}$$

which leads to an observation sum of the squares of error S_{e_2}

$$S_{e_2} = S_{\mathrm{T}} - S_{\mathrm{T}_1} \tag{12}$$

With the aid of these values and the knowledge of the treatment factor degree of freedom f_j for the j variants and f_{e_1} and f_{e_2}, the dependencies of the residual stress on the parameters can be expressed as a percentage following the equation

$$p_j = 100 \frac{S_j - f_j (S_{e_2}/f_{e_2})}{S_{\mathrm{T}}} \tag{13}$$

The standard test programme on compatibility with statistical evaluation conforming to Dixon and Gruber that can be found in reference [**13**] was performed to verify that the statistic analysis is valid.

For the present sensitivity study, the following dependencies could be found. The winding angle exerts an influence of 27 per cent, the number of layers an influence of 9 per cent and the mandrel temperature an influence of 8 per cent on residual stress. All other parameters are below the level of 99 per cent probability for significance. The tape force still lies within a confidence level of 95 per cent probability, whereas the other parameters are not within these levels. Therefore, they are not considered to have a significant influence on the residual stress. To determine the level of confidence, the F_j value is compared with known values for F and their levels of 99 or 95 per cent tabulated in the literature, which is known as the F-test. In the present case F (99 per cent) = 7.82 and F (95 per cent) = 4.26 can be found [**12**]. Here, F_j is a function of the variance V, as can be seen in the equation

$$F_j = \frac{V_j}{V_{e_2}} \tag{14}$$

where V_j (in this particular equation j also stands for e_2) is

$$V_j = \frac{S_j}{f_j} \tag{15}$$

Table 4 shows the equivalent values.

The winding angle influences the residual stress in the circumferential direction by means of material properties as described in equation (1), and it seems logical that, with smaller winding angles and less wall thickness, the amount of residual stress is lower. However, both parameters are a

Table 4 Results of the analysis of variance

	f_j	S_j	F_j	p_j (%)
Mandrel temperature	1	1.57×10^{-2}	9.06	8.43
Annealing	1	3.43×10^{-2}	19.8	19.71
Tape material	1	1.51×10^{-4}	8.75×10^{-2}	0.95
Liner	1	2.00×10^{-3}	1.16	0.16
Winding angle	1	4.77×10^{-2}	27.6	27.85
Tape tension	1	7.28×10^{-3}	4.27	3.36
Number of layers	1	1.66×10^{-2}	9.59	8.99
e_2	24	4.15×10^{-2}	—	—

function of the design layout of a component and therefore cannot be freely chosen.

The annealing and the mandrel temperature are functions of the processing of thermoplastic fibre reinforced materials and can, within reasonable limits, be used to generate a desired residual stress profile. For example, the thermal residual stresses that are generated during processing also vary with the mandrel temperature and the annealing. From the analysis performed here it can be seen that the residual stress increases with annealing at high temperatures as well as with hot mandrel temperatures (see Table 5). In a fractional factorial concept of the experiments it is necessary to sum, for example, all results of the experiments where the mandrel temperature is at a higher level and divide them by the number of experiments with this particular treatment factor and its level multiplied by the number of such samples. This means, for example, that all strain results for a mandrel temperature of 260 °C are summed and are divided by 4 as there are four experiments out of the eight that have a mandrel temperature of 260 °C (the other four have a mandrel temperature of 50 °C) and then again divided by 3 as three samples of this experiment were tested. The same has to be done for the lower level of the mandrel temperature. The results for level 2 have to be subtracted from those for level 1. The definition of the levels is according to Table 2. If this result is positive the gradient between levels 1 and 2 leads to increasing residual strain. For the mandrel temperature the difference is 0.613, and for the annealing it is 0.907 which means the residual stress increases with increasing mandrel and annealing temperatures. The calculation can be done by summing the corresponding average (of three) values from Table 6, dividing them by 4 and then subtracting the results for the levels of the desired treatment factor in the described way. Table 5 shows the influence that the changes between the levels have.

The tape tension results show at first glance that the residual stress increases with decreasing tape tension. This suggests that, with no tape tension at all, the residual stress is at its maximum. This is true for the thermally induced residual stresses because they reach their maximum when no tape tension is working against them. However, it is also true that, if the tape tension increases further, the residual stress will at a certain point be dominated by mechanically induced stresses that are superimposed upon the thermally induced stresses. In this case the tape tension applied on the tape before the matrix is molten has to be supported almost alone by the fibres once the flame melts the matrix material. Thus, the tensioned fibres set the matrix under stress when it is resolidified. By having an increasing tape tension through the radius, the desired stress state shown in Fig. 1 is achieved. Further research work is in progress to document the abilities of this procedure. Preliminary tests justified further experiments.

Table 5 Influence of parameter changes on residual stress

Parameter	Change	Influence on residual stress creation
Mandrel temperature	$0.9T_c$ instead of RT	Increase
Annealing	At $0.9T_c$ for 20 min instead of RT	Increase
Tape material	GF/PP instead of CF/PEEK	Decrease
Liner (yes/no)	Use of liner	Increase
Winding angle	60° instead of 90°	Decrease
Tape force	70 N instead of 5 N	Decrease
Number of layers	10 instead of 5	Increase

4 TYPICAL PARTS WITH INDUCED RESIDUAL STRESS

Figure 4 shows a sample of CF/PEEK rings with a liner that was produced within the test programme. It was possible to generate residual stress that led to a closing ring (Fig. 4) as well as an opening ring in Fig. 5. The closing ring is from treatment combination number 8 of Table 3, and the opening ring is from treatment combination number 2. Opening rings have compressive residual stress on the inner surface which means that, as shown in Fig. 1, they are suitable for reducing the stresses in parts that are charged with internal pressure, whereas the closing parts are suitable for external pressure. According to the analysis, the influence of the temperature control during the process seems to be responsible for the change in stress profile.

Table 6 Results for the residual strain measured on the outside of the samples

Treatment combination	A	B	C	D	E	F	G	Average strain on outer surface (%)
1	1	1	1	1	1	1	1	0.02428
2	1	1	1	2	2	2	2	−0.0289
3	1	2	2	1	1	2	2	0.1126
4	1	2	2	2	2	1	1	0.0239
5	2	1	2	1	2	1	2	0.0337
6	2	1	2	2	1	2	1	0.0537
7	2	2	1	1	2	2	1	0.0269
8	2	2	1	2	1	1	2	0.221

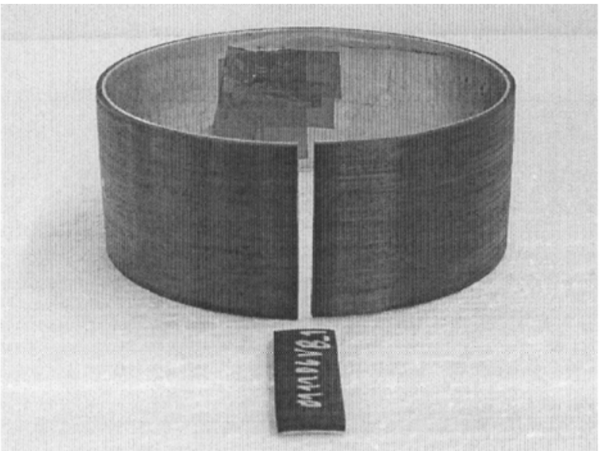

Fig. 4 Closing ring sample

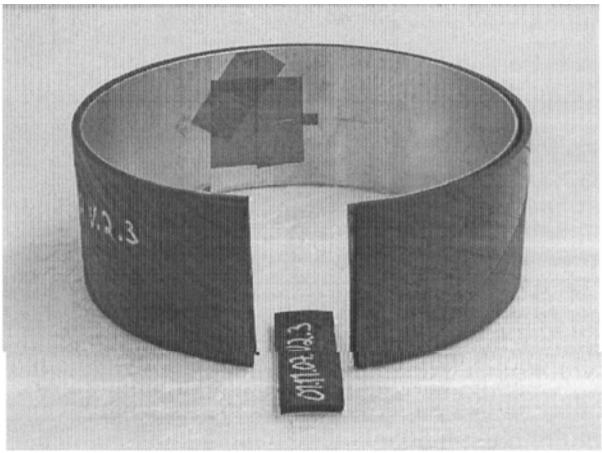

Fig. 5 Opening ring sample

5 CONCLUSION

Using the analysis of variance it was possible to determine the significant influence of process parameters on the residual stress occurring during the production of continuous fibre reinforced thermoplastic filament-wound sample parts. The parameters were winding angle, wall thickness, the annealing temperature of the samples, the mandrel temperature and, to a smaller extent, the tape tension. As winding angle and wall thickness depend on the application, the focus for further research work is on the temperature control of the process and the tape tension. With the established continuous data acquisition system it becomes possible to establish a practical oriented guide for inducing residual stresses in thermoplastic filament-wound parts.

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REFERENCES

1 **Olson, W.** and **Bert, C.** Analysis of residual stresses in bars and tubes of cylindrically orthotropic materials. *Expl Mechanics*, 1966, 451–457.
2 **Knight Jr, C.** Orthotropic photoelastic analysis of residual stresses in filament-wound structures. SESA Fall Meeting, Boston, 18–22 October 1970.
3 **Weitsmann, Y.** Residual thermal stresses due to cool-down of epoxy resin composites. *J. Appl. Mechanics*, September 1979, **46**, 563–567.
4 **Aleong, C.** and **Munro, M.** Effect of winding tension and cure schedule on residual stresses in radially-thick fiber composite rings. *Polym. Engng and Sci.*, 1991, **31**(18), 1344–1350.
5 **Di Vita, G., Perugini, P., Kenny, J.** and **Marchetti, M.** Process simulation models for filament winding technology. ICCM International Conference on *Composite Material*, Madrid, 12–16 July 1993, pp. 438–446 (Woodhead Publishing Limited, Abington, Cambridge).
6 **Nairn, J.** Thermoelastic analysis of residual stresses in unidirectional, high-performance composites. *Polym. Composites*, 1985, **6**(2), 123–130.
7 **Nairn, J.** and **Zoller, P.** Matrix solidification and the resulting residual stresses in composites. *J. Mater.*, 1985, **20**, 355–367.
8 **Cirino, M.** and **Pipes, R.** In-situ consolidation for the thermoplastic composite ring residual stress state. *Composites Mfg*, 1991, **2**(2).
9 **Tzeng, J.** and **Pipes, R.** Thermal residual stress analysis for in-situ and post consolidated rings. *Composites Mfg*, 1992, **3**(4), 273–279.
10 **Michaeli, W., Huybrechts, D.** and **Wegener, M.** *Dimensionieren mit Faserverbundkunststoffen*, 1994 (Carl Hanser, Munich–Vienna).
11 **Schlottermüller, M., Lü, H., Roth, Y., Himmel, N., Schledjewski, R.** and **Mitschang, P.** Thermal residual stress simulation in thermoplastic filament winding process. *J. Thermoplastic Composites Mater.*, 2003, **16**(6), 497–519.
12 **Krottmaier, J.** *Versuchsplanung: Der Weg zur Qualität des Jahres 2000*, 1991 (TÜV Rheinland, Zürich).
13 **Scheffler, E.** *Einführung in die Praxis der Statistischen Versuchsplanung*, 1986 (Deutscher Verlag für Grundstoffindustrie, Leipzig).
14 **Rasch, D., Verdooren, L.** and **Gowers, J.** *Fundamentals in the Design and Analysis of Experiments and Surveys*, 1999 (Oldenbourg Wissenschaftsverlag GmbH, Munich–Vienna).
15 **Dean, A.** and **Voss, D.** *Design and Analysis of Experiments*, 1999 (Springer, Heidelberg).
16 ASTM D 2290-92 Standard test method for apparent tensile strength of ring or tubular plastics by split disc method, 1992 (ASTM, West Conshohocken, Pennsylvania).
17 **Gould P.** *Static Analysis of Shells*, 1977 (Lexington Books, Toronto).
18 **Funck, R.** *Entwicklung Innovativer Fertigungstechniken zur Verarbeitung Kontinuierlicher Faserverstärkter Thermoplaste im Wickelverfahren*, 1996 (VDI Verlag, Düsseldorf).
19 **Ersoy, N.** and **Vardar, Ö.** Measurement of residual stresses in layered composites by compliance method. *J. Composite Mater.*, 2000, **34**(07/2000), 575–596.
20 **Knight, Jr, C.** Orthotropic photoelastic analysis of residual stress in filament-wound rings. *Expl Mechanics*, 1972, 107–112.