Abstract

Filament winding is today a well established production technique for fiber reinforced pressure vessels. Most of the parts are still made using thermosets as matrix material, but parts with thermoplastic matrices are today on the edge to mass production. Usually these parts are made from fully consolidated unidirectional fiber reinforced thermoplastic tapes. During processing the matrix material is molten and the tapes are placed on the substrate where they re-solidify. A wide range of material combinations are available on the market. The materials used in the present investigation are semi-crystalline thermoplastics and glass or carbon fiber i.e. carbon fiber reinforced Polyetheretherketone, glass fiber reinforced Polyetheretherketone and glass fiber reinforced Polypropylene.

Applications can be found in the field of medium and high pressure vessels like they are used for natural gas and hydrogen storage or for tubes and pipes for their transport. During the design of such parts mostly idealized properties as for example tensile strength are used. Residual stresses which are inherent for composite materials are only considered as part of the safety factor.

The present work investigates the generation of residual stresses for in-situ consolidation during filament winding. Within this process consolidation of the tape material and the substrate takes place immediately after the tapes are placed. This is contrary to the normal curing of thermoset materials and has a large influence on the generation of the residual stress. The impact of these stresses on the behavior of the produced parts during service is one of the topics of this investigation. Therefore the background of thermal residual stresses in semi-crystalline thermoplastic parts is discussed and a closer look on the crystallization behavior of the matrix materials was taken. As the beginning of the crystal growth is a major point in the generation of thermal residual stress.

The aim of the present work is to find process parameter combinations that allow to compensate the thermal residual stresses and to generate a residual stress profile that – unlike the thermal residual stresses - brings about structural benefit. Ring samples with a defined geometry were made to measure the generated stresses.

The geometry of the samples was chosen in a way that prevents influences of the boundary conditions of the free edges on the measuring point.

In the investigations the residual stresses were measured in circumferential direction using a method where the ring samples were cut in radial direction and the deformation was measured using strain gages. From the strain the local stress can be determined.

It was tried to minimize the number of experiments. Therefore the influence of filament winding process parameters on the residual stress were investigated using a Design of Experiments approach where the main influences on the residual stress generation can be found from a relatively small number of experiments such as 8 instead of 128. As a result of these experiments it was found that the winding angle, the mandrel temperature, the annealing, the wall thickness and the tape tension have a significant influence on residual stresses. With increasing winding angles the influence on the measured circumferential stresses increase regardless to kind of residual stresses. The mandrel temperature has a large influence on the temperature difference that causes the stress between fiber and matrix. They are caused by different thermal expansion coefficients of fiber and matrix. Structural benefit through annealing is only theoretically possible because the required outside temperatures along with internal cooling of the parts can not be realized within an industrial processes. Increasing wall thickness leads to also increasing residual stress but it can not be the aim to build oversized parts for the sake of residual stresses. The applied tape tension was identified as a parameter that can be used to achieve the desired residual stress state with reasonable efforts.

Different ways of varying the tape tension with increasing wall thickness were investigated. The tape tension was increased with every layer to a chosen maximum value or, after half of the layers were placed, in one step to the maximum value. Furthermore a continuously high tape tension and a variant without tape tension was investigated. The experiments led to the conclusion that increasing tape tension with increasing wall thickness is a viable way to have structural benefit from residual stress. The increasing in one step gave the best results.

The impact of the thermal history during production is discussed as well. Temperatures must not exceed the softening point of the matrix. Otherwise a part of the tape

tension gets lost by relaxation. In a particular case the relaxation reached an amount where the compensation of the thermal stresses failed. Thermodynamic calculations led to the conclusion that the energy transfer into the material by mandrel heating and melt energy caused a temperature above the softening point.

The impact of tape tension on material quality is documented. Very low tape tension can not guarantee a proper consolidation. On the other hand excessive tape tension can lead to matrix squeeze out and in particular cases to cracks due to too high residual stresses. Therefore the tape tension profile should be well adapted to work load, the composite and its properties.

Investigations on the relaxation behavior of the residual stresses showed that relaxation occurs and that a part of the residual stress relaxes when the samples were exposed to higher temperatures. Test at room temperature showed no significant sign of relaxation. When the temperature was raised – in this case to 80 °C - the samples clearly relaxed. The amount of induced residual stress sank to half of its initial value.

Investigations on the structural benefit showed that material savings of up to 23 % of weight are possible for high pressure applications and fiber reinforcements with relatively low fiber volume content. Higher fiber volume contents which also mean higher strengths reduce the benefit. As the strength of the material increases the benefit reduces in relation to it.

Nevertheless there is a potential in material saving and one should keep in mind that the costs to establish the equipment to control the tape tension is cheap in comparison to the achievable result.