Kurzfassung

Kontinuierlich faserverstärkte Thermoplaste (Organobleche) bieten ein großes Potential für den Einsatz in großvolumigen Sichtanwendungen. Es existieren jedoch einige material- und prozesstechnische Hindernisse hinsichtlich der Umsetzung dieses Potentials. Mit dieser Arbeit soll dazu beigetragen werden, das nötige, tiefgehende Verständnis bei der material- und prozesstechnischen Auslegung von optisch hochwertigen Organoblechbauteilen bereitzustellen. Die Arbeit umfasst:

- Untersuchungen zu material- und prozesstechnischen Parametern
- Eine analytische sowie eine FE-Modellbildung der Oberflächenausbildung samt Verifizierung
- Die Entwicklung eines Werkzeugkonzepts zur Verbesserung des isothermen Verarbeitungsprozesses

Die Untersuchung des Einflusses der textilen Gewebeparameter Faserdurchmesser und Maschenweite auf die Oberflächenwelligkeit von Organoblechen zeigen eine zunehmende Welligkeit mit steigendem Faserdurchmesser bzw. Maschenweite. Es wurde eine Grenzwelligkeit $W_{z25} = 0{,}5$ µm ermittelt, ab der subjektiv keine Welligkeit mehr wahrgenommen wird. Im Prozessvergleich zwischen isothermer und variothermer Verarbeitung besitzen variotherm verarbeitete Organobleche eine um 40 – 50 % geringere Welligkeit. Dieser Effekt wird auf die geänderte thermische Prozessführung während der Abkühlphase zurückgeführt. Die Erkenntnisse wurden in einem analytischen Prozessmodell beschrieben, welches neben den thermischen Eigenschaften auch das rheologische Matrixverhalten berücksichtigt. Auf dem entwickelten Modell aufbauend wurde eine FE-Prozesssimulation entwickelt und an experimentellen Daten verifiziert. Das Modell ermöglicht die Vorhersage der Oberflächenwelligkeiten von Organoblechen variabler Laminatkonfiguration bei variothermer Verarbeitung und beschreibt zusätzlich das Verhalten der Organobleche unter ebener Scherung.

Um die oberflächenverbessernden Eigenschaften der variothermen Verarbeitung auch im isothermen Prozess nutzbar zu machen, wurde ein neuartiges Werkzeugkonzept entwickelt, welches die Prozessfenster über angepasste thermische Werkzeugeigenschaften gezielt einstellen kann. Neben einer verbesserten Bauteiloberfläche kann durch eine optimierte Prozessauslegung die Gesamtprozesszeit verkürzt und der Energiebedarf verringert werden.

Abstract

The use of continuous fiber-reinforced thermoplastic materials, so called organic sheets, offers great potential for industrial applications. However, the manufacturing of Class-A surfaces made of organic sheets for use in body parts is subject to some material - and process-inherent conditions, which so far prevent a low-cost operation. There is little scientific information about the influence of certain material- and process-specific parameters on the surface development of thermoplastic composites. Existing models are not fully capable of predicting the composite surface properties. In this work material- and process-specific influences on surface properties of continuous fiber-reinforced polycarbonate during thermoforming are examined and assessed.

Looking on the material parameters the selection of the matrix, the reinforcement as well as the near-surface laminate composition determines the component's surface. A polymer coating of some hundred micrometers significantly reduces the maximum waviness. Through the use of nonwoven fabrics, only a slight reduction in the waviness could be measured for the used GF/PC-organic sheets. However, the irregular arrangement of nonwoven fabrics leads to a reduced subjective perception of the fabric texture and a visually more homogeneous surface. The influence of fabric fiber diameter and mesh size could be evaluated through the use of steel wire fabrics instead of multi-filament fabrics. The used reinforcement strongly influences the expression of surface waviness. There is a direct proportionality between waviness and fiber diameter and mesh size, respectively. A steel wire fabric with a fiber diameter $d \leq 50$ µm and a polymer surface layer with a thickness of 100 µm resulted in a maximum waviness $W_{z25} \leq 0{,}5$ µm which cannot be perceived by the human eye anymore. This limit is consistent with the measured maximum waviness of a variothermic manufactured PC plate, which also has a maximum waviness $W_{z25} = 0.5$ µm. An increase in mesh size also leads to an increased mesh volume, which leads to higher shrinkage and therefore an increased waviness.

Variothermic processing with an inductively heated tool shows a significant dependence of surface properties and process parameters. An increase in the press pressure from 25 bar to 200 bar reduces the waviness to almost 50 %, with a concurrent decrease in the tensile strength of the organic sheets by 6 %. A significant effect of the cooling rate could not be proven for a ΔT/t between 6 K / min and 46 K / min.

Furthermore, a process comparison between variothermal and isothermal processing was performed. If identical organic sheets are processed either isothermal or variothermal, a 40 – 50 % decrease in waviness can be measured for variothermal processed organic sheets depending on the laminate composition under otherwise comparable process conditions. Main reason for this phenomenon is the different thermal process control, which leads to longer process windows for variothermal thermoforming. To describe the behavior, an analytical process model was developed and successfully validated with experimental data. Additional to the thermal properties the model includes the rheological behavior of matrix material, therefore taking into account a compensating matrix flow which reduces a part of the thermally induced waviness during the thermoforming process at sufficiently long process windows. This effect is responsible for lower waviness values when processed variothermal compared with isothermal processing.

To predict the surface waviness and the rheological matrix behavior a functional, mesoscopic FE model was developed which can adequately reproduce plastic deformations of the matrix. The model supports the theory of compensating matrix flow during the production process and enables a prediction of the expected waviness depending on the textile parameter. This goal was achieved by modeling the matrix as a fluid and integrating a shear frame model in the unit cell.

Shear tests and simulations show that local increases in thickness of the organic sheets in the area of pure shearing arise mainly due to matrix squeeze out. Only at high shear angles roving interactions and therefore changes in cross sections contribute to the surface deformation. Additionally, an analytical approach to calculate the repressed matrix was derived and validated with experimental data.

The knowledge gained from these studies was used to develop a novel isothermal tool concept that allows extended thermoforming process windows by optimizing the thermal tool properties. Compared to a conventional steel tooling the process window could be increased by the factor of 14, which leads to better component surface properties. Together with an intelligent process design the surface properties can be increased and at the same time the total process time can be shortened and energy costs reduced.

For each material composition exists an optimum process window, where the waviness, influenced by the forming process, is minimal. The optimum is reached when the compensating plastic of the matrix is possible to the no-flow-temperature of the polymer. A further extension of the process window leads to no further reduction of waviness. For the used GF/PC organic sheets the optimum process window is assumed to be between two to four seconds.

As the mechanical and surface properties of the tool influence the components optical properties, a study on tool stiffness and tool surface roughness was performed. The result of the tool stiffness study can be stated as: the higher the stiffness of the tool, the less the maximum waviness of the components. Structured tool surfaces significantly affect the perceived surface of organic sheets, as increased roughness causes a drop in the degree of gloss and structural perception of the human eye on matte surfaces is severely restricted. In extreme cases, the existing waviness cannot be perceived by the viewer. Following applies: the higher the tool-induced roughness, the weaker the characteristic surface texture. An increase in maximum tool surface roughness R_{z25} from 4.9 µm to 30.6 µm proportional increases the maximum roughness of the organic sheet. The surface results as a superposition of shrinkage-induced and tool-induced structure. While the waviness is only slightly modified by the roughness of the tool, the micro-structure of the tool surface is molded into the organic sheets. An average polymer layer thickness of 10-20 µm is sufficient for this purpose.