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Influence of carbon black and indium tin oxide absorber particles on laser transmission welding

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ABSTRACT

For laser transmission welding of polypropylene carbon black and indium tin oxide (ITO) are used as absorber particles. Additionally, the colorant titanium dioxide is mixed to the absorbing part, while the transparent part is kept in natural state. The absorption coefficients of ITO and carbon black particles are obtained, as well as the scattering properties of polypropylene loaded with titanium dioxide (TiO_2). At similar concentrations the absorption coefficient of ITO is an order of magnitude smaller than that of carbon black. Simulations of radiation propagation show that the penetration depth of laser light is smaller for carbon black. Therefore, the density of the released heat is higher. Adding TiO_2 changes the distribution of heat in case of ITO, whereas for carbon black the effect is negligible. Thermal simulations reveal the influence of the two absorbers and TiO_2 on the heat affected zone. The results of the thermal simulations are compared to tensile test results.

1. Introduction

Plastics play an important role in almost every facet of our lives in a wide variety of markets, from everyday products such as food and beverage packaging, furniture and building materials to high tech products in the automotive, electronics, aerospace, medical and other areas. Since the monolithic construction is impossible in most of the cases , the joining technology plays a central role for the complete manufacturing of polymeric products. Starting with the development of the high power diode lasers in the mid 1990s, the laser welding of polymers enjoyed a continuous increase of its application fields and became an established process [1–4]. To assemble polymer parts, laser transmission welding has been introduced in industrial applications, but is still also a topic of investigations [4–6]. The fields of industrial application are e.g. household appliance, automotive and medical products, where a variety of polymers are used [7,8]. In laser transmission welding one part of the components is transparent to the laser radiation, the other absorbing. Both parts are brought in thermal contact using a clamping pressure, and the heat released in the absorbing part will diffuse into the transparent part (Fig. 1). Welding takes place if local melting occurs in both parts [4].

A commonly used absorbing agent is carbon black (CB). It is suitable for most laser wavelengths due to the electronic states of the graphite structure [9]. CB absorber particles change the appearance of the parts, which is not tolerable in many applications. An alternative is indium tin oxide (ITO) active in a wavelength regime between 1000 and 2000 nm [10]. For absorber concentrations, which are usually used in laser transmission welding ($<1\%$), both absorbers show different absorbing characteristics. An additional mixture with other additives, which scatter the radiation but do not absorb it, influences the absorption characteristic. A widely used additive is the colorant titanium dioxide (TiO_2) giving polymers a white appearance. Depending on the concentration TiO_2 changes the optical properties of the polymers due to scattering of radiation [11]. So an additional mixture with TiO_2 might also change the absorbing characteristic. In this sense, the choice of absorbers and additives will influence the welding result such as geometry and strength of the weld seam. Colorants and absorber particles can be homogeneously dispersed in the polymer matrix using a twin-screw extruder, where the polymers are melted and mixed with additives.

For the present investigations polypropylene (PP, SABIC 579S) and polycarbonate (PC, Makrolon) samples with dimensions $120\times40\times1\ mm^3$ manufactured by Treffert GmbH & Co.KG have been used. CB particles are supplied by "Orion Engineered Carbons GmbH, Germany". The diameters of the primary particles are not known, but are likely to be smaller than 100 nm [12,13]. ITO particles are supplied by "Evonik Industries AG" with diameters smaller than 10 nm. The TiO_2 pigments are supplied by "Kronos Titan GmbH, Germany" with particle diameters about 300 nm [14].

The geometry of the weld seam could be visualized by microtome cuts of the samples [15] or by simulating the temperature

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distribution according to the welding process [16–18]. For the simulation, the distribution of the released heat, generated by the absorption of laser radiation, has to be known. With this input the temperature distribution and the position of the melt isotherm could be calculated indicating the dimensions of the weld seam. The width of the seam perpendicular to the welding velocity is correlated to the strength of the join. Therefore, tensile shear tests are made giving the resistance of the seam in units of a force.

This article reports on the results of UV–vis–NIR spectroscopy measurements, radiation propagation and thermal simulations and tensile shear tests to investigate the influence of carbon black and ITO absorber together with TiO_2 on the welding process of polypropylene.

2. Optical properties and UV–vis–NIR spectroscopy

The optical properties considered here are scattering C_s, absorption coefficient C_a, anisotropy factor g and refraction index n. Whereas the coefficients give the probability of scattering and absorption, the anisotropy factor indicates the main direction of the scattered radiation [19,20,11]. To obtain the scattering properties, the transmittance T, the reflectance R and directed transmittance T_d of samples are measured for different wavelengths using an UV–vis–NIR spectrometer. The value of the refraction index of the polymer is taken from the literature. From these data scattering properties could be calculated. The experimental setup and the procedure of calculation are outlined in [20]. For 1 mm PP samples loaded with 0% and 2% TiO_2 the scattering properties are taken from [11] (Table 1).

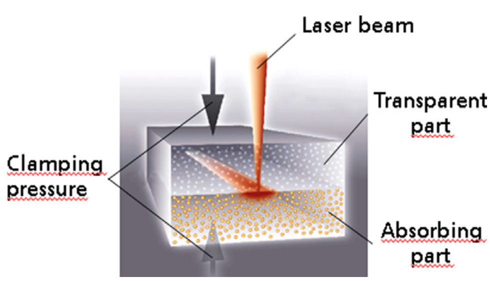

Fig. 1. Schematic representation of laser transmission welding.

The absorption coefficient of ITO is obtained from PC sample loaded with an ITO-concentration of 0.5 wt%. In the following text instead of wt% only % is used. Due to its amorphous structure PC is virtually a non-scattering polymer and radiation propagation is only influenced by the absorber particles and the surface reflection.

Scattering of additives/absorbers could be neglected if transmittance and direct transmittance have (approximately) the same value (cp. Table 1). Therefore, to calculate the absorption coefficient of non-scattering polymers/additives simple Beer's law is sufficient. Otherwise, more complex radiation propagation models, like the 4-flux-model discussed in [11,20,21],have to be used. The value of the surface reflectance for PC is set to constant 5% [11].

As seen from Fig. 2, the values of the transmittances T with and without ITO differ less than 10% from each other for wavelengths between 600 and 1000 nm. So absorption is negligible in this wavelength regime. Between 1000 and 1600 nm the transmittance T decreases for ITO and the absorption coefficient increases. The dips of the transmittances data are due to the absorption of radiation caused by carbon–hydrogen bonds [22]. At the corresponding wavelengths PC absorbs radiation without any additional absorber. The absorption coefficient of CB is taken from literature [10,23].

The scattering properties of PP with and without TiO_2, as well as the absorption coefficient of ITO and CB at 1530 nm (wavelength of the welding laser) are summarized in Table 1.

Due to its partly crystalline structure, PP also scatters radiation at this wavelength without any TiO_2 (Table 1, first line), but the coefficient is much smaller for 2% TiO_2. The absorption coefficient of ITO is much smaller for CB at a similar concentration indicating a stronger interaction of CB particles with the laser light. Unfortunately, we do not have samples with the same concentration. But for the investigation the small difference is not important.

3. Simulation of radiation propagation

Once scattering and absorption properties are known, the propagation of radiation in a polymer sample can be simulated. For this purpose we use the ray tracing software ZEMAX® [24]. In extension to the previous work [11] the present simulations also include absorption of rays. The simulations are carried out for two

Table 1
Optical properties at 1530 nm obtained for 1 mm PP samples (except fourth data-line where PC is used), * indicates properties, which are not given, T: transmittance, R: reflectance, T_d: direct transmittance, C_s: scattering, C_a: absorption coefficient, g: anisotropy factor.

TiO_2 (%)	ITO (%)	CB (%)	T (dimensionless)	R(dimensionless)	T_d (dimensionless)	C_s (mm^{-1})	C_a (mm^{-1})	g (dimensionless)
0	0	0	0.90	0.10	0.71	0.25	0	0.7
2	0	0	0.34	0.60	0.003	4.6	0.02	0.47
0	0.5	0	0.47	*	0.43	*	0.65	*
0	0	0.4	*	*	*	*	20	*

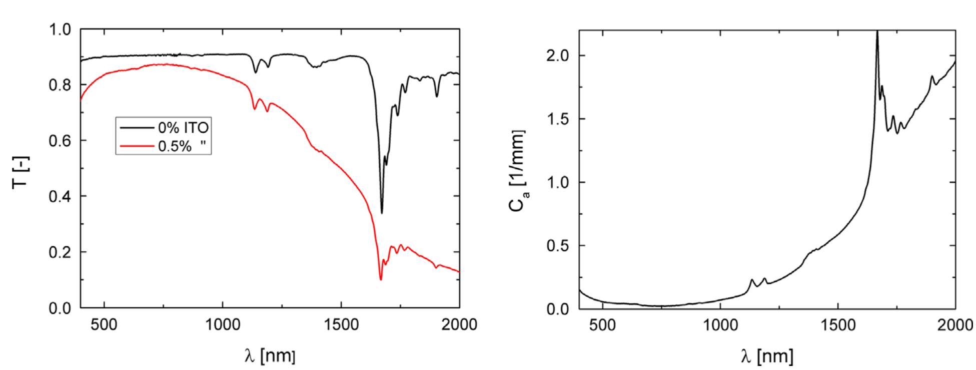

Fig. 2. Transmittance T of 1 mm PC sample with and without ITO (left) and the calculated absorption coefficient Ca (right).