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RESEARCH ARTICLE

Study on the transparency of polymer materials in case of Nd:YAG laser radiation

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Abstract

The exact knowledge of laser-polymer interaction and polymer behaviour is a fundamental requirement to establish good joint quality in the case of transparent-absorbent joining. In the course of this study, the authors investigated the effect of different material properties and laser settings, like thickness, additives, laser power and pulse characteristics, on the transparency in the case of poly(methyl methacrylate) and polypropylene materials. A new method was developed to detect the limits of material tolerance, which can be the basis of further research on polymer-polymer and polymer-metal hybrid joints.

Keywords

transparency · polymer · laser · hybrid joining

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1 Introduction

In the last years the expanding application of plastics can be observed in many fields of the industry. There are several beneficial properties of polymer materials, like good specific mechanical properties and low price compared to weight and density, which cause the growing utilization, especially in the vehicle industry due to weight and fuel consumption reduction intentions (Farazila et al. [6], Cenigaonaindia et al. [4], Bereczky et al. [3]). However, since metallic structural materials can not be totally substituted in our structures, the joining of metals and plastics have to be solved, to take advantage of both materials beneficial properties simultaneously (Grujicic et al. [7], Roesner et al. [9]). New joining technologies developed in the last few years are the transparent-absorbent laser welding and the laser assisted metal-plastic joining (Devrient et al. [5], Bauernhuber et al. [1], Katayama et al.[8]). In both cases there are two different joining partners, one with high transparency and one with high absorption on the wavelength of the laser radiation. The transparent material is clamped with the absorbent one in an overlapped geometry, while the laser radiation transmits the upper layer and is absorbed in the lower material. The absorbed laser radiation heats the absorbent joining partner, which transmits the heat to the other upper partner with heat conduction. After cooling down a bond is created, in the case of two plastic joining partners a welding seem, in case of hybrid materials an adhesive bond (Bauernhuber et al. [2]). The transparency of the applied materials is crucial in the joining process to achieve an appropriate bond. However there is relatively few data available in the topic, which describes the optical properties of the plastic materials, especially in cases different from the technologies introduced in the industry. Therefore the authors developed a new method to measure the transparency of the different plastic materials in the case of pulse mode Nd:YAG laser beam, and measured the transparency of the materials to expand the research in the field of laser assisted metal plastic joining.

2 Experiments

In the course of the experiments a Lasag SLS 200 type pulse mode Nd:YAG laser source was used, the wavelength of the laser radiation generated in this kind of solid state lasers is 1064 nm. The power of the laser radiation transmitted through the plastic material was measured with a Labmaster Coherent type laser power meter. The schematic view of the experimental setup can be seen in Fig. 1. The investigated materials were poly(methyl methacrylate) (PMMA), polypropylene (PP), polyamide (PA), polycarbonate (PC) and acrylonitrile butadiene styrene (ABS). In the case of polypropylene the effect of different additive materials were investigated as well. The applied filler materials and contents were: 20% glass fibre, 4%, 12% and 30% of boron nitride and 10%, 20%, 30% and 40% of talcum, separately. The thickness of the plastics was 2 mm, except the investigation of the effect of thickness, where PMMA sheets with thicknesses of 2 mm, 5 mm and 10 mm were used. The effect of the focal spot diameter, the average laser power and different laser pulse settings were investigated as well. The experiments were repeated three times, the duration of radiation was 10 s. The base laser settings were following: average power: Pa = 200 W, pulse frequency: fp = 100 Hz, pulse time: tp = 0.5 ms, pulse energy: Ep = 2 J. The value of average power was modified by adjusting the pulse frequency, by investigating the laser settings, the applied settings are shown in Tab. 1. By measuring the transparency of different plastics, the average power was 40 W, by investigating the laser settings, the laser spot diameter was ⌀3 mm in case of PMMA and ⌀5 mm in case of PP. The applied shielding gas was 4.25 l/min argon.

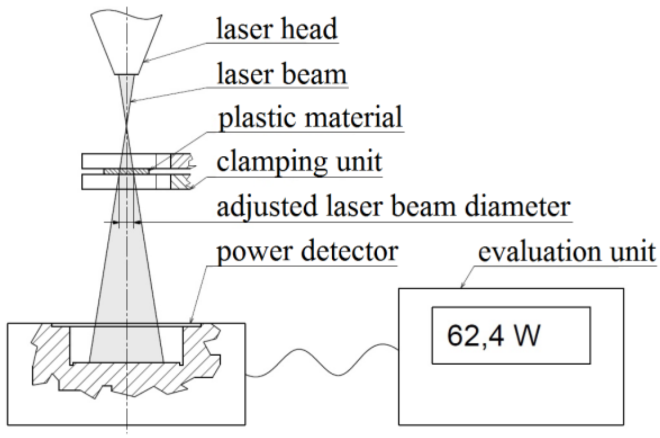


Fig. 1. Experimental setup

Tab. 1. Laser settings and materials applied in the experiments

Setting Nr.	P_a (W)	f_p (Hz)	t_p (ms)	E_p (J)
1.	200	100	0.5	2
2.	200	5	10	40
3.	200	26	10	7.5
4.	200	10	10	20

The measured power can be followed very well by a typical transparency curve, shown in Fig. 2, where relative power is represented in the function of irradiation time. Relative power is the quotient of power value P_4 and P_2. The process can be divided into 4 phases. In the first phase, the measured laser power reaches its maximal value; due to the inertia of the laser power meter, the equipment needs some seconds to follow the changes in power. In phase II the measured power is constant. Some seconds after reaching the constant and maximum laser power, corresponding with 100% transparency, the plastic is pushed into the way of the laser beam. In phase III the measured transparency decreases until it reaches a constant value. In the residual irradiation time, that is, phase IV, the measured power is constant. This constant value can be identified as the transparency of the plastic material. The transparency value can be calculated from the maximal power measured in phase II (P_2) and the constant power measured in phase IV (P_4). The plastic was radiated 10 s long, in each case. In the further diagrams, only that part of the transparency curve is shown which characterizes the plastic properties (phases III and IV).

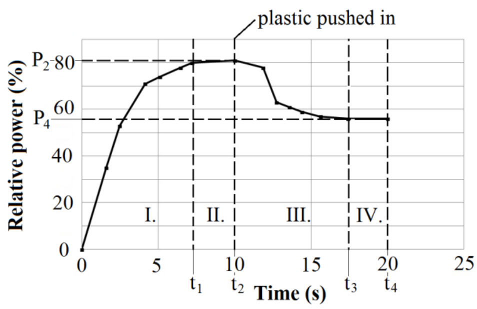


Fig. 2. Typical transparency curve and of the way the transparency value can be calculated

$$\text{Transparency} = \frac{P_4\,(t_4)}{P_2\,(t_2)} \cdot 100\,(\%) \tag{1}$$

It is also possible to estimate the transparency in cases where the curve does not have a constant value in phase IV. The position of the curve between the horizontal curve representing 100% transparency and the curve tending to zero, representing the 0% transparency gives the transparency value. The gradient of this second curve is a function of the inertia of the laser power meter. The described method is shown in Fig. 3.

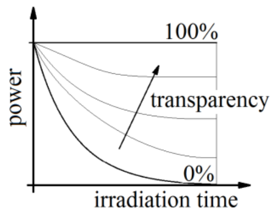


Fig. 3. Determining transparency from the position of the transparency curve

3 Results

3.1 Classification of materials based on the response to the laser radiation

Analyzing only phase III and phase IV in the measured curves, the laser-material interactions can be divided in three

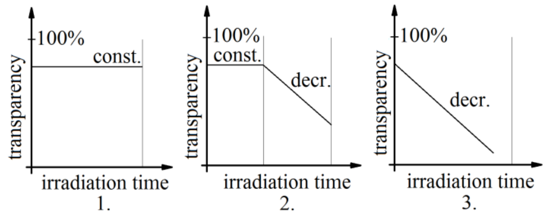
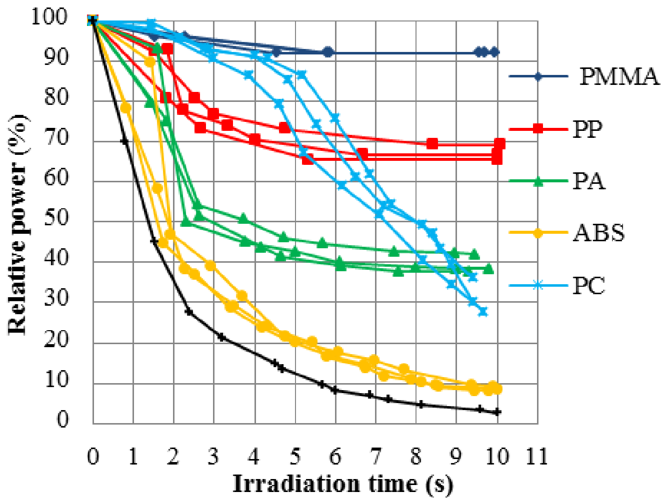


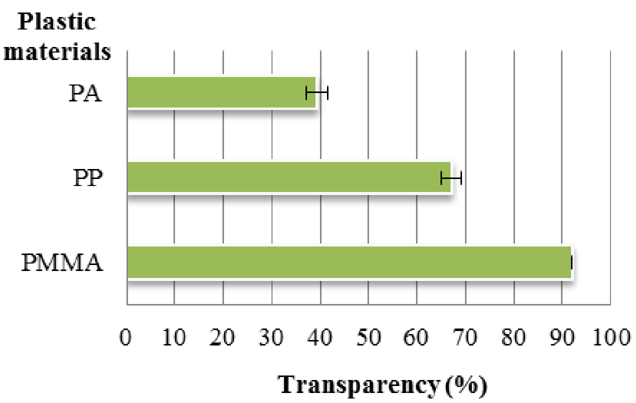
Fig. 4. Models for classifying laser-material interactions based on their transparency properties

different groups, shown in Fig. 4.: in group 1, the measured transparency is constant during the experiment; in this case it is possible to calculate the transparency in the given way. In group 2 the material tolerates the laser beam only for a certain time, after this it loses from its transparency. In group 3, the materials do not tolerate the laser beam and their transparency starts falling immediately, often to the zero value. However the behaviour and therefore the classification of the materials depend strongly on the applied laser beam settings: the average and pulse power density, pulse time, interaction time and pulse frequency.

3.2 Investigation of different plastic materials



(a)



(b)

Fig. 5. Measured transparency of different plastics

At first different kind of plastics were investigated to compare their transparency properties. It can be seen in Fig. 5a, that PMMA, PP and PA reaches a constant transparency value while the curve of PC and ABS materials decreases throughout the whole experiment. In this case the materials were burned and it was not possible to define the transparency. In the case of PMMA, PP and PA the calculated transparency values are shown in Fig. 5b. In the further investigations the transparency properties of PMMA and PP are detailed.

3.3 Investigation of PMMA material

In Fig. 6 the effect of the material thickness is plotted. A small decrease in average transparency, about 2%, can be identified by increasing the sheet thickness from 2 mm to 10 mm. To summarize the results, it can be stated, that the thickness does not has a significant effect on the transparency in case of PMMA.

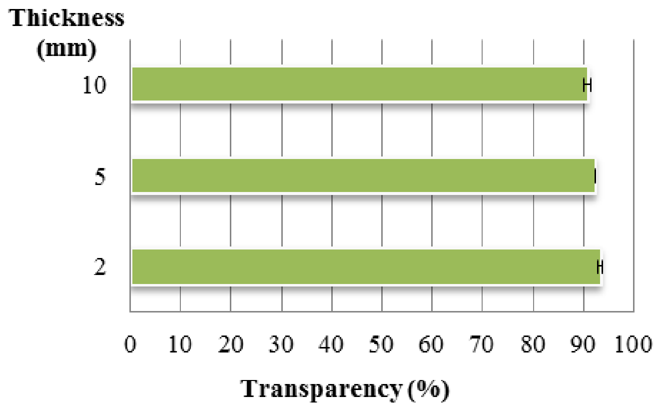


Fig. 6. Effect of PMMA thickness on transparency

The effect of average laser power on the transparency was investigated as well. To adjust the average power the pulse frequency was modified between 20 Hz and 100 Hz. The changes in the average power do not have any evincible effect on the transparency in the investigated range. The measured transparency was constant, about 93%.

In Fig. 7 the effect of focal spot diameter is shown. In the case of spot diameters of 5 mm and 4 mm the effect is small, the transparency is constant. At a spot diameter of 3 mm, the transparency curves begin to fall after a different radiation time, and at the diameter of 2.5 mm the curves fall strongly immediately after the beginning of radiation. This phenomenon can be explained with the growing power density and the degradation of the PMMA material. If the spot diameter decreases, the power density increases quadratically, and it reaches a value which can be tolerated by the material only for a shorter period, or cannot be tolerated even for a short time. In this case, the absorbed laser energy heats up the material, which reaches its decomposition temperature. The decomposition induces a radical destruction of optical properties in the material, and the increasing amount of absorbed heat even accelerates the process through decom-

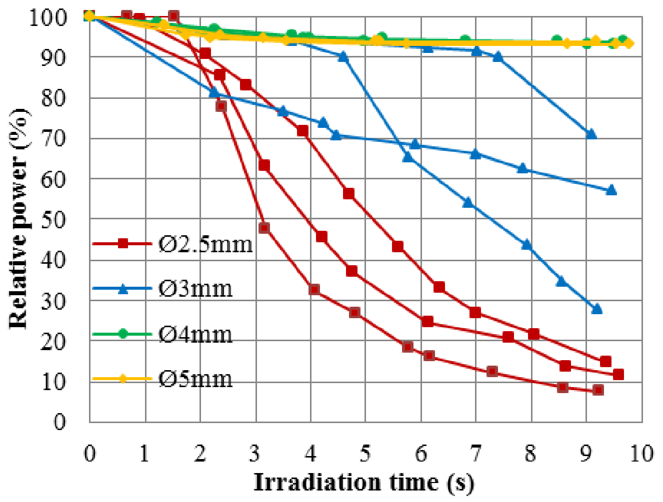


Fig. 7. Transparency curves at different laser spot diameters in the case of PMMA

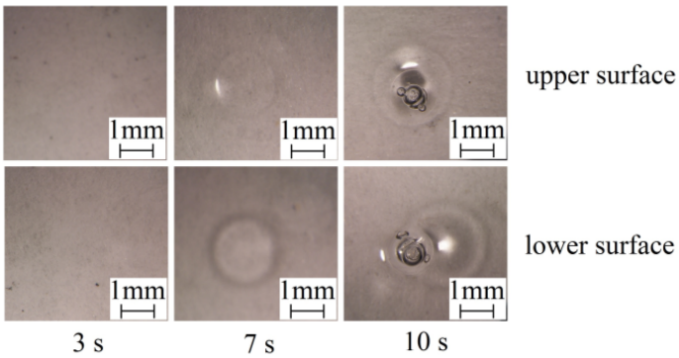


Fig. 8. Surface of PMMA samples after radiation times of 3 s, 7 s and 10 s at a 3 mm laser spot diameter

position. The result is a transparency value converging to zero. The degradation process of the PMMA material, using a laser spot diameter of 3 mm can be seen in Fig. 8.: after 3 seconds, there are no changes to be discovered on the surface. In the 7th second, the material melts and the surface deforms, after 10 s bubbles can be seen in the material which indicate the decomposition. The degradation starts in each case on the lower surface of the material, where the laser beam leaves the material. To explain the reason of this phenomenon further investigations are needed.

In the case of PMMA, the effect of pulse time, pulse power and pulse energy were investigated as well. In this phase of the experiment, a spot diameter of 3 mm was used to reach a critical power density, where the effect of the setting is detectable. Average power of 200 W was applied when investigating the effects of spot diameter, the results are shown in Fig. 9.

The highest pulse energy and pulse power is used in the case of setting 2 (E_p = 40 J, P_p = 4.35 kW). This setting shows an immediate falling of transparency and material degradation. The second highest pulse power can be found in setting 1 (E_p = 2 J, P_p = 4 kW). In this case, the material degrades at 3 different times, but in two cases not immediately, which means a higher tolerance against the radiation. The third highest is setting 4 (E_p = 20 J, P_p = 2.17 kW), where one of the samples do not degrades, and two samples degrade only at the end of the radiation. By using setting 3 (E_p = 7 J, P_p = 0.7 kW), the samples do not degrade, they keep the constant transparency through the whole experiment. The effect of the settings can be compared through the time needed for degradation of the samples. If this incubation time is longer, the material tolerates the laser setting better and vice versa. As it can be seen by comparing the values of pulse power, pulse time and pulse energy by the settings of 6 and 12, the most important effect on the incubation time has the pulse power, and the pulse time plays a role as well. Therefore the laser pulse shape has an effect on the degradation process not just the average characteristics.

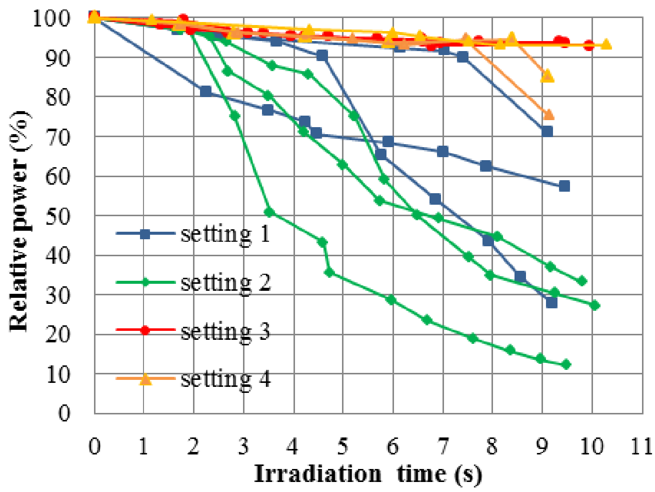


Fig. 9. Effect of laser settings on transparency changes at 3 mm laser spot diameter and 200 W average power

3.4 Investigation of PP material

In the case of polypropylene material, the effect of average power was investigated at first. The transparency was measured between 40 W and 200 W, average power was adjusted by changing the pulse frequency. The measured transparency was almost the same in the whole power range however, when using 140 W average power or higher, the transparency increases about 2%. In this case, the material starts to melt at the lower surface, which means a structural change in the material. This phenomenon can cause a slight transition of the transparency. In further investigations an average power of 120 W was used.

In Fig. 10. the effect of spot diameter can be seen. At a diameter of 5 mm and 4 mm the known curve of transparency can be identified: the curve shows a constant transparency during the examination time. By the diameter of 3 mm, the curve does not keep its constant value, but it increases after reaching its local minimum, which can be caused by thickness reduction. In this case, the plastic starts to melt, and forms a hole at the lower surface. The depth of this hole grows during the radiation time. At a diameter of 2.5 mm a similar effect can be seen as in the case

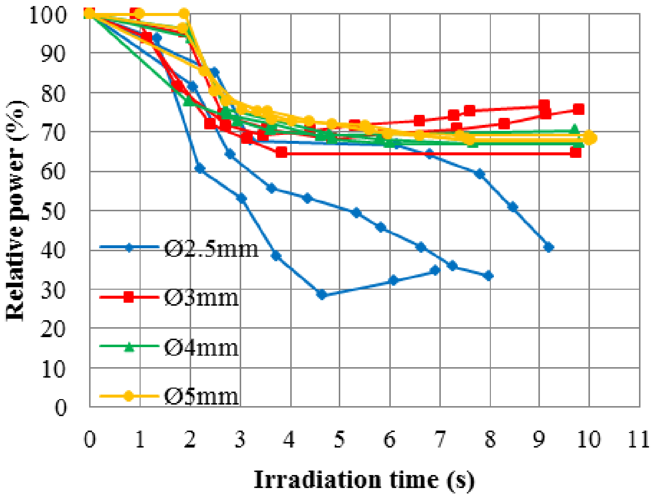


Fig. 10. Transparency curves at different laser spot diameters in the case of PP

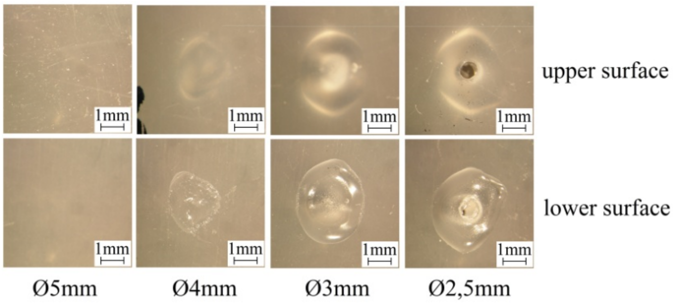
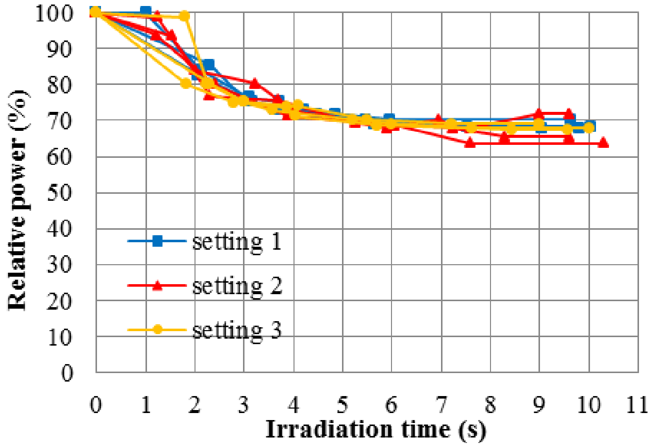
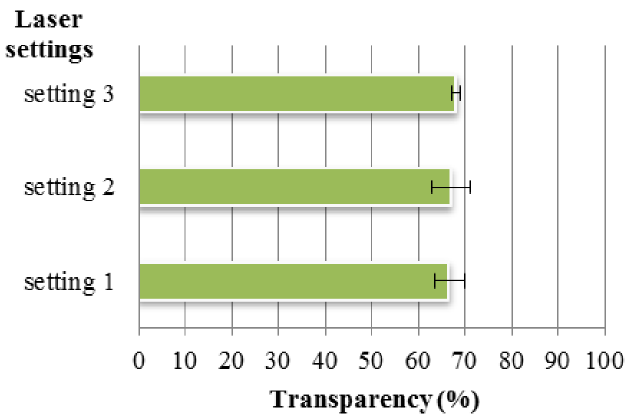


Fig. 11. Degradation of surfaces of PP samples at different laser spot diameters



(a)



(b)

Fig. 12. Effect of laser settings on the transparency of PP at 5 mm laser spot diameter and 200 W average power

of PMMA: the curves start to fall immediately after starting the radiation with a high deviation, and finally the material perforates. The steep falling can be explained with the degradation of the material, as described in case of PMMA. The hole might be caused by the growing indentation, which finally perforates the plastic, nevertheless the exact understanding of the process needs further investigation. In Fig. 11 the surfaces of the samples are shown at different spot diameters.

The results of laser setting investigations can be seen in Fig. 12. Three different laser setting were used, listed in Tab. 1. Unlike in the case of PMMA, no effect can be observed in the investigated range, the transparency remains constant during the experiment.

The effect of additive materials on the transparency of PP can be seen in Fig. 13. 20% of glass fibre results in a reduction of transparency from 67% to 12% as compared to the additive-free material. Although the glass is transparent for Nd:YAG laser radiation, the fibres scatter the radiation in the material, and enhance the amount of absorbed energy, and reduce the transparency. By using boron-nitride and talcum additives, even the lowest applied amount (4% boron-nitride, 10% talcum) results in a transparency of 0%, of course the higher additive contents results in a transparency of 0% as well. So the additive materials have a high influence on the transparency thus on the joining process too.

4 Conclusion

Summarizing the results of this research work, the following conclusions can be drawn:

- The authors developed a novel method for measuring the transparency in the case of pulse mode Nd:YAG laser source,
- This method is suitable for determining the critical parameters for laser-material interaction and thus also exploring the application possibilities of laser hybrid joining
- The laser-material interactions can be classified into 3 models which characterise the transparency properties of plastics
- Outside the critical parameter range the transparency value is constant, but reaching a critical area the investigated plastic materials start to decompose in the described way and transparency decreases radically
- The critical values at the same average laser power density and interaction time strongly depend on laser pulse characteristics, like pulse peak power and pulse duration. With this method the critical pulse shape can be determined too.

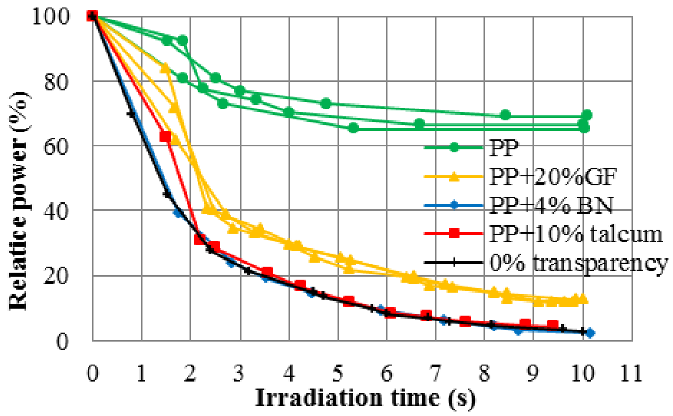


Fig. 13. Effect of additives on the transparency of PP

- Outside the critical parameter range the PMMA has 92%, the PP has a 65% and the PA has a 40% average transparency value. The PC and ABS polymers are not transparent in the investigated region.
- The investigated additives in the PP decrease the transparency. In case of 20% glass fibre content the transparency reduced to 20% and the BN and talcum eliminated the transmitted part of laser in the investigated region.
- Thickness does not has a significant effect on transparency in the case of PMMA under critical conditions.

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