THROUGH TRANSMISSION LASER WELDING PROCESS OPTIMIZATION FOR SEMICRYSTALLINE AND AMORPHOUS PLASTICS

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The paper is focused on the research in welding of plastic materials PP, PA 6.6 a ABS. This study deals with the optimization of individual parameters of the transmission laser welding process. The welds' quality evaluation was based on the testing of thermal and mechanical properties. The plastic materials were modified using the colouring pigments, nucleation agents and glass fibres.

KEYWORDS

TTLW, PP, ABS, PA66, glass fibres, nucleation agents

1 INTRODUCTION

Despite the efforts of designers to produce compact parts with many integrated elements, there are many products that are too complex and subject to high demands that it is not technically and economically possible to produce them as a single part of one piece of material. Joining plastic parts made of the same or different types of plastics, with metals and other materials, is thus often used in cases where the final assembly is too large or it is required with respect to the functionality of the resulting product. Methods of joining plastic parts can be divided into three main categories: mechanical joining, adhesive bonding and welding. Mechanical joining involves the use of fasteners, such as metal or plastic screws, or use of integrated components that are formed into the plastic parts, such as snap or press-fit joints. Mechanical joints thus belong to demountable joints, while gluing and welding technology creates permanent joints [Negin 2010].

Plastic welding is a joining method suitable only for thermoplastics. Unlike elastomers and rubbers, thermoplastics soften under the action of heat and thus change from a solid to viscoelastic state and subsequently into a melt. During welding, a joint is formed at a defined interface as a result of the simultaneous action of heat and pressure. The applied heat must ensure the melting of the welded surfaces and at the same time or subsequently the applied pressure ensures the mixing of macromolecules in the joint. The permanent joint is subsequently formed by solidification of the molten and mixed material into the resulting homogeneous structure, potentially achieving the properties of the original material. During welding, the macromolecular chains should be intensively mixed and the attractive forces restored, which requires constant pressure on the components to be joined [Van de Ven 2007, Becker 2002].

Today through transmission laser welding is one of the most efficient methods of welding plastics, in which a laser beam passes at the interface between two overlapping plastic parts. The principle of this technology is primarily based on the optical properties of both joined materials, where the upper covering part must be made of optically clear material for the acting beam of electromagnetic waves in the infrared spectrum. The lower part must be made of a material that is able to absorb the energy of the laser beam so that heat is generated at the welded interface, which melts both welded materials [Grewell 2016]. The main limitation of this method is the aspect of temperature when the joined materials are melted. In the case of "related" plastic materials, the structure is melted and the macromolecules of both connected parts are melted at the set welding parameters. If the joined parts are not melted at the same time sufficiently, a joint with the required strength will not be created [Kagan 2016].

Regarding optical phenomena, especially laser beam attenuation in polymers, there are several experimental approaches to quantify the effect of fillers, pigments, reinforcing materials, the combined effect of thickness, etc. In general, Beer-Lambert's law is used, which is a mathematical expression of electromagnetic radiation absorption by the material through which the radiation passes through [Ilie 2009]. This approach is suitable for absorbent polymers, but not for low absorbency and dispersing media. Laser beam scattering is an important phenomenon because it has a great influence on the energy distribution in materials, especially at the interface where the heat source must be placed [Elhem 2009].

2 EXPERIMENTAL PROCEDURE

The tested assemblies were prepared using a JK 400FL fibre laser with a power of 400 W and a wavelength of 1080 nm, see Fig. 1. In the frame of carried out analyses, 2 mm thick injected specimens were used. The surfaces of the welded bodies were only freed of dirt and degreased.

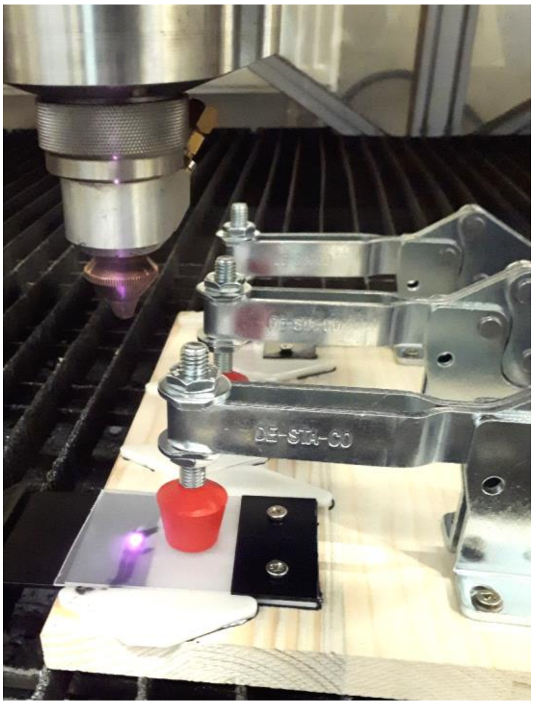

Figure 1. JK 400FL fibre laser preparing the testing specimens

Table 1. Individual temperature profiles

Heating / cooling regime	Materials PP	PA 6.6	ABS
1st heating range [°C] / rate [°C/min]	25 to 200 / 10	25 to 300 / 10	25 to 150 / 10
cooling range [°C] / rate [°C/min]	200 to 25 / 10	300 to 25 / 10	150 to 25 / 10
2nd heating range [°C] / rate [°C/min]	25 to 200 / 10	25 to 300 / 10	25 to 150 / 10

Basic optimization of welding parameters was performed on materials PP, ABS and PA 6.6. The effect of material composition was evaluated on the basis of the presence of talc nucleating agents, glass fibre reinforcing additives and colouring pigments in the concentrations recommended by the manufacturer. All the materials were coloured with pigments that are transparent to infrared waves [Kagan 2016]. These materials were chosen mainly for their wide use. ABS is an amorphous complex mixture consisting of the styrene-acrylonitrile copolymer and polybutadiene rubber and is therefore optically inhomogeneous. PP and PA 6.6 are semicrystalline polymers whose morphological arrangement (spherulites present) also scatters passing electromagnetic waves [Prabhakaran 2016].

In the first step, the top / covering transparent parts were always welded without any modification of the material to the dark substrate material, which contained particles for absorbing radiation, thus generated heat at the interface. Optimal welding parameters ensure that a sufficient amount of energy is released at a given speed of movement of the laser beam to melt the two joined parts without degrading the material. The heat released is directly proportional to the amount of energy that passes at the interface to the area of contact of the welded parts. The resulting thermo-physical phenomena and induced temperature gradients should provide ideal conditions for the formation of a structure achieving the desired properties [Van de Ven 2007].

2.1 *Mechanical properties*

All mechanical properties were determined at ambient temperature (23 °C). The specimens after injection moulding had been stored in a climatic chamber by temperature 23 °C, relative humidity 50 % for 10 days before testing. Maximal applied tensile force to the welds was determined using the basics of the method ISO 527 and the testing rate 50 mm/min. Measurements were carried out on TiraTest 2300 (Labortech, Czech Republic) device with the Epsilon axial extensometer Model 3542 (Epsilon Technology Co., USA).

2.2 *Differential scanning calorimetry analysis*

Differential scanning calorimetry (DSC) method on DSC 1/700 calorimeter (Mettler Toledo, Switzerland) according ISO 11357 was used for the evaluation of thermal properties of welds. The instrument was calibrated via indium and zinc standard. About $(10 \pm 0{,}4)$ mg of sample was prepared from the cross-section of the test specimen on a rotating microtome Leica RM2255 (Leica Biosystem, Germany). These cuttings were put into an aluminium pan (about volume 40 μl), sealed and then placed in the DSC chamber. An empty pan was used as a reference. An individual temperature profile was chosen for each material according to normative requirements (see Table 1). The heating-cooling cycle analysis run at 10 °C/min heating/cooling ramp in a nitrogen atmosphere (flow rate 50 ml/min) to determine thermal transitions.

2.3 *Thermogravimetric analysis*

The study also included thermogravimetric analysis, which was performed on a TGA 2 instrument (Mettler Toledo, Switzerland) in a dynamic mode, in an atmosphere of inert nitrogen, which removed the released fumes. The analysed samples were exposed to a precisely controlled temperature regime. The initial temperature was chosen to 25 ° C and the material samples were heated up to 800 ° C at a rate of 10 ° C / min.

3 RESULTS AND DISCUSSION

3.1 *Tensile strength of the weld*

For polypropylene without any modifications, the strongest joints were made using 200 W laser power and a movement rate of 40 mm/min, see Table 2. Slightly lower strength levels were achieved when using 100 W and a movement rate of 30 mm/min. The negative effects, in this case, were the speed of the laser at the 100 W power setting and too high a laser power at the 200 W setting, which caused too much heat to be released when the laser moved slowly, resulting in an inhomogeneous structure that did not achieve the desired properties.

After determining the basic optical behaviour of the PP matrix (influenced mainly by the structure of the material) in interaction with the laser, specimens made of PP matrix with black pigments were used as the upper / covering part in the second step, which should be transparent to infrared radiation. In the analysed range of welding parameters, the joint strength decreased by more than 60% compared to the basic combination, where the covering part was made of PP without any modification. The reason is probably too much scattering of radiation caused by the pigments, where only a fraction of the energy reached the interface and generated a lack of heat.

Table 2. Maximal applied tensile force [N] to the welds (No mod. – no modifications of the matrix, Pigments – black colour)

Welding parameters	PP		PA 6.6		ABS	
	No mod.	Pigments	No mod.	Pigments	No mod.	Pigments
100 W / 20 mm/min	1673	397	2727	2669	2325	1134
100 W / 30 mm/min	1801	513	2984	2880	2187	768
100 W / 40 mm/min	1109	302	3290	3183	2177	831
200 W / 20 mm/min	1034	659	2688	2365	1163	576
200 W / 30 mm/min	1396	437	2828	2677	1998	704
200 W / 40 mm/min	2051	388	2781	2826	2215	939

Other materials were evaluated similarly (ABS and PA 6.6). In the case of amorphous ABS, in terms of mechanical properties, the best weld quality in the selected range of parameters was achieved at a power of 100 W and a movement rate of 40 mm/min. Under these conditions, the optimal amount of energy passes at the interface in the analysed range, thus creating the best thermo-physical conditions for the formation of the desired structure. The dye for ABS fulfils its declared function under the selected welding conditions and the resulting welds are mechanically comparable to the variant with a transparent cover part. The weld of polyamide 6.6 reached the best strength at parameters of 100 W and a feed rate of 20 mm/min. As the speed of the laser movement increases, the amount of energy penetrating the interface of the welded parts decreases. At 200 W, the energy level at the interface was already too high. The colouring of the cover led to similar results as for polypropylene. The presence of the pigment and the associated change in the structure of PA 6.6 induced a decrease in strength of more than 50% in the tested range of welding parameters.

Table 3. Maximal applied tensile force [N] to the welds made of PP modified by talc

Welding parameters	Talc wt. %				
	2	4	6	8	10
100 W / 20 mm/min	1834	1987	1531	682	67
100 W / 30 mm/min	1602	1482	1127	511	79
100 W / 40 mm/min	1249	913	772	268	x
200 W / 20 mm/min	1194	1371	1287	948	411
200 W / 30 mm/min	1343	1629	1914	1086	363
200 W / 40 mm/min	1928	2185	2267	1603	554

Excluding the colouring pigments, one of the most commonly used additives are nucleating agents and reinforcing glass fibres. Both additives are widely used mainly in polypropylene so that a polypropylene matrix was used to test the effect of the presence of these modifiers on the through transmission laser welding process. The effect of talc was analysed in the range of 2 to 10 wt. %, see Tab. 3. Talc is primarily intended to form a very fine semicrystalline structure, but at the same time, it also has a slightly reinforcing function and, with increasing concentration, it significantly changes the optical properties of the matrix. The complexity of the problem was revealed by the results, when the changing optical properties of the covering part due to the presence of talc and increasing crystallinity together with the reinforcing character of talc affected the passage electromagnetic waves so that the best conditions in the range of tested parameters were achieved at 200 W power and movement rate 40 mm/min and a concentration of 4 to 6 wt. %.

Similar tests were performed to study the effect of glass fibres on the behaviour of the thoroughgoing laser beam and on thermo-physical phenomena occurring at the interface of welded parts. For the purpose of separating the two aspects, two testing sets were prepared and both included glass fibre concentrations ranging from 5 to 30 wt. %. In the first set, the concentration of glass fibres changed only for the substrate, which absorbs the energy of the beam, and the covering part was always made of transparent polypropylene without any modification, see Tab. 4.

In the case of the study of the glass fibres' presence impact on the electromagnetic waves, the substrate was made of PP with carbon black and the concentration of the fibres was changed only for the covering part, see Tab. 5. The values show that when using a completely transparent covering part, the results have similar trends as in the basic variant (black substrate with transparent covering part without any further modifications).

Table 4. Maximal applied tensile force [N] to the welds made of PP modified by glass fibres (substrate)

Welding parameters	Glass fibres wt. %					
	5	10	15	20	25	30
100 W / 20 mm/min	1898	2129	2479	2615	2579	2706
100 W / 30 mm/min	1841	2376	2426	2719	2786	2865
100 W / 40 mm/min	1394	1932	2259	2473	2591	2662
200 W / 20 mm/min	1284	1839	2173	2316	1728	1424
200 W / 30 mm/min	1507	1971	2094	2521	2032	1667
200 W / 40 mm/min	1966	2152	2267	2684	2853	3015

Table 5. Maximal applied tensile force [N] to the welds made of PP modified by glass fibres (covering part)

Welding parameters	Glass fibres wt. %					
	5	10	15	20	25	30
100 W / 20 mm/min	1588	1665	1814	2152	2394	2701
100 W / 30 mm/min	1962	2133	2342	2472	2553	2861
100 W / 40 mm/min	1356	2097	2629	2540	2926	3482
200 W / 20 mm/min	1261	1388	1557	1836	2493	3204
200 W / 30 mm/min	1676	1913	2245	2216	2622	2985
200 W / 40 mm/min	2282	2479	2634	2783	3061	2667

The strength of the weld is increased in comparison with the basic variant by the fibres penetrating into the weld. The best results in the analysed testing range were achieved using a power of 200 W and a movement rate of 40 mm/min. Very similar weld quality was achieved even at a setting of 100 W and a movement rate of 30 mm/min. The best mechanical properties were observed in variants with a substrate filled with 25 to 30 wt. % of glass fibres. When changing the optical properties of the covering part, the problem was again more complex.

Table 6. TG analysis - T5 temperature **[°C]**

Welding parameters	Materials		
	PP	PA 6.6	ABS
100 W / 20 mm/min	409.1	391.5	387.0
100 W / 30 mm/min	407.7	390.7	384.6
100 W / 40 mm/min	409.5	392.0	388.8
200 W / 20 mm/min	370.5	372.5	373.3
200 W / 30 mm/min	391.6	384.2	382.6
200 W / 40 mm/min	409.5	388.9	386.7
Original material	408.4	385.9	390.8

Due to the significant reinforcing effect of the glass fibres, this phenomenon again appears to be dominant in the evaluation of the strength of the resulting joint, with the best results being obtained using 100 W and a movement rate of 40 mm/min. However, very good results were achieved even at a setting of 200 W and movement rates of 30 and 40 mm / min, all at a concentration of 30 wt. % of glass fibres.

3.2 Thermal analysis

Analyses of the mechanical properties of the created welds pointed to significant structural changes that occurred in polymers under the action of various amounts of released heat, which depend on basic parameters such as power and movement rate. These changes can be also studied using thermogravimetry and DSC. Thermogravimetric analysis (TG or TGA) reveals the stability of the resulting structure. In this case, the evaluation was based on a comparative test. For this purpose, the substrate was always first analysed, which was used as a standard for the structures formed in the weld. The results are summarized in Tab. 6. The temperature at which the weight of the sample decreased by 5% (T_5) after the evaporation of residual moisture in the sample was chosen as the characteristic temperature. This temperature indicates the first structural changes associated with material degradation. The lower the temperature T_5, the lower the overall stability of the polymeric material is, and the greater the volume of sample material had undergone degradation prior to analysis. The values were subtracted from the obtained thermograms. The evaluation of the polypropylene matrix clearly shows that more significant structural changes in terms of degradation occur at parameters of 200 W and speeds of 20 and 30 mm/min, in other words at the setting when the largest amount of energy passes to the welded interface. Very similar results were obtained with the second semicrystalline material PA 6.6, where signs of at least slight degradation of the material were recorded at all tested settings at power 200 W. As mentioned earlier, the amorphous structure is not so clearly characterized by first-order phase transitions. However, deviations at temperature T_5 also indicated that with ABS, at a setting of 200 W and a speed of 20 mm/min (at the maximum energy concentration) certain structural changes occurred within the material.

To verify the results of thermogravimetric analysis, DSC analysis was used, which also allows the evaluation of the structure of polymeric materials based on the comparison of exposed parts with the substrate without any heat load. It is thus possible to evaluate the thermal history of the material, which it went through.

The evaluated parameters for semicrystalline plastics PP and PA 6.6 were the melting point of crystallites $T_{p,m}{}^1$ and $T_{p,m}{}^2$, where indices 1 and 2 indicate the first and second heating, furthermore, $\Delta H_m{}^1$ and $\Delta H_m{}^2$, which represent the change in the specific enthalpy of melting of the crystallites. Similar characteristics can be used to describe the solidification phase when the labelling is $T_{p,\,c}$ and ΔH_c, which is the crystallization temperature of the melt and the change in specific enthalpy of crystallization. For amorphous plastics, these first-order phase transitions are not applicable, and therefore the evaluation of structural changes in ABS was based on the second-order phase transition, which is characterized by the glass transition

Table 7. DSC analysis

	$T_{p,m}{}^1$ [°C]	$\Delta H_m{}^1$ [J/g]	$T_{p,c}$ [°C]	ΔH_c [J/g]	$T_{p,m}{}^2$ [°C]	$\Delta H_m{}^2$ [J/g]	$T_g{}^1$ [°C]	*$\Delta c_p{}^1$ [J/g.K]*	$T_g{}^2$ [°C]	*$\Delta c_p{}^2$ [J/g.K]*
PP										
Original material	166.4	90.4	129.3	-100.6	165.8	107.0				
100 W / 20 mm/min	166.1	93.6	129.5	-101.5	166.1	106.7				
100 W / 30 mm/min	165.8	96.1	128.9	-100.0	165.0	106.9				
100 W / 40 mm/min	165.6	91.7	129.2	-100.9	165.2	107.1				
200 W / 20 mm/min	162.9	90.9	127.4	-95.9	161.4	104.2				
200 W / 30 mm/min	163.3	92.2	126.8	-97.7	162.1	105.8				
200 W / 40 mm/min	166.4	96.4	129.2	-101.3	165.6	107.3				
PA 6.6										
Original material	219.4	59.0	189.9	-69.7	223.2	69.8				
100 W / 20 mm/min	219.5	57.8	190.7	-68.4	222.6	70.5				
100 W / 30 mm/min	218.9	58.3	190.3	-69.2	222.4	71.0				
100 W / 40 mm/min	219.7	57.5	190.7	-69.4	222.7	70.7				
200 W / 20 mm/min	217.4	43.6	184.3	-64.1	220.1	66.2				
200 W / 30 mm/min	218.9	55.0	187.4	-65.9	220.7	68.2				
200 W / 40 mm/min	219.5	59.4	190.6	-68.7	221.6	68.8				
ABS										
Original material							105.4	*0.258*	105.4	*0.273*
100 W / 20 mm/min							107.8	*0.246*	102.4	*0.223*
100 W / 30 mm/min							106.6	*0.248*	103.7	*0.235*
100 W / 40 mm/min							104.9	*0.262*	104.6	*0.248*
200 W / 20 mm/min							106.2	*0.183*	100.9	*0.255*
200 W / 30 mm/min							105.7	*0.231*	104.1	*0.261*
200 W / 40 mm/min							104.8	*0.244*	105.0	*0.252*

temperature (T_g^1 and T_g^2) and the change in specific heat capacity in this region (c_p^1 and c_p^2). Significant structural changes indicating morphological differentiation or possible degradation of the material are indicated primarily by a decrease in melting point. The first heating shows the effect of structural inhomogeneities and material degradation can be captured during the second heating cycle. When evaluating the characteristics of the glass transition, the interpretation is again not so obvious. The differences in the obtained values of the observed characteristics are not significant, but when considering the results of further analyses, certain nuances can be observed, confirming possible material degradation in PP and PA 6.6 using setting with the power of 200 W and 20 and 30 mm/min movement rates, see Tab. 7. In the frame of ABS material evaluation, no unambiguous conclusion can be stated and further analyses will be performed, which could contribute to the optimization and parameterization of the through transmission laser welding process of amorphous plastics.

4 CONCLUSIONS

In this study, the influence of basic welding parameters on the resulting strength of the welded joint was analysed. For this purpose, selected types of plastics were connected using through transmission laser welding technology, namely PP, ABS and PA 6.6. For all materials, the natural variant was analysed and the effect of the presence of black pigments was evaluated. The pigments should potentially transmit electromagnetic waves. Glass fibres, which were added to the PP matrix in a concentration of up to 30 wt. %, nucleating agents were also added to the PP in a concentration of up to 10 wt. % were other evaluated additives.

In terms of mechanical properties, the best results were obtained for PP welded assemblies using a power of 200 W and a movement rate of 40 mm/min. The presence of the pigments almost completely prevented the passage of energy into the weld area and the resulting joint strength was reduced to a minimum. In terms of the presence of talc, the best results were obtained with the same parameters and at a content of nucleating agents from 4 to 6 wt. %. With the increasing proportion of glass fibres, an increase in the strength of the weldment was also recorded. If the glass fibres were present only in the substrate, then the best mechanical properties were again achieved at a power of 200 W and a feed rate of 40 mm/min. Otherwise, when the glass fibres were present in the covering part of the assembly, the highest strength was measured at a lower laser power (100 W and a feed of 40 mm/min). The second semicrystalline material (PA 6.6) showed the best mechanical properties at a power of 100 W and the slowest analysed movement rate (20 mm/min), while the presence of the pigments again reduced the strength of the joint to a minimum. For amorphous ABS, the best results were obtained at 100 W and a movement rate of 40 mm/min. Only for the amorphous material, the pigments met the declared optical properties and the decrease in strength using the most appropriate setting represented only a statistical deviation.

Thermal analyses further confirmed the possible degradation of semicrystalline materials at parameters where the largest amount of energy was concentrated at the welded interface at a power of 200 W and movement rates of 20 and 30 mm/min.

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