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Selecting Nylon-Based Plastics for Laser Welding Technology

ABSTRACT

Selecting thermoplastics for welded, under-the-hood, automotive parts strongly depends on the plastic material properties, part design, as well as the molding and joining / welding technology conditions. Laser transmission welding (LTW) requires preferential deposition of energy and subsequent melting and diffusion of the material in the interfacial / weld-plane zone. This is optimized when the laser beam is transmitted through the thermoplastic transparent part and absorbed by the adjoining part to be welded. Energy deposition can be controlled to some extent by adjusting laser power, choice of beam focussing optics, sweep rate, etc.

The thermoplastic material properties and composition (reinforcements, fillers, additives, pigments, etc.) may have the greater influence and need to be characterized for optimum material selection for the transmission welding application. Commercial nylon based thermoplastics cover a large array of compositions, which may affect the laser transmission welding (LTW) process.

To provide a guide to nylon based thermoplastics selection for these applications we have evaluated the influence of specific material composition factors and properties, such as fiber-glass, mineral filler, impact modifier content, and color / pigment version on the Near InfraRed (NIR) transmission characteristics, including the laser wavelength (1.06 μm) . We have related these findings to the mechanical performance of nylon welded joints in terms of the influence of transmission laser welding technology parameters (laser power, welding speed, laser beam spot diameter, clamp pressure, etc.) and thermoplastic composition (reinforcements, fillers, additives, pigments, etc.).

Comprehensive results of this evaluation will assist plastic parts designers and technologists in selecting nylon based thermoplastics and developing new products using laser transmission welding (LTW) technology.

INTRODUCTION

Laser technology is seemingly everywhere from heavy machinery to microsurgery. The thermoplastics processing technology including joining of multi-shelves plastic part is not an exception. Different welding methods are used for joining and assembling hollow, automotive thermoplastic parts. In this study we will mention publications that are known to us . The articles and reports referenced below are critically important for a clear understanding of the advantages and disadvantages of the laser transmission welding technology for manufacturing thermoplastic, automotive hollow parts: ultrasonic [1], linear vibration [2-6], orbital vibration [7-8], spin [9], hot plate / tool [6-7, 10], infrared [11-15], and laser beam [16-20] welding. Technical results related to the joining / welding processing technology for thermoplastics, and mechanical performance of welded plastics have been presented widely to SAE, SPE, AWS, etc. [4, 6-7, 30]. These joining technologies all share the following typical welding phases:

- joining plastic parts placement / nesting and gripping in specially designed tools;
- contacting / pressing of the surfaces together for joining before material heating phase. Note: This phase is typical for the laser transmission and ultrasonic technologies, but is not typical for the frictional welding methods (linear vibration - LVW, orbital vibration - OVW, and spin), hot plate / tool – H-P/T welding technologies.
- material heating in the areas to be joined;
- local melting of surfaces at the jointed areas;
- contacting / pressing of the surfaces together for joining after heating and local melting. Note: This phase is not typical for the laser transmission welding (LTW), but typical for frictional and hot plate / tool welding (H-P/T) technologies.;
- cooling in the joint interface and other areas;
- removal of a welded part from the welded tool / nest and machine.

Material heating principles utilized in the first laser welding machines were similar to principles used for the hot plate welding machines / systems. Hot plate / tool (H-P/T) welding, although very efficient and reliable for many industrial applications [6], may cause problems with melt residues sticking to the surface of the hot plate / tool [7,19]. With non-contact (radiant) heater welding there is a possible risk of heat damage to polymer (degradation, de-coloration, etc.) and additives in the joining areas and an unpredictable over heating of the installed electronic parts / devices and welded thermoplastic component itself.

ADVANTAGES OF LASER WELDING TECHNOLOGIES (LWT)

Laser technology provides a highly attractive method / tool for engineering materials applications [21]. In the plastics industry there are many different applications for laser processing [22-23]. At the current time laser applications like “laser marking and labeling”, “laser surface enhancing for improved adhesion“, “laser cutting”, “laser drilling”, and “laser rapid prototyping” are well-established processes in the field of thermoplastics treatment. “Laser welding” of thermoplastic parts is at the initiation stage for wide industrial application. For joining of nylon based plastics there are two laser welding methods having possible wide industrial applications:

- laser fusion welding (butt joints);
- laser transmission welding (shear and butt joints).

Advantages of laser welding technologies (LWT) are mainly in an accurate, non-contact, heat transfer as well as the possibility to optimize welding temperatures (to weld interface). For laser transmission welding (LTW), it is critically important to achieve a sufficient and consistent heating of the thermoplastic in the region of the join during pre-, melt and fusion phases. This condition will produce consistent thicknesses for the weld.

Laser transmission welding permits welding of pre-assembled thermoplastic components. In this case the parts can be placed into nests with the same orientation and position as the final assembled product. For the laser transmission welding (LTW) there are virtually no limitations to the geometry and the size of the thermoplastic parts to be joined. Welding speeds as fast as 10 m/min. are attainable, allowing welding of long plastic parts where the weld seams reach a length of 1m (and more) within reasonable welding cycle time. Design freedom is enhanced because the weld seams may take on virtually any shape of the joined parts upon without concerns about the laser welding process.

Further advantages of the LTW are the absence of high (ultrasonic, from 15 to 40 kHz) and moderate (linear, about 240 Hz) vibrations in the joining process, as well localization of the heat affected zone and controlled melt flash in join area [25-26]. Even sensitive electronic and medical components are not damaged thermally or mechanically (vibrations), contrary to other plastic welding methods.

BASIC TYPES OF LASER WELDING SYSTEMS

Three laser types are mostly used for welding of polymer based materials: the CO_2 laser, the Nd:YAG laser and the diode laser [17-19]. The CO_2 laser uses a gas mixture to produce laser energy with a wavelength of 10,6 μm. These lasers are now available in the power range from 300W to 40kW and operate in a continuous wave mode. The Nd:YAG laser uses a solid crystal and produces laser energy with a wavelength of 1.06 μm. Nd:YAG lasers are now available in the power range from 39W to 2kW. For laser transmission welding (LTW) it is also possible to use diode lasers which generate infrared energy in the wavelength range from 800 to 950 nm. Laser welding methods have the following level of efficiency [18]:

- CO_2 laser – 10%;
- Nd:YAG laser – 3%;
- diode laser – 30%.

Laser welding equipment and welding tools and nests are not very expensive, and the laser welding process is not that time consuming. Laser welding machines for thermoplastics are available in Europe, North America and Asia [15, 18, 21-22, 25-26].

In this study we used the following lasers:

- Nd:YAG laser for optical characterization of an analyzed nylon 6 based thermoplastics;
- diode laser (MAGNA International) to weld plastic joints.

BASIC PRINCIPLES OF LASER TRANSMISSION WELDING (LTW)

In laser transmission welding (LTW) the parts to be joined are brought into direct contact prior to welding (see Figure 1). The welding process requires two thermoplastic materials, which transmit the laser energy to different degrees. The optically transparent (at the laser wavelength) part (**A**, such as natural, or colored with non-absorbing pigment) is in contact with an optically dense part (**B**, typically carbon black filled, or colored with absorbing pigment). The laser beam is transmitted through part **A** with minimal losses and totally absorbed within the surface (interfacial) layer of part **B**. Direct contact between the parts ensures heating of part **A** at the joint interface. Welding occurs upon melting and fusion of both materials (**A** and **B**) at the interface.

As rule automotive, thermoplastic made, parts are colored / pigmented. Uncolored plastics are only used for the automotive, under-the-hood, fluid reservoirs. The wavelength of CO_2 lasers will not pass through the exterior (colored) plastic part to reach an interior contact surface. In contrast, the beam generated by Nd:YAG or diode lasers may pass through colored, thermoplastic parts with no effect on polymer properties.

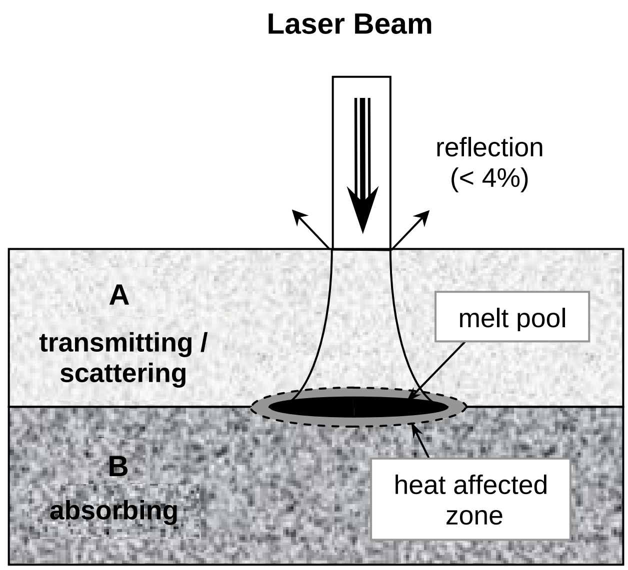

Figure 1: Principle of the laser transmission welding. Part A is a thermoplastic having variable transmission/ scattering. The thermoplastic in part B absorbs the transmitted light at the interfacial region

Various thermoplastic properties and processing parameters will influence the weld quality for a given laser power. The relative thickness of each part in welds of natural / black nylon 6 depends on carbon black content, becoming equal for contents exceeding 1 %. [19-20]. In general we expect laser transmission to be degraded by addition of reinforcement, fillers, colorants, and impact modifiers as well as by the crystallinity and thickness of the thermoplastic parts.

NYLON BASED PLASTICS - MATERIAL OF THE CHOICE FOR WELDED AUTOMOTIVE PARTS

Under-the hood (UTH) nylon use in North America and Europe has grown from 87,500 tons to 145,000 tons in 1997 and is projected to be 230,000 tons in 2005 [6,24]. Nylons (polyamides - PA) are high performance semi-crystalline thermoplastics with a number of attractive physical, chemical and mechanical properties. Welded nylon components are used in many industrial products, the largest being automotive. There are more than a dozen classes of nylon resins, including nylon 6, nylon 66, nylon 46, nylon 12, etc.

Reinforced nylon plastics (with 30 – 35 wt.% fiber-glass) are commonly used in design of air intake manifolds (AIM). Fiber-glass reinforced and mineral filled nylon plastics (40 wt.% GF/MF) are used in design of engine covers. Typically, the weight of nylon-based automotive components is 40-50% less than a similar design made from pressure-cast aluminum. Market projections for nylon welded manifolds are 60-65% by year 2005, and 70-75% by 2007 [27]. Nylon 6 is the material of choice for the welded air intake manifolds (AIM), resonators, because it lends itself to improve weldability and weld strength [27]. Nylon 6 molded manifolds have higher resistance to burst pressure than nylon 66. At the current time most welded air intake manifolds (AIM) are produced by linear vibration welding (LVW).

Hot plate / tool (H-P/T) and laser transmission welding (LTW) technologies may have a good chance to replace linear vibration welding technology (LVW) for welded, under-the-hood (UTH), plastic components. Comprehensive results on the performance of PMMA, PP, PE, HDPE based plastics for laser welded joints were presented in [20,25-26]. Weldability and optical data for nylon made joints is limited to the results (for non-reinforced, natural and carbon black pigmented plastics) published by H. Potente and F. Becker [19-20, 28].

MATERIALS DATA NEEDED FOR DESIGN IN LASER TRANSMISSION WELDING (LTW)

Design of nylon made parts requires development and analysis of the influence of material composition, processing technology and end-use conditions (time, temperature, moisture, ultraviolet exposure, etc.) on weld strength and life data. Properties of the base polymer (matrix), reinforcements and fillers, pigments, various additives of thermoplastic composition affects what happens to the laser energy absorption, reflection and transmission.

The following properties of plastic(s) used for welding of injection molded parts are very important for modeling and understanding the laser process :

- plastic(s) density;
- plastic(s) composition, by wt.% (fiber-glass reinforcement, mineral fillers, impact-modifiers, heat stabilizers, and other various additives);
- color / pigments (type and content, by wt.%);
- material state in joined parts / specimens before welding (dry as molded – DAM, moisture content, by wt.%);
- melt point;
- heat capacity;
- thermal conductivity;
- laser energy transmission;
- laser energy absorption;
- laser energy reflectivity.

We focused this study on the full optical characterization of non-colored (natural) and colored / pigmented nylon 6 based thermoplastics to determine the influence of reinforcement (non-filled, fiber-glass reinforced, mineral filled, impact modified, etc.) conditions. At the current time this specific optical data is limited to nylon 6 based thermoplastics and is not widely available in published articles and reports.

OPTICAL CHARACTERISTICS OF NYLON PLASTICS FOR LASER TRANSMISSION WELDING (LTW) APPLICATIONS

To establish optimized processing parameters for laser transmission welding (LTW) we have evaluated the influence of the following basic thermoplastic parameters on laser transmission and absorption through nylon 6 based samples / plaques:

- plastic composition (content of fiber-glass reinforcements, mineral fillers and impact modifiers);
- color / pigment;
- thickness of the plastic part.

We present measurements of laser transmission and the absorbance of the nylon 6 NIR peak at 1.39 μm. This comprehensive information should provide the first practical guidelines in thermoplastic selection for design and in understanding the joining process when laser transmission welding (LTW) will be used.

PROCEDURES AND EQUIPMENT FOR THE LASER TRANSMISSION MEASUREMENT

We measured the NIR (Near-Infrared) transmission characteristics of nylon plaques using two methods:

- Nd:YAG laser transmission (1,06 μm) ;
- Fourier Transform - NIR spectroscopy (0,95 – 2,0 μm).

Figure 2 shows the experimental arrangement for laser transmission measurements. The laser output beam is expanded and approximately collimated to a diameter of ~ 0,25 mm at the detector. The face of the detector has a diffusing screen and aperture of 1mm diam. The laser transmittance ($\mathbf{T = I_t / I_o}$) is calculated by measuring the laser beam intensity before ($\mathbf{I_0}$) and after ($\mathbf{I_t}$) placing the plastic sample / molded plaque directly in front of the detector. This position provides the best estimate of the transmittance at the outer surface of the sample.

When measuring the NIR spectrum the molded plaque is placed in the sample compartment, which is about 60 cm from the detector. A large fraction of the transmitted light does not reach the detector. Hence the measured transmittance is far lower compared to Nd:YAG based method. Although not useful for measuring the transmittance at 1,06 μm, the NIR spectrum can be used to discriminate between scattering and absorbance characteristics of the materials.

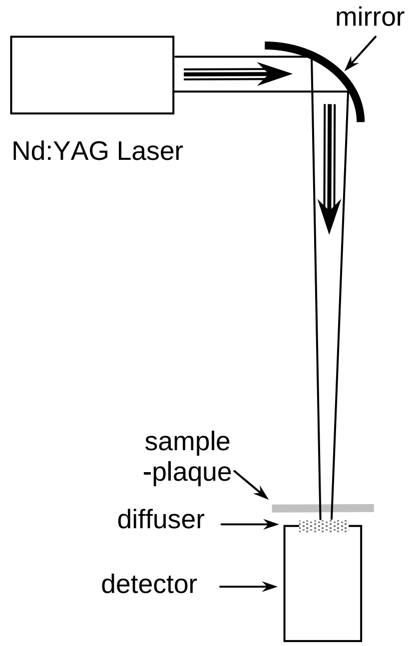

Figure 2: Apparatus for measuring laser transmission at 1.06 μm

The effect of internal scattering (due to nylon crystallinity and/or additional components) is to increase the effective pathlength of light transmitted though the sample. This produces two effects on the NIR absorption spectrum – see Figure 3 for a representative spectrum, plotted in absorbance ($\mathbf{A = log_{10}(T)}$) mode, of natural nylon 6 plaque. There is a broad, sloping, baseline which increases dramatically with scattering as does the intensity of the individual peaks. The effective pathlength can be quantified in a relative sense by monitoring the (baseline corrected) nylon absorbance at 1,39 μm. The appearance of new spectral peaks will indicate contributions due to additional components (such as colorants/pigments, etc.). This is especially important at the laser wavelength.

MATERIALS AND SPECIMENS

The thermoplastics used in this investigation were heat stabilized nylon 6 (commercial available Capron® series from AlliedSignal) plastics. For the base investigation we used non-colored (natural, as molded) and pigmented carbon black plastics (Tables 1 and 2). For the optical study on the effects of colorant we used commercial and experimental colored, non-reinforced plastics (Table 3). We analyzed plastics having the following composition (level of reinforcements, fillers and additives):

- short fiber-glass loading: from 6 to 45 wt.% (Table 1);
- combined loading of a short fiber-glass and minerals (one composition: 16 wt.% fiber-glass and 24 wt.% minerals) - Table 2;
- impact modifiers (three compositions) - Table 2.

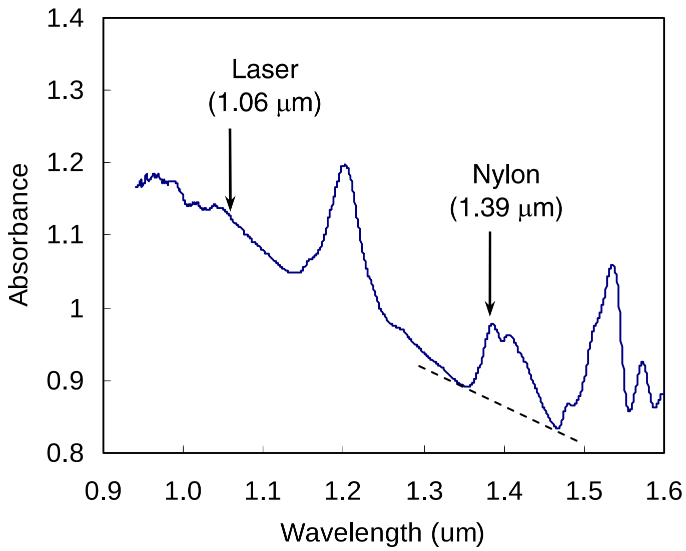

Figure 3: Representative NIR spectrum of a natural nylon 6 plaque (sample thickness = 3.2 μm). The nylon peak absorbance at 1.39 μm is measured from the baseline (---------) drawn from 1.33 to 1.47 μm

Injection molded, rectangular plaques were used for the optical characterization of the evaluated thermoplastics (Tables 1-3). Sizes (length x width) of molded plaques are: 150 mm by 100 mm (approximately) at three thickness (1,6; 3,2 and 6,25 mm). For the base investigation we used the 3,2 mm thick plaques. To examine the effect of thickness we used specimens / plaques of four thicknesses (0,8; 1,6; 3,2; 6,25 mm).

Table 1: Fiber-Glass Content Of Capron® (Nylon 6 Based) Plastics

Trade Name of Fiber-Glass Reinforced Plastics	Fiber-Glass (GF), % by weight	Used (in Welding) Colored Version (Black* - 0.1 wt.% of Carbon Black, BK-102,)
Capron 8202 HS	0	Natural / Black*
Capron 8230G HS	6	Natural / Black*
Capron 8231G HS	14	Natural / Black*
Capron 8232G HS	25	Natural / Black*
Capron 8233G HS	33	Natural / Black*
Capron 8234G HS	45	Natural / Black*

The specimens / plaques at 0,8 mm thick were machined from molded plaques 1,6 mm thick. The molded surface of the machined plaques faced the incident laser beam.

EFFECT OF REINFORCEMENTS AND FILLERS

We did not find published technical data related to optical characterization (at wavelength = 1,06 μm) of short fiber-glass reinforced, semi-crystalline plastics for the laser transmission technology. For the short (180-320 μm), fiber-glass reinforced, nylon 6 plastics, the

Table 2: Filled And Fiber-Glass Reinforced Capron® (Nylon 6 Based) Plastics

Trade Name of Glass / Mineral & Reinforced / Filled and Impact Modified plastics	Fiber-Glass (GF), wt.% (by weight)	Mineral Fillers (MF), % by weight	Impact Modifiers (IM), % by weight
Capron 8267G HS	16	24	0
Capron 8260 HS	0	40	0
Capron 8350 HS	0	0	28
Capron 8351 HS	0	0	28
Capron BU50I	0	0	20
Capron 8333G HS	0	33	5

Table 3: Colored Versions Of Non-Reinforced, Nylon 6 Based, Capron 8202 HS

Color or Pigment Version	Specification / Trade Version	Pigment Content (wt.%) by Weight
Natural	Natural	0
Carbon Black	BK-102	0,1 - 0,2
Carbon Black	BK-5602	1,0
Carbon Black	BK-106	2,0
Green	Experimental	0,5
Red	Experimental	0,5
Yellow	Experimental	1,0
White	Experimental	1,0

transmission decreases monotonically with increasing fiber-glass content from 0 to 45 wt.% (Figure 4). The decrease in transmission is due to increased light scattering. This can be seen in Figure 5 which shows an increase in effective pathlength, as displayed by the (baseline corrected) 1.39 μm nylon absorption peak. The absorbance/nylon content (wt.%) does not remain constant as the fiber-glass content increases from 0 to 45 wt.%. The increased effective pathlength at high fiber-glass contents is a direct consequence of light scattering from the short fiber-glass.

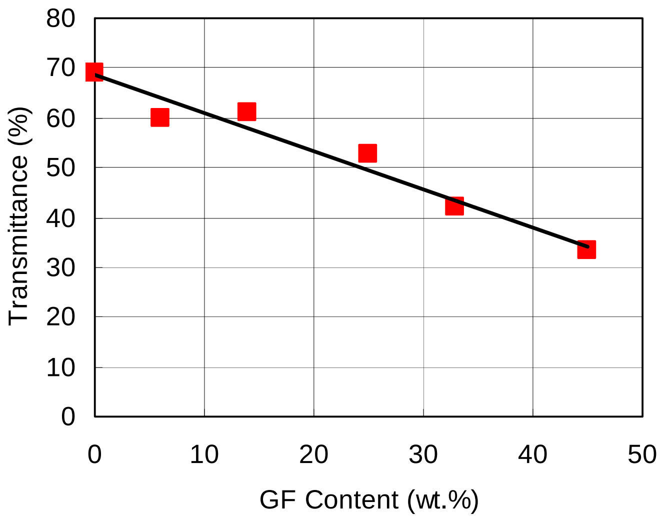

Figure 4: Influence of fiber-glass content (wt.%) on laser transmission at 1.06 μm (sample thickness = 3.2 μm)

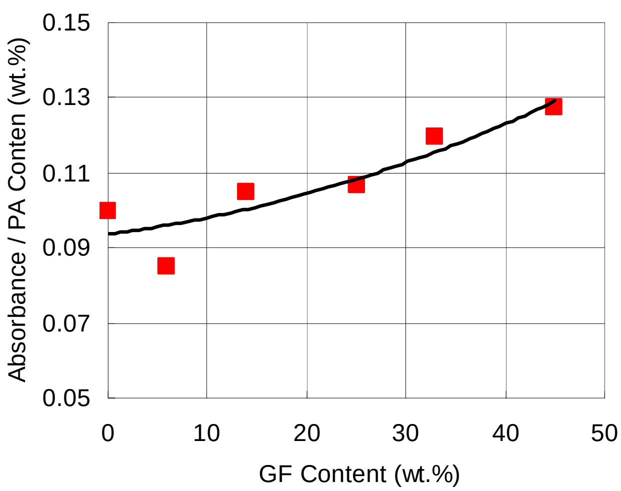

Figure 5: Influence of fiber-glass content (wt.%) on nylon absorbance at 1.39 μm (normalized to nylon 6 content), (sample thickness = 3.2 mm)

Figure 6 shows the influence of a short fiber-glass reinforcements and mineral fillers commonly used in nylon plastics. The addition of mineral filler is far more detrimental to the laser transmission than a short fiber-glass reinforcement. This is attributed to differences in particle size and possibly refractive index. Typical short fiber-glass dimensions are about 10 μm diameter with lengths in the range 180-320 μm in molded parts. In contrast mineral particle sizes are much finer. For the same filler / reinforcement content the filler has a far greater number of scattering centers. This results in the effective pathlength for the nylon at 40 wt.% mineral filler being 4,2 times that for 45 wt.% fiber-glass reinforcement (Figure 7).

The difference in scattering with filler / reinforcement has two implications for laser welding applications (at constant laser power and filler/reinforcement content). Mineral fillers much more severely reduce the available energy at the interface. In addition the energy will be spread out over a wider area. If transition laser welding is to be achieved with highly filled materials, the laser power and / or irradiation would need to be increased considerably relative to natural nylons.

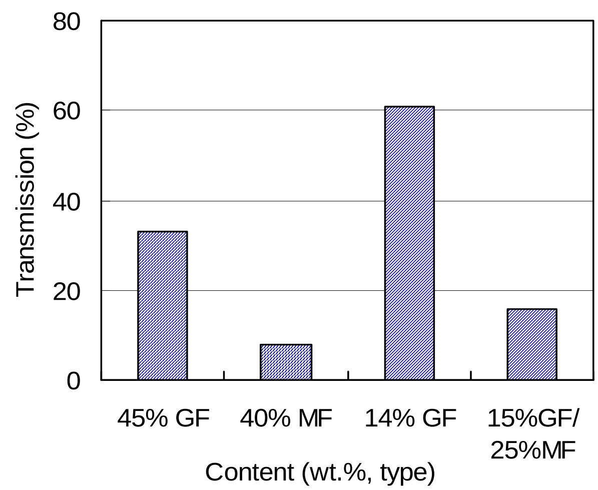

Figure 6: Influence of fiber-glass (GF), mineral filler (MF) and content (wt.%) on laser transmission at 1.06 μm (sample thickness = 3.2 mm)

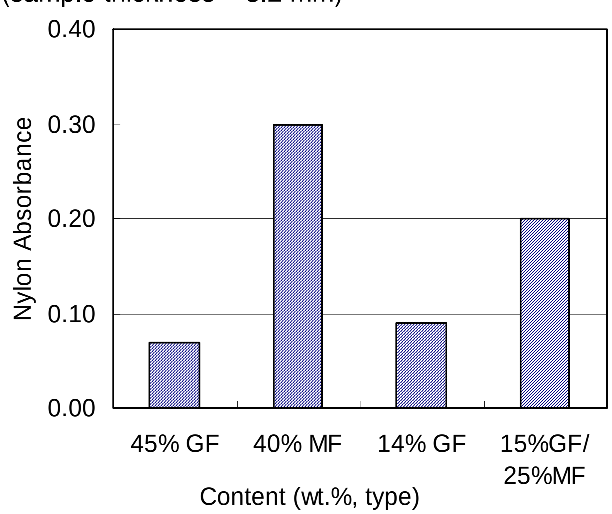

Figure 7: Influence of fiber-glass (GF), mineral filler (MF) and content (wt.%) on nylon absorbance at 1.39 μm (sample thickness = 3.2 mm). The absorbance for natural nylon 6 is 0.10

EFFECT OF COLORANTS / PIGMENTS

Pigments / colors, coatings are the other components of a thermoplastic formulation that affect laser transmission. For optimized design we need to have a clear understanding of these effects in order to enhance the optical performance of the two thermoplastic(s) parts to be joined. They have opposite requirements: one part should have acceptable transmission at the laser wavelength; the second should absorb the laser energy at the weld area (see Figure 1).

The effects of different colors (blue, green, orange, yellow and red) and carbon black pigments on the transmission behavior of acrylonitrile-butadiene-styrene (ABS) for through-transmission infrared welding (TTIRW) were published by H. Yeh and R. Grimm [29]. These authors state: “Materials have a certain color because they absorb all colors from the spectrum and re-emit the observed color. Thus, the red samples should be re-emitting the red color that constitutes the largest part of the visible output. However, the temperatures sensed with the red samples are lower than for other colors. Thus less energy is transmitted through the red ABS than through any other color. The blue polymer is re-emitting the blue color constitutes only a small part of the visible output”. In this study [29] were presented results on the effects of carbon black level on transmission through PE based plastic. This work shows that absorption is very sensitive to the level of carbon black in the thermoplastic. The sensitivity occurs at very low levels of carbon black (0,03 wt.% for the thin film of 0,25 mm and 0,07 wt.% for the film at 0,5 mm).

The effects of pigment concentration (from 0 wt.% to 0.20 wt.%) on optical properties (transmission, absorption and reflection) of nylon 66 plastic were reported in [25]. At a pigment level equal 0,1 wt.% all three properties were satiated. At the range of a color content from 0,1 wt.% to 0,2 wt.% the optical behavior changed slowly.

H. Potente, J. Korte and F. Becker analyzed [19] the influence of a carbon black on the ratio of the melt thickness for non-reinforced / filled nylon 6 as a function of the laser transmission welding parameters (laser power intensity and scanning rate). With the laser scanning rate increase from 4,6 mm/s to 7,7 mm/s carbon black content of the absorbing plastic part increased from 0,2 wt.% to 1 wt.%. This increase changed the melt thickness ratio ($\mathbf{m_{A,\,natural}}$ **/** $\mathbf{m_{B,\,colored}}$) from 0,1 to 1,0. If the carbon black content of the absorbing part is high (more than 1 wt.%), the thickness of the melt layers will be similar in the non-colored / transparent ($\mathbf{m_{A,\,natural}}$) and absorbing / colored ($\mathbf{m_{B,\,colored}}$) plastic parts. The authors of this investigation[19] state: “A high carbon black content (or any other pigment which provide a high absorption constant) in the absorbing part, a similar temperature distribution can be expected in both thermoplastic parts being welded”.

For the base investigation on the effects of colorants / pigments we used pigmented (green, yellow, red, white and carbon black) and non-pigmented (natural) nylon 6 (non-filled / non-reinforced) plastics (Table 3, Figures 8 and 9). For the black pigmented materials we used three levels of a carbon black loading (0,2 wt.%, 1,0 wt.% and 2,0 wt.%) typical for commercial nylon 6 grades. All carbon black levels have a very low transmission (< 0.3%, Figure 10).

This investigation shows that color markedly influences laser transmission (Figure 8). Two effects may contribute to the observed color differences: increased absorption by the colorant and particulate scattering. The NIR spectra in the region of the laser line do not change appreciably for these materials suggesting that the intrinsic absorption by the colorants contribute minimally to the laser transmission characteristics. Scattering is the dominant effect, confirmed by the different effective pathlengths for nylon 6 observed for the samples (Figure 9). If absorption at the laser

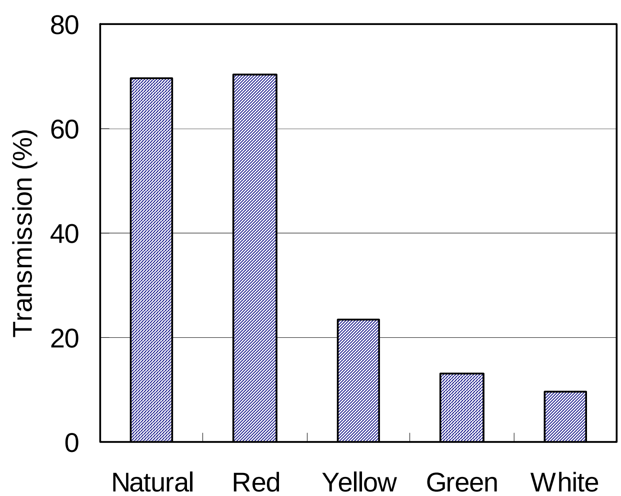

Figure 8: Influence of color version on laser transmission at 1.06 μm (sample thickness = 3.2 mm)

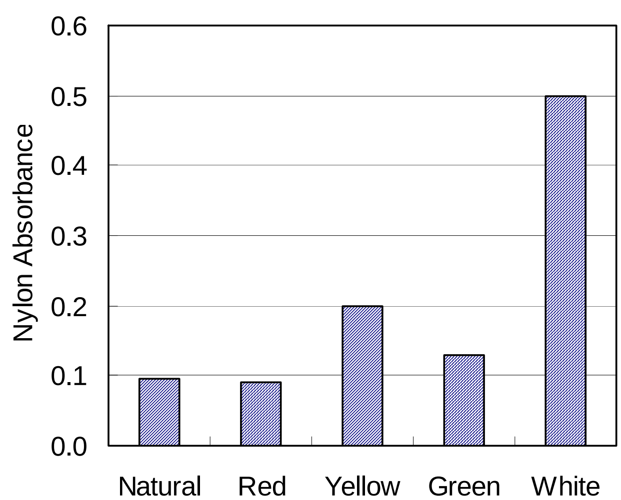

Figure 9: Influence of color version on nylon absorbance at 1.39 μm (sample thickness = 3.2 mm)

wavelength is not significant why is the scattering component so variable with colorant? We suggest that the reason lies in the type of colorant used. Organic pigments will form homogeneous solutions with the polymer but inorganic pigments will not dissolve. Rather they will have small particle sizes and behave similarly to mineral fillers. We infer that red is most likely an organic pigment while yellow, green and white are likely to be inorganic. This implies that the use of organic pigments in nylon materials may broaden the range of colored materials used to transmit the laser energy in laser welding applications. Conversely the use of inorganic materials will most likely prevent their use in such applications.

COMBINED EFFECT OF THICKNESS AND COLOR / PIGMENT

The laser transmittance is a function of plastic part thickness for semi-crystalline materials. Comprehensive data on the influence of specimen thickness on Nd:YAG laser transmission (Figure 10) was developed by I. Jones (TWI – The Welding Institute) and presented during the seminar on the laser technology for polymeric materials (Cambridge, UK, March 1999), [33]. For all three evaluated semi-crystalline plastics (PA, HDPE and PP) the transmission decreases monotonically with increasing of thickness of the plastic part (0,5 mm to 10 mm). Nylon (type was not specified) was less sensitive to the effects of thickness in comparison to HDPE and PP, materials that are widely used for welded plastic parts.

We evaluated the influence of thickness (from 0,8 mm to 6,25 mm) for pigmented (green, yellow, red, white and carbon black) and non-pigmented (natural) nylon 6 (non-filled / non-reinforced) plastics (Figure 11). The composition of these nylon 6 based plastics is presented

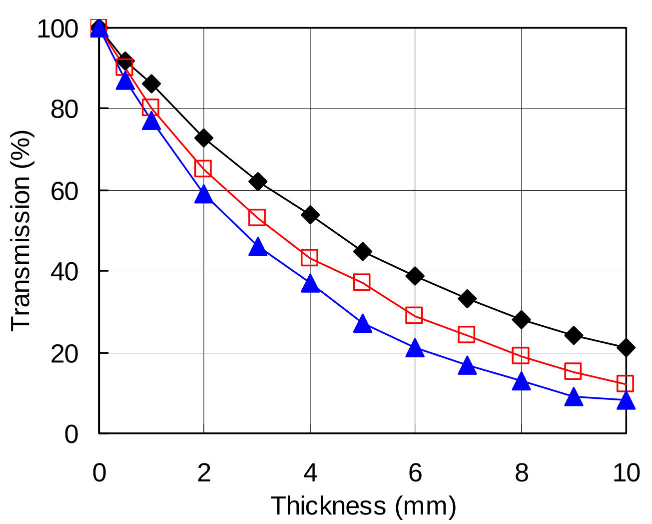

Figure 10: Influence of thickness on laser transmission of semi-crystalline non-colored (natural) plastics at 1.06 μm. Legend: PA (♦); HDPE (□); PP (▯) [33]

in Table 3. Although the transmission characteristics for natural nylon are consistent with a Beer's Law dependence on sample thickness this is most likely fortuitous. This observed dependence is likely due to scattering within the sample. This is confirmed by the measured effective pathlength of the 1,39 μm nylon peak absorbance which increases with thickness for the white, yellow and green samples.(Figure 12). The red colored material follows the same dependence as natural nylon indicating addition of red colorant does not contribute to either increased absorbance or scattering for the laser transmission. For laser welding applications it may be possible to use thickness larger than 6,25 mm for both natural and red colored materials as the optically transparent part. For a 12,5 mm thickness the transmittance predicted by the observed "Beer-Lambert law" dependence is 17% compared to 41% at 6,25 mm.

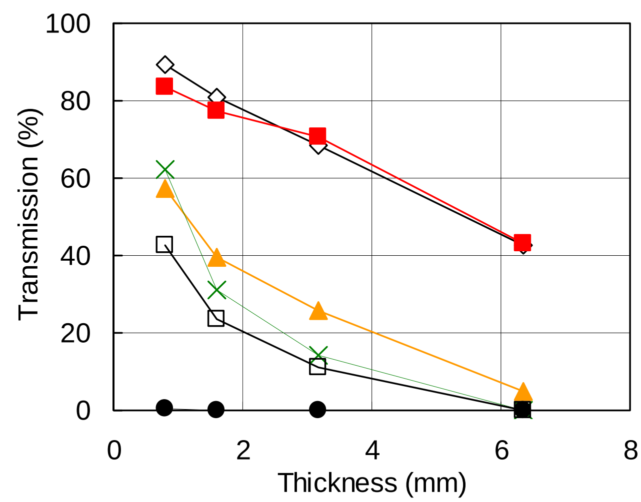

Figure 11: Influence of plaque thickness and color version on laser transmission at 1.06 μm. Legend: natural (◊); red (■); yellow (▯); green (X); white (□); black (●)

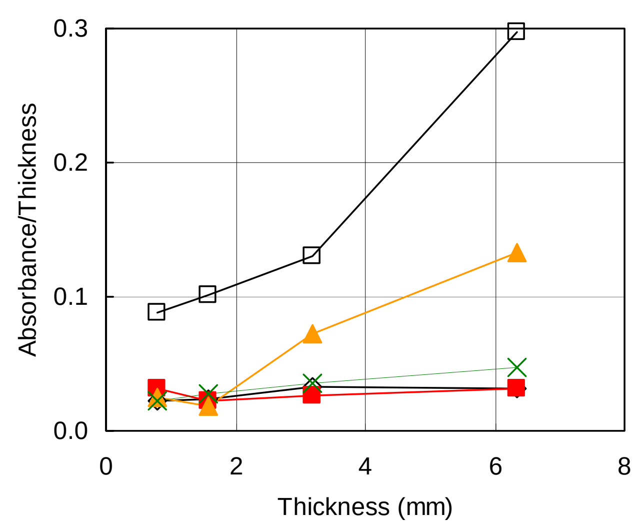

Fig. 12: Influence of thickness on the effective pathlength for (natural) nylon 6 measured by the nylon absorbance (normalized to thickness) at 1.39 μm. Legend: natural (◊); red (■); yellow (▯); green (X); white (□)

Since it is possible to laser weld with natural nylons at 6,25 mm thickness, it would appear possible to use other colors (yellow, green and white) with much smaller thickness (e.g. 0,8 mm) using equivalent laser powers and irradiation times. Increases in both laser power and / or irradiation times may extend the range of thickness for colored molded parts that can be successfully welded

EFFECT OF IMPACT MODIFIERS (IM)

Impact modifiers can substantially influence the laser transmission (Figure 13). The effect depends on impact modifier type and reduces laser transmission by about 50% for natural nylon materials. This is larger than the effect produced by addition of fiber-glass reinforcement.

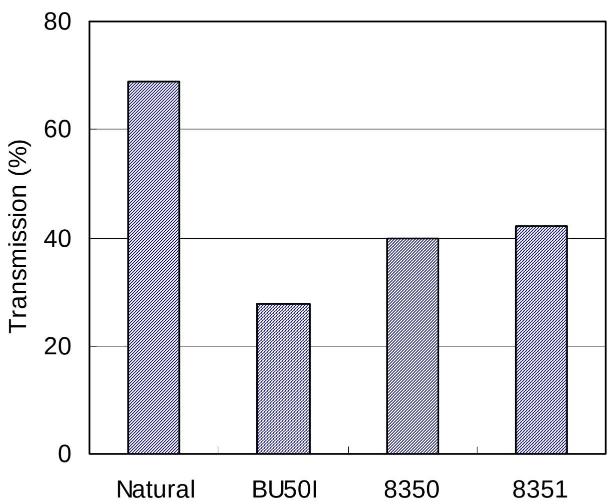

Fig. 13: Influence of impact modifier type (see Table 2) on laser transmission at 1.06 μm for natural nylon 6 (sample thickness = 3.2 mm)

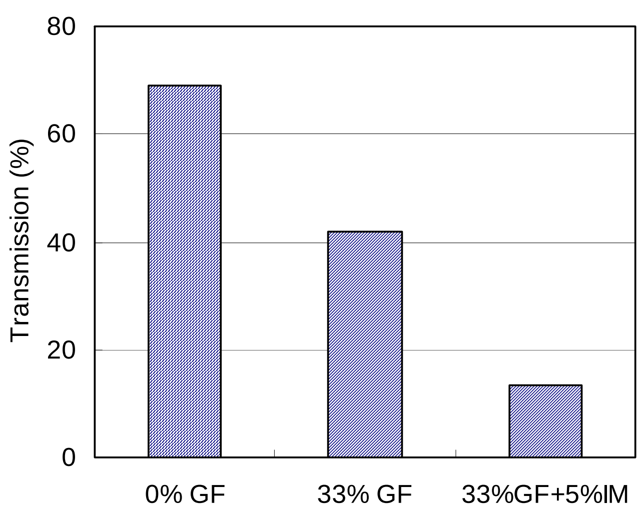

Fig. 14: Combined influence of impact modifier and fiber-glass reinforcement (see Table 2) on laser transmission at 1.06 μm for nylon 6 (sample thickness = 3.2 mm)

A fiber-glass reinforced, impact modified, plastic (33 GF wt.%, 5 IM wt.%) further reduces the laser transmission to about 14 % (Figure 14). The relatively strong effect of impact modifier is attributed to scattering by small inhomogeneities introduced by the modifier, the size distribution being smaller than glass fibers.

SUMMARY: OPTICAL CHARACTERIZATION

Tables A1 and A2 (in appendix) present data on the optical characteristics for key nylon 6 plastics. This will assist designers in using laser transmission welding to develop new welding applications and in manufacturing welded components based on thermoplastic materials.

OPTIMIZED PERFORMANCE OF LASER TRANSMISSION WELDING (LTW)

Previously we reported to SPE'96, SPE'99, GPC'99 the optimized mechanical performance of linear vibration, orbital vibration and hot plate for welded nylon 6 and nylon 66 butt joints [4, 6-7, 30]. Under the conditions for optimized material composition and welding processing the tensile strength at the linear vibration (LVW), orbital vibration (OVW) and hot plate (H-P/T) butt joints was equal to or 14% higher than the tensile strength of the base polymer (matrix) [4, 31].

H. Potente and F. Becker successfully applied the laser transmission welding (LTW) technology (Nd:YAG solid state laser) to several non-reinforced semi-crystalline plastics (PP, HDPE, etc.) and they achieved [32] a tensile strength of the butt joint equal to the tensile strength of the base polymer (weld factor f_{wm} = 1). For a non-reinforced nylon 6 based plastic the maximum tensile strength of a welded butt joint was equal 65 MPa (76% of the tensile strength of the base polymer, weld factor f_{wm} = 0,76) [28]. The AWS G1 standard injection molded specimens were used for welding and testing the butt joints.

D. Grewell evaluated mechanical performance of several welded plastics (PC, ABS, PP and PS), using the *IRAM*™ method (Infrared Assembly Method). These results were published [15] and presented [33] during the seminar on laser technology for polymeric materials (TWI, Cambridge, UK, March 1999).

Welding using *IRAM*™ in transmission mode is based on the wavelength range from 800 to 950 nm. The same as in [28, 32], AWS G1 standard injection molded specimens were used for welding and testing of butt joints. At optimized welding conditions (melt collapse, clamp pressure, power level, etc.) it was possible to achieve 60-75% of the parent material strength (weld factor f_{wm} = 0.6 - 0.75). Maximum weld strength results were achieved at a weld clamp pressure of 2 MPa.

The relative low tensile strengths for PA 6 (by laser transmission welding, [28]) and shear strength for PC, ABS, PP and PS (by *IRAM*^{TM} welding, [15, 33]) joints can be explained in the following ways:

- non optimized pigment content in an absorbing thermoplastic part;
- dimensional non-stability of the AWS G1 standard specimens;
- non fully optimized welding conditions;
- non-identified geometry and sizes of the butt / shear joints combined with the influence of the peculiarities of thermoplastics heating, melt-pool and welded joint formation (see Figure 17) for transmission welding (LTW).

MATERIALS AND GEOMETRY OF WELDED JOINTS

We analyzed efficiency of laser transmission welding technology for the following commercial nylon 6 based plastics (see Table 1):

- non-reinforced / non filled Capron 8202 HS;
- short fiber-glass reinforced Capron 8231G HS (GF = 14 wt.%);
- short fiber-glass reinforced Capron 8233G HS (GF = 33 wt.%);
- short fiber-glass reinforced Capron 8234G HS (GF = 45 wt.%).

The mechanical properties of these plastics (the tensile strength from 82 MPa to 208 MPa, level of fiber-glass reinforcement from 0 to 45 wt.% respectively) in combination with the capability to weld butt joints from these materials (Table 5) covers a wide area of a possible applications. At this time we did not evaluate the influence of carbon black content in the absorbing part and we used recommendations published in [19].

For a mechanical performance evaluation of the laser transmission welding (LTW) we used the recommended butt joint design, consisting of two beads 3,2 (4,0) mm thick and 6,25mm welded together from the following injection molded plaques:

- 150 mm x 60 mm x 3,2 (or 4,0 mm);
- 150 mm x 38 mm x 3,2 (or 4,0 mm). In T-shape area the sizes are: width = 6,25 mm, thickness = 3,2 (or 4,8) mm.

Figure 15 shows a schematic of a welded T – type assembly and a machined test specimen . The width of the test specimen is 20 mm. It is possible to make 5 - 6 machined test specimens from one welded plaque that allows representative, tensile test data to be obtained.

THE PECULIARITIES OF THERMOPLASTICS HEATING, MELT-POOL AND WELDED JOINT FORMATION FOR LASER TRANSMISSION WELDING (LTW)

For the frictional welding methods (linear vibration and orbital vibration) a melt front profile / shape forms as a function of design / geometry of the butt joint (bead thickness, directions of oscillation, etc.). The temperature distribution at the weld interface and the melt-pool formation profile for the frictional welding methods is symmetric. Linear vibration welding (LVW) is less sensitive to dimensional tolerances than contact (hot plate / tool) welding because it is self-adjusting in the bead contact areas. It is possible to close a gap up to 5 mm wide, between two joined surfaces with optimized clamp pressure (see microtomed cross section in Figure 16).

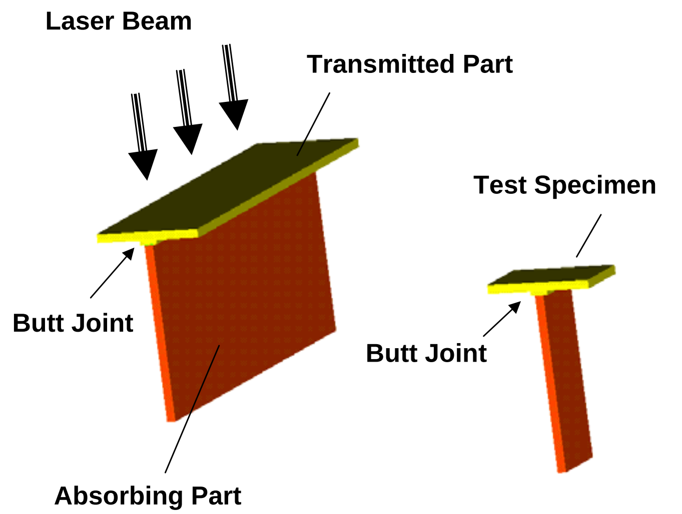

Figure 15: T-type joint for the laser transmission welding (LTW)

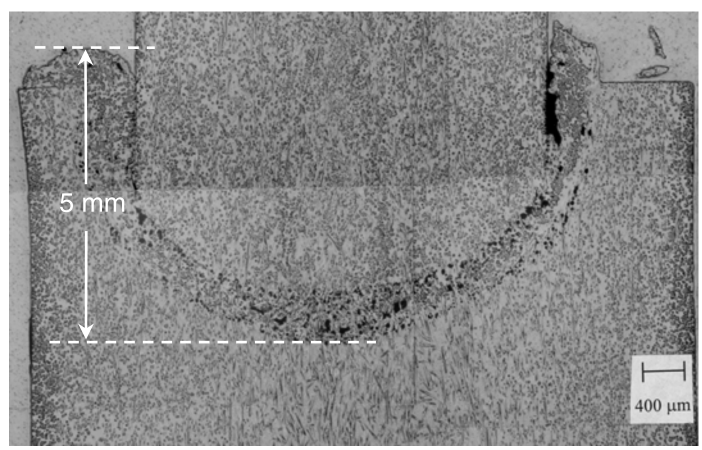

Figure 16: Wide gap adjustment for linear vibration welding (LVW): nylon 6, 33GF wt.% (longitudinal oscillations, melt-down = 5 mm)

The heating and melting (melt-pool) behavior of nylon(s) as formed / welded joints in a focused laser beam was investigated by several special experiments. During these welding trials the laser beam was moved along the surface of a flat transmitting plaque (lap joint) or T-shape butt assembly (Figures 17-19). The following laser transmission welding parameters were changed during this experiment:

- laser power level;
- laser beam scanning rate (welding speed);
- laser beam focus (laser beam diameter $\mathbf{w}_{LB}$ at the font of transmitting plastic).

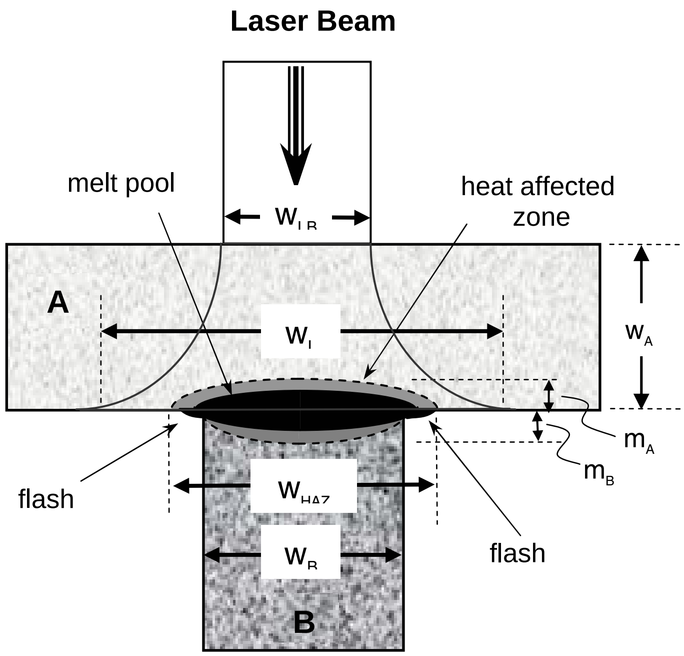

Figure 17: Principles of the butt joint and the formation of the melt pool within the heat affected zone for laser transmission welding. Legend: A is a thermoplastic having variable transmission/ scattering; B is thermoplastic that absorbs the transmitted light at the interfacial region; .W_{HAZ} = width of heat affected zone; W_B = width of part B; W_L = width of laser beam at joint; W_{LB} = width of laser beam at face of part A; m_A = depth of heat affected zone, part A; m_B = depth of heat affected zone, part B

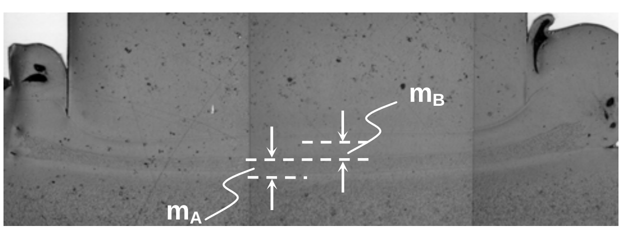

Figure 18: Butt joint structure for laser transmission welding of nylon 6 based plastics. Legend: $m_{A,}$ – melt layer thickness of the weld related to laser transmitting plastic; $m_{B,}$ – melt layer thickness of the weld related to absorbing plastic

Figure 18 shows the microtomed cross section of a butt joint formed by laser transmission welding (LTW). The melt layer thickness of the transmitting plastic part, $\mathbf{m}_{A,\ natural}$ and the absorbing plastic part, $\mathbf{m}_{B,\ colored}$ are approximately equal. For more pigmented (carbon black content > 0,3 wt.%) material, the melt pool will be slightly larger. Because the heat transferred / penetrated from the weld bead occurs mainly into the absorbing plastic part, the edges of bead are melted more deeply than the middle part of the zone. The same configuration of the weld bead is also typical for linear vibration welding (Figure 16).

Laser butt welds without a pronounced melt-pool do not have a double bead, which means that previous statements about cooling also apply here. This is also confirmed by the fact that, for laser butt welds without a melt-pool, an increase in strength was to be expected with increasing melt layer thickness. We observed the same positive effects of the thickness of melt-layer for linear vibration and orbital vibration welding technologies [4, 6]. The deeper the material is melted, the more slowly the middle of the weld cools down. We can therefore assume that the level of internal / residual stresses in a laser butt weld will have a greater effect on the weld strength than (due to heat dynamic generated by the laser beam) in hot plate or frictional welding methods (linear vibration and orbital vibration).

Under non-optimized welding conditions (including non-controlled temperature distribution) it is possible to create conditions for material damage (including vaporization) in the central part of the joint. Figure 19 shows an example of a defect that was created from the laser transmission plastic part side.

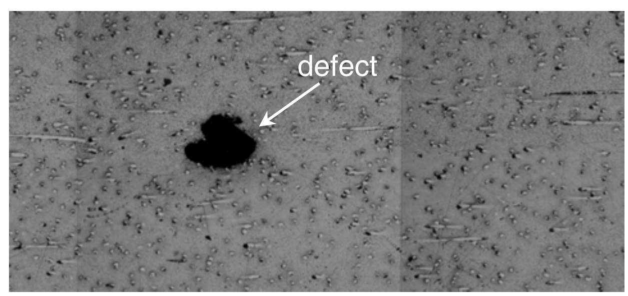

Figure 19: Butt joint structure for non-optimized laser transmission welding (LTV) of nylon 6 based plastics

WELDING MACHINE WITH COMPLETE ROBOTIC SYSTEM AND PROCESSES

MAGNA International is using laser welding system specially developed for thermoplastics applications [22, 25] . A fiber coupled 100 W diode laser system operating at 808 nm was used to transmit energy through the uncolored thermoplastic to the weld bead at the joint with the heat absorbing plastic part. The experimental set up of this welding system is shown in Figure 20.

In the experiments laser transmission welding was done on specially prepared specimens having a T-joint which allowed transmission welding with the laser, and tensile test measurements on the butt joints. Pneumatic clamps were used to apply a clamping force along the joint of the coupon. The T-joints were then transmission welded using a robot (Figure 21) to move the focussed laser beam over the joint. A computer controlled the laser, robot, and the pneumatic clamps, with the wavelength close to the parameters applied in reference [15].

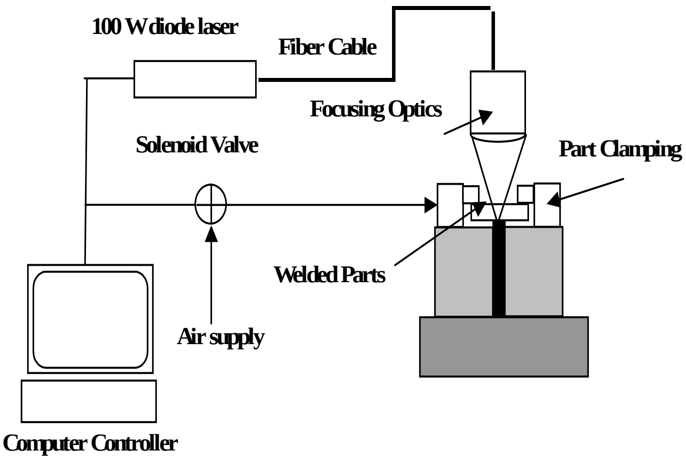

Figure 20: Set-up for laser transmission welding machine

JOINT STRENGTH

The following parameters, joint design and weld quality issues for laser transmission welding were evaluated in this study:

- laser power level;
- laser beam scanning rate (welding speed);
- laser beam focus (laser beam diameter w_{LB} at the front of transmitting plastic);
- clamp pressure;
- butt joint design (shear / lap with butt);
- butt joint design limitations related to optical characteristics of nylon 6 based plastics;
- peculiarities of weld interface formation for a lap shear joint configuration;
- quality of the weld

At an initial phase of the weld (LTW technology) strength studies 3,2 mm thick injection molded rectangle plaques were welded using a lap shear joint configuration. Sizes (length x width) of molded plaque are: 150 mm by 60 approximately. A lap shear joint configuration often has

been used for laser transmission welding [15, 17-18, 25-26] of amorphous and semi-crystalline thermoplastics. Figures 1 and 16 shows principles of the melt pool and joint formation with the influence of the laser transmission through semi-crystalline plastics.

For calculation of the shear strength of a lap joint we need to have the correct size (width of the weld: $\mathbf{w_{HAZ}}$, see Figure 1).

The size (diameter) of the focused laser beam at the front of transmitting plastic **A** ($\mathbf{w_{LB}}$) and the size (width) of heat affected zone (width of the weld: $\mathbf{w_{HAZ}}$) are not the same. The width of the weld ($\mathbf{w_{HAZ}}$) depends upon the thermoplastic composition (Table 4). For the short fiber-glass reinforced nylon 6 plastics the width of the weld ($\mathbf{w_{HAZ}}$) increases monotonically from 2,5 mm to 4,4 mm (on average), with increasing fiber-glass content from 0 to 45 wt.%. For lap joint applications the configuration / shape of the weld (between two plaques 3,2 mm thick) was not uniform (Figure 22) for the following reasons:

- design limitation on welding of planar, long rectangular plaques (100 mm x 60 mm) without prepared weld beads;
- non-uniform clamping conditions for flexible plaques 3,2 mm thick;
- non-uniform melt-pool and weld formation along the length of the clamped / pre-joined plaques.

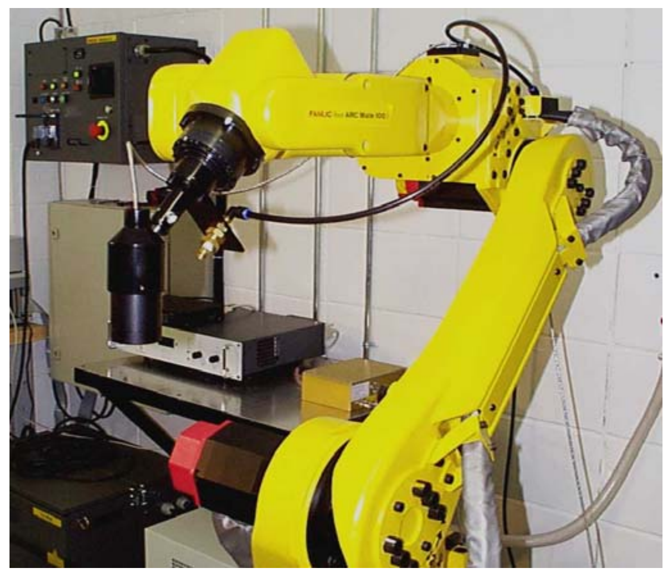

Figure 21: Laser transmission welding (LTW) machine with complete robotic system

Table 4: Effects Of Nylon 6 Composition (Fiber-Glass Content, Wt.%) On Size Of The Heat Effective Zone For A Lap / Shear Joint (Thickness Of Transmitting Plastic Part = 3,2 Mm). Laser Beam Diameter $\mathbf{W_{lb}}$ ~ 2,2 Mm

Trade Name of Fiber-Glass Reinforced Plastics	Fiber-Glass (GF), % by weight	Range of the size (maximum width of the heat effective zone $\mathbf{w_{HAZ}}$) for the lap / shear joints, in mm (Figure 22)
Capron 8202 HS	0	2,5 - 2,8
Capron 8231G HS	14	3,2 - 3,5
Capron 8232G HS	25	3,5 - 3,9
Capron 8233G HS	33	4,1 – 4,4
Capron 8234G HS	45	4,3 – 4,6

The above mentioned reasons and issues related to non-fully optimized, welding conditions are key drivers of low mechanical performance of a lap / shear joints.

For the base investigation we used the tensile test (at room temperature, 23 °C) for T-shape butt joints (Figure 15). A minimum of five welded and machined T-shape specimens (20 mm width) were tested using ISO 527 procedures. The weld flash / “bead” was not removed from the weld area. The specimen was loaded until it fails. All tensile test results were used to optimize performance of the laser transmission welding. Samples with high tensile strength were selected (Figure 18) to perform morphology analysis in the weld zone (interface). We also evaluated samples containing material and weld defects, including damage of polymer as the result of overheating (Figure 19).

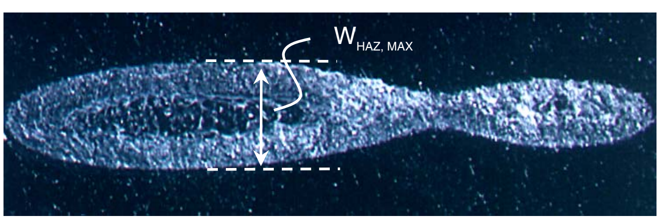

Figure 22: Weld and melt-pool profile for a lap / shear joint (See Table 4)

Table 5 summarizes the results of the tensile strength of short fiber-glass reinforced nylon 6 based plastics and welded joints from frictional (linear vibration welding) and the laser transmission welding (LTW) technologies.

Table 5: Influence Of Fiber-Glass Reinforcement On The Tensile Strength (At 23^{o}C, Dry As Molded) Of Linear Vibration And Laser Welded Butt Joints (Optimized Processing Conditions). Legend: N / A* - Data Will Be Presented Later

Wt.%, GF	Tensile Strength of Fiber Glass Reinforced Plastic (MPa)	***Vibration Welding Technology*** Tensile Strength of Weld (MPa)	***Laser Welding Technology*** Tensile Strength of Weld (MPa)
0	82	81	≥ 82
6	85	83,1	N / A*
14	125	90,7	N / A*
24	160	90,2	76,9
33	185	83,6	75,4
45	208	80,1	70,4

Data on the efficiency of six welding technologies for 33 GF wt.% nylon 6 plastic is presented in Table 6. For the comparison we used the following two, welding factor, parameters:

- welding factor f_{wm} related to the tensile strength of the base material / polymer;
- welding factor f_{wpl} related to the tensile strength of the reinforced plastic.

Table 6: Efficiency Of Welding Technologies For Fiber-Glass Reinforced Nylon 6 Based Plastics (33 Wt.% GF, At 23^{o}C, Dry As Molded, Optimized Processing Conditions)

Type of the Welding Technology	Weld Factor f_{wm}	Weld Factor f_{wpl}
Linear Vibration	1,08	0,46
Orbital Vibration	1,10	0,47
Hot Plate (Contact)	1,12	0,48
Ultrasonics	0,34	0,15
Laser (Transmission)	0,92	0,41

The mechanical performance (tensile strength at 23 °C) of laser welded nylon 6 plastics is equal / close to the tensile strength of frictionally (linear vibration and orbital vibration) or hot plate welded joints. For thermoplastic components welded from nylon 6 based plastics, all these technologies (including laser transmission) are three times more efficient than ultrasonic welding (see Table 6).

In [6-7] we presented our findings on optimized welding pool / interface temperature related to efficiency of mechanical performance of the nylon welded joints. We explained this improvement by "memory effects" for semi-crystalline plastics [34-35].

MEMORY EFFECTS FOR SEMI-CRYSTALLINE THERMOPLASTICS AND OPTIMIZED TEMPERATURES IN THE WELD INTERFACE (MELT-POOL)

A factor effecting the crystallization process of slowly or moderate slowly crystallizing polymers is called the "crystalline memory" and its results are usually lumped together under the umbrella of "memory effects". It is manifested as the formation of a defined degree of macromolecular order in the welded interface / phase, as well as a rise of the melting temperature (T_m) of the semi-crystalline systems in the melt-pool [6, 34-35]. "Memory effects" are a reflection of the thermal history of the injection molded part(s) and, in addition, are affected by the melt-pool temperature and welding time spent in the molten state. The highest temperature at which polymer crystal may survive is the equilibrium melting point T_{mo} [35]. For nylon 6 the equilibrium melting point T_{mo} may be about 270°C (Table 7). Other T_{mo} values obtained for nylon 6 by various extrapolations, range from as low as 215 °C to as high as 306 °C. The anneal temperature T_a (the temperature at which the melt is kept in order to remove the nuclei) must be higher than T_{mo}. For nylon 6 anneal temperatures as low 260 °C were sufficient to eliminate "memory effects", but 270 °C and even 280 °C are now recommended as temperatures for which "memory effects" are completely erased [34]. In all cases, it is assumed that $T_{mo} \leq T_a$.

Table 7: Manufacturers Recommended Molding / Melt Temperatures For Fiber-Glass Reinforced Nylon 6 Plastics. Legend: $*^1$ And $*^2$ – Recommendations Provided By Manufacturers (1) And (2), Respectively.

Fiber-Glass (GF), wt.% (by weight)	Recommended $*^1$ Melt Temperature (T_m), °C	Recommended $*^2$ Melt Temperature (T_m), °C
0	240 ~ 270	250 ~ 270
14	260 ~ 280	270 ~ 290
25	271 ~ 293	270 ~ 290
33 (35)	271 ~ 293	270 ~ 290
45 (40)	271 ~ 293	270 ~ 290
50	271 ~ 304	280 ~ 300

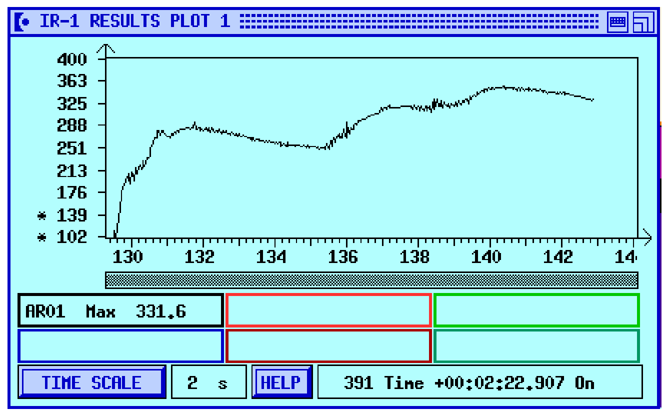

Figure 23: Time-temperature profile for welding of 33wt.% fiber-glass reinforced nylon 6 plastic

Similar results [35] were observed (Table 8) in several nylons (in pellets). Variations in the applied pressure of the amorphous phase of semi-crystalline polymers may affect changes in glass transition T_g, melt T_m, and anneal T_a temperatures [35].

The manufacturer's recommended melt temperatures for nylon 6 are presented in Table 7. The high melt, and mold (cavity) temperatures delay freezing to facilitate filling long, thin sections. (This is similar to localized re-melting and melt-pool formation processes in weld bead areas). It is also encourages greater crystallization of the semi-crystalline resins, which affects both mechanical properties and dimensions. Optimized mechanical performance of welded joints (Tables 5-6) was achieved at maximum for a weld-melt (melt-pool) temperature above (Δ_2) of the crystalline melting point (30 to 60 °C). Observed values of the maximum temperatures of the weld interface / melt-pool (T_{mw}, Figure 23) are very close to the anneal temperature (T_a) for evaluated nylon 6 specimens (Table 9). These results help to explain observed “memory effects” by the Hypothesis of the Minimum Flow Rate.

Table 8: “Memory Effects” Of Nylon 6 Plastic (Non-Reinforced / Non-Filled)

Temperature Conditions	Nylon 6, Raw Pellets	Nylon 6, Ground 3 Times
Glass Transition Temperature(T_g), ^{0}C	54,8	51,1
Melting point, (T_{mp}), ^{0}C	221,6	218,9
Anneal Temp., (T_a), ^{0}C	270	270
Recommended Molding (Melt) Temp., (T_m), ^{0}C	238 ~ 270	238 ~ 270

Table 9: Relationship Between Processing (Molding And Welding Temperatures) Conditions And “Memory Effects” For Nylon 6 Plastics (33 GF Wt.%)

Thermal properties of nylon 6 plastic and welded joint (33 GF wt.%)	Temperature in ^{0}C
Melting point	223
Anneal temperature (T_a)	270 ~ 306
Recommended melt temperature (T_m)	270 ~ 290
Maximum temperature of weld interface (melt-pool) temperature (T_{mw})	270 ~ 295
Temperature difference $\bullet_1 = T_m - T_{mp}$	47 ~ 67
Temperature difference $\bullet_2 = T_{mw} - T_{mp}$	0 ~ 5
Temperature difference $\bullet_3 = T_{mw} - T_a$	0 ~ (- 11)

Optimization of mechanical performance of welded nylon joints should be based on the “memory effects” noted above and the need to keep the weld interface temperature above the melting point (Table 9). The analysis of melt weld / melt-pool temperatures, kinetics and observed “memory effects” for injection molding, frictional (LVW and OVW) and hot plate welding should be typical for laser transmission welding (LTW) also. At present we do not have time-temperature data for the laser transmission welding (LTW) to strengthen these considerations.

CONCLUDING REMARKS

Nylons (polyamides - PA) are high performance semi-crystalline thermoplastics with a number of attractive mechanical and technological properties. Welded nylon components are most widely used in the automotive industry.

Laser transmission welding (LTW) was shown to effectively join a variety of nylon plastics (non-reinforced, fiber-glass reinforced, non-colored, colored, etc.). It is faster than hot plate welding.

Comparison studies of linear and orbital vibration (LVW and OVW) and hot plate joining technologies demonstrated that LTW process is very efficient for nylon and may be used as alternative to frictional and hot plate technologies.

For the short fiber-glass reinforced (GF) nylon 6 plastics the laser energy transmission decrease monotonically (from 70% to 33%) with increasing fiber-glass content from 0 to 45%. Mineral fillers (MF) are more effective in energy reduction (transmission is equal 6,5% at 40 MF wt.% or five time less than for 45 GF wt.%). Impact modifiers can reduce laser transmission by 50%. (Above data refer to specimens of 3.2 mm thickness.)

Plastics of different colors display marked differences in transmission of the laser energy. Transmission of red specimens is close to natural color, while yellow and green colors can reduce the transmission by 75-85%. Two basic effects may contribute to the optical performance of the plastic: increased absorption by the colorant and particulate scattering lead to decreased transmission at the laser wavelength.

For non-colored nylon 6, the laser energy transmission decreases monotonically (from 85% to 42%) with increasing thickness of the molded plaque / part from 0,8 mm to 6,25 mm. Colored plastics are behaving differently: transmission of red is similar to natural / non-colored; colored (yellow, green and white) plastics can reduce transmission from 60-40% to 1-3% with increasing thickness over the same range (from 0,8 to 6,25 mm).

Both the thickness and composition of the joined part transmitting the laser beam strongly effect the laser beam width and energy density at the joint interface. For each material It is critically important to adjust the dimensions of the laser beam incident at the surface of the transmitting part to optimize the spread of the laser beam at the weld bead. Furthermore the laser beam must be properly aligned / oriented with respect to the weld bead axis and weld joint plane during the welding process.

At optimized processing conditions the mechanical performance (tensile strength at 23 °C) of laser welded (LTW) nylon 6 plastics is equal / close to tensile strength of frictionally (linear vibration and orbital vibration) or hot plate welded joints.

An increase in melt-pool (in weld interface) temperature at welding time correlated well with the "memory effects" of semi-crystalline nylon 6 systems.

Further investigations are needed to:

- develop optical properties, needed for LTW technology for other than nylon 6 plastics;
- develop mechanical performance data and optimize welding processing conditions for the various colored thermoplastic(s) especially in regard to the influence of composition (types and levels of fillers, reinforcements, pigments, etc.);
- determine welding depth and an efficient size / volume of a melt-pool to close existing gap(s) between joined parts;
- determine the optimized LTW processing conditions corresponding to various molding conditions, especially in regard to the influence of plastic(s) optical properties, the part design (thickness of the joined parts, dimension properties, tolerances, possible gaps, etc.) .

In summary, LTW of PA (nylon) was very successful at welding together carbon black and natural nylon parts with a respectable butt joint strength. This makes LTW technology an excellent joining method for semi-crystalline thermoplastics.

This paper presented and discussed results on the optical characteristics (transmittance, absorbance, etc.) and the mechanical performance (tensile and shear strength) of welded joints (shear and butt) using laser transmission welding (LTW) technology. This will allow designers to recommend LTW technology for developing new welding applications and manufacturing welded components based on thermoplastic materials.

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KEY WORDS

Nylon, polyamide, thermoplastics, welding, joining, laser, beam, infra-red, absorption, transmission, wavelength, fiber-glass, mineral fillers, pigments, colors, weld strength, melt layer, thickness, butt, shear.

APPENDIX

TABLE A1: OPTICAL CHARACTERIZATION OF LASER TRANSMISSION FOR NYLON 6 PLASTICS (SAMPLE THICKNESS = 3.2 MM, PLASTIC STATE – DRY AS MOLDED)

GF wt.%	MF wt.%	IM wt%	Color / Pigment Version	Laser Energy Transmittance, % (at 1.06 μm)
0	0	0	Natural	69
6	0	0	Natural	62
14	0	0	Natural	58
25	0	0	Natural	53
33	0	0	Natural	42
45	0	0	Natural	33
16	24	0	Natural	16
0	0	20	Natural	28
0	0	28	Natural	40
33	0	5	Natural	14

Table A2: Optical Characterization Of Colored, Non-Reinforced / Non-Filled, Nylon 6 Plastics (Sample Thickness = 3.2 Mm.; Plastic State – Dry As Molded)

Color or Pigment Version	Pigment Content, wt.%	Laser Energy Transmittance, % (at 1.06 μm)
Natural	0,0	70
Red	0,5	70
Yellow	1,0	24
Green	0,5	13
White	1,0	10
Black	0,2	< 0,2

ABBREVIATIONS

AIM – air intake manifold; AWS – American Welding Society; BK – carbon black (pigment version); CO_2 – laser type (carbon oxide, gas state) f – welding factor (short-term strength criteria); IM – impact modified (in wt.%); GF – fiber-glass reinforcement (in wt.%); LVW – linear vibration welding; MF – mineral filled (in wt.%); Nd:YAG – laser type (diode, solid state); NIR - Near Infra-Red ; PA – polyamides; PP – polypropylene; SAE – Society of Automotive Engineers; SPE – Society of Plastic Engineers

Term:

absorbance - negative log (base 10) of the transmittance;

effective pathlength - distance traveled by light beam through a sample as a result of light scattering;

reflectance - fraction of incident, light beam intensity that is reflected from the sample;

transmittance - fraction of incident, light beam intensity that passes through the sample;

melt layer thickness ratio = $\mathbf{m_{B,\ natural}} / \mathbf{m_{B,\ colored}}$

$\mathbf{m_{A,\ natural}}$ – melt layer thickness of the weld related to laser transmitting plastic;

$\mathbf{m_{B,\ colored}}$ – melt layer thickness of the weld related to absorbing plastic;

A - absorbance, measured at specific wavelength or wavelength range;

I_0 - intensity of light beam incident on the sample surface;

T - transmittance of a sample, measured at specific wavelength or wavelength range;

I_T - intensity of light beam after passing through the sample;

f_{wm}- related to tensile strength of the reinforced plastic;

f_{wpl} - related to tensile strength of the base material / polymer;

$\mathbf{w_{LB}}$ – laser beam diameter / width at the front of transmitting plastic;

$\mathbf{w_B}$ – thickness of the specimen / part to be welded (butt joint);

$\mathbf{w_A}$ – thickness of the transmitting specimen / part (A)

$\mathbf{w_{HAZ}}$ – width of the weld;

wt. % - nominal loading of fiber-glass fibers, minerals, impact modifiers, pigments in % by weight.

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