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LASER TRANSMISSION WELDING OF SEMI-CRYSTALLINE THERMOPLASTICS - PART I: OPTICAL CHARACTERIZATION OF NYLON-BASED PLASTICS

Abstract

Optimization of welding for thermoplastic parts strongly depends on the material properties, part design, as well as the welding operating technology conditions. Laser transmission welding requires preferential deposition of energy and subsequent melting of the material in the interfacial zone. This is optimized when the laser beam is transmitted through the transparent part and absorbed by the adjoining part to be welded. Energy deposition can be controlled to some extent by adjusting laser parameters (power, choice of beam focussing optics, sweep rate etc.)

The thermoplastic material properties may have the greater influence and need to be characterized for optimum material selection. Commercial nylon type materials cover a large array of compositions, which may affect the welding process. To guide selection of nylon based plastics for a range of applications we have measured the influence of specific factors such as fiber-glass, mineral filler, impact modifier content, additives, and color versions on the Near InfraRed (NIR) transmission properties.

In a following paper (Part II) [a1] we have related these findings to the mechanical performance of shear and butt joints produced under various laser welding technology conditions (laser beam power, welding speed, laser beam/spot diameter, clamp pressure, plastic color, etc.). Comprehensive results of this evaluation will assist designers and technologists in thermoplastics selection for laser welding applications. The purpose of this report is to increase the understanding of the plastics engineering community regarding the usefulness and possible applicability of laser transmission welding (LTW) technology for nylon made components.

[a] Kagan, V. A., Pinho, G. P., "Laser Transmission Welding Of Semi-Crystalline Thermoplastics - Part II: Analysis of Mechanical Performance Of Welded Nylon-", - Plastics … the Magical Solution, Proceeding of the SPE 58 th Annual Technical Conference and Exhibits (ANTEC'2000)

INTRODUCTION

Laser technology is now commonplace from satellite ranging and heavy machinery to microsurgery. Not to be excluded is thermoplastics processing technology including joining of multi-shelves plastic part. Different welding methods are used for joining and assembling hollow, automotive thermoplastic parts. The following articles and reports are critically important for a clear understanding of the advantages and disadvantages of the laser transmission welding technology for manufacturing thermoplastic, automotive hollow parts: infrared [1-5], and laser beam [6-13] welding. Technical results related to the joining / welding processing technology for nylon based plastics, and mechanical performance of welded joints have been presented widely to SAE, SPE, AWS, etc. [14-15]. 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.

Laser Welding Technologies

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 may cause problems with melt residues sticking to the surface of the hot plate / tool [9-12]. 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.

Laser technology provides a highly attractive method / tool for engineering materials applications [11]. In the plastics industry there are many different applications for laser processing [12-13]. Laser welding of thermoplastic parts is at the beginning stage for wide industrial application. For joining of thermoplastics there are two laser welding methods having possible wide applicability:

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

Advantages Compared to Other Technologies

Specific advantages of laser transmission welding technologies (LWT) are:

- accurate, non-contact, heat transfer with the possibility of optimizing the welding temperatures (at the weld interface);
- welding of pre-assembled thermoplastic components, with the parts in the same orientation and position as the final assembled product;
- minimal limitations on the geometry and the size of the thermoplastic parts to be joined;
- rapid welding speeds permitting welding of long plastic parts with acceptable weld times;
- absence of vibration in the welding process (in contrast to ultrasonic and linear welding technologies) permitting welding of sensitive electronic and medical components;
- improved localization of the heat affected zone and control of melt flash in the join area.

Basic Types of Laser Welding Systems

Three types of lasers are mostly used for welding of polymer based materials [7-9]:

- CO_2 laser (10.6 μm);
- Nd:YAG laser (1.06 μm);
- diode laser (808 ± 10, 830 ± 10 or 940 ± 10 nm).

Their wavelengths of operation are the most critical feature for laser transmission welding (LTW) applications. Since most plastics absorb strongly at 10.6 μm, the CO_2 laser is impractical for most applications. An exception may be very thin (micron-thick) materials. In contrast both the Nd:YAG and diode lasers operate in the near-IR where plastics have minimal intrinsic absorption, permitting successful laser transmission welding of parts having millimeter thickness.

The cost of laser welding equipment, welding tools and nests is not high, and the laser welding process is reasonably rapid. Laser welding machines for thermoplastics are commercially available in Europe, North America and Asia.

Basic Principles of Laser Transmission Welding

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.

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 thickness for the weld.

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 %. [9-10]. 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.

Material Properties Needed For Design and Manufacturing of Plastic Parts by 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 [14-17]. Properties of the base polymer (matrix), reinforcements and fillers, pigments, various additives in a thermoplastic composition affect what happens to the laser energy absorption, reflection and transmission.

For welding of injection molded parts the materials and optical properties of the thermoplastic and the components (additive and polymer) are very important for modeling and understanding the laser process:

Plastic properties:

- 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. %);
- plastic(s) density,
- heat capacity;
- thermal conductivity;
- material state in joined parts / specimens before welding (dry as molded, moisture content, by wt. %).

Component (polymer and additives) properties:

- polymer crystallinity;
- polymer melt point;
- additive particle size.

Optical properties:

- laser energy transmission;
- laser energy absorption;
- polymer and additive refractive indices.

Tables 1 and 2 compare specific values (or ranges, as appropriate) of some of these properties for nylon 6, nylon 66 and nylon 46 plastics.

The present study focuses on the optical characterization of non-colored (natural) and colored nylon 6 based thermoplastics to determine the effect of reinforcements/additives (non-filled, fiber-glass reinforced, mineral filled, impact modified, etc.). Only limited data on the relevant optical properties of nylon materials is available in published articles and reports [14].

Optical Characterization of Nylon Plastics

To establish optimized processing parameters for laser transmission welding (LTW) we have evaluated the effect 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, impact modifiers and additives);
- color / pigment;
- thickness of the plastic part.

We present measurements of laser transmission at 1.06 μm 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.

General Principles for NIR Transmission Measurements

Figure 2 depicts two situations for the transmission of light through a sample plaque of a typical thermoplastic. In general the transmission (**T**) of a sample is given by the Beer-Lambert Law:

$$\mathbf{T = 10^{-A}} \qquad (1)$$

A represents the absorbance by the sample components (resin, colorants etc.) and is defined by:

$$\mathbf{A = a \cdot \rho \cdot l} \qquad (2)$$

where **a** is the absorption coefficient of the material, ρ the density and **l** is the sample (plaque) thickness. Under conditions where the absorbance is low (as in the NIR region) we can approximate eqn. (1) by:

$$\mathbf{T = 1 - A - R} \qquad (3)$$

where we have added an additional term – the sample reflectance (**R**) - to account for reflectance from the sample surfaces. Under ideal conditions (e.g. glass-like polymers, such as polycarbonates) only specular reflectance occurs at the two plaque surfaces (typically ~7% of the incident beam intensity), as shown in Figure 2(a).

Many thermoplastic materials are not homogeneous (either due to additional components or presence of crystallinity) and light transmission is better depicted as in Figure 2(b). Theoretical description of the transmission properties becomes very complex but eqn. (3) above is still useful for describing the overall process. In Figure 2(b) the reflected component is enhanced: specular reflection from the front surface still occurs but this is minor compared to multiple specular reflectance (termed diffuse scattering) from the additional components within the polymer matrix. A substantial portion of the light transmitted through the sample may be deflected from the incident beam direction, reducing the energy density at the back surface. Furthermore the effective pathlength ($\mathbf{l_{eff}}$) of the transmitted light may be somewhat greater than actual sample thickness (**l**), thereby increasing the sample absorbance and decreasing laser transmission. It is therefore critical to assess how strongly reinforcements, fillers, colorants etc. diffusely scatter the incident light. The extent of diffuse scattering will depend on additive composition, particle size and refractive index (relative to the base polymer).

The intrinsic absorption of the resin in the NIR region results from excitation of the overtones and combinations of the fundamental vibrations. These overtones/combinations typically involve the X-H (X = C, N, O) bonds both as stretches (e.g. N-H and C-H) and bending modes (e.g. C-N-H) . The intrinsic absorption in the IR region due to the fundamental vibrations limits application of CO_2 lasers (at 10.6 μm) to extremely thin samples (<20 μm). The intrinsic absorbance of the plastic matrix (nylon) in the NIR region from 0.8 to 1.1 μm is several orders of magnitude lower than for the IR region. This permits much thicker samples (mm range) to be used for welding applications using NIR lasers without substantial loss in transmission due to matrix absorbance. In general we expect that intrinsic absorbance by the matrix will be even less severe near 0.8 nm relative to 1.1 nm.

The addition of reinforcements, fillers etc. are not likely to increase the intrinsic absorbance due to their vibrational motions: many of these materials possess much less H content than plastics and/or are present at relatively low wt. %. For colorants/pigments there may be a significant contribution from their electronic transitions. Colorants/pigments having blue to yellow appearance typically have some absorption in the red and may contribute to reduced transmission in the NIR range. Red colorants/pigments typically have strong absorption in the blue to yellow regions of the visible spectrum and may have less effect on transmission in the NIR region. Inorganic colored materials often have extensive visible transitions that may extend in to the NIR and be more of a problem than similarly colored organic pigments. The sensitivity to color may be greater for laser welding applications employing diode lasers in the range 0.8 to 0.95 μm than for Nd:YAG lasers at 1.06 μm.

Experimental Procedures for NIR Transmission Measurements

We measured the NIR 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 3 shows the experimental arrangement for laser transmission measurements. The laser output beam is expanded and approximately collimated to a diameter of ~ 2.5 mm at the detector. The face of the detector has a diffusing screen and aperture of 10 mm diameter. 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, as explained above. 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.

The effect of internal scattering (due to nylon crystallinity and/or additional components) produces two effects on the NIR absorption spectrum – see Figure 4 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 ($\mathbf{l_{eff}}$) can be quantified in a relative sense by monitoring the (baseline corrected) nylon absorbance at 1.39 μm, normalized to the nylon content. 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.

Analyzed Materials and Samples

The thermoplastics used in this investigation were heat stabilized nylon 6 (commercially available Capron® series) plastics. For the base investigation we used non-colored (natural, as molded) and pigmented carbon black plastics (Tables 3 - 5). To study the effects of colorant and additives we used commercial and experimental colored, non-reinforced plastics (Tables 6 and 7). We analyzed plastics having the following composition (level of reinforcements, fillers and additives):

- short fiber-glass loading: from 6 to 63 wt. % (Table 3);
- combined loading of a short fiber-glass and minerals (one composition: 15 wt. % fiber-glass and 25 wt. % minerals) - Table 4;
- impact modifiers (three compositions) - Table 5.
- colorants (red, green, yellow, white and black (both carbon and non-carbon), < 2%) – Table 6;
- masterbatch and flame-retardants - Table 7.

Injection molded, rectangular plaques were used for the optical characterization of the evaluated thermoplastics (Tables 3-7). 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 plaques of four thicknesses (0.8; 1.6; 3.2; 6.25 mm).

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 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 transmission decreases monotonically with increasing fiber-glass content from 0 to 63 wt. % (Figure 5). The decrease in transmission is due to increased light scattering. This can be seen in Figure 5, which shows an increase in effective pathlength(nylon absorbance (1.39 μm) / nylon content (wt. %)) . as the fiber-glass content increases from 0 to 63 wt. %. The increased effective pathlength at high fiber-glass contents is a direct consequence of light scattering from the short fiber-glass.

Figure 6 shows the influence of 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 at 40 wt. % mineral filler being four times that for 45 wt. % fiber-glass reinforcement. 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 and the energy will be spread out over a wider area (i.e. lower energy density). To achieve transmission laser welding with highly filled materials will require a substantial increase in, the laser power relative to natural nylons.

Effect of Colorants

Colorants and 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 [19]. They also 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 colorant concentration (from 0 wt. % to 0.20 wt. %) on optical properties (transmission, absorption and reflection) of nylon 66 plastic were reported in [16]. 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 [9] 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 [10] 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 we used pigmented (green, yellow, red, white and black) and non-pigmented (natural) nylon 6 (non-filled / non-reinforced) plastics (Table 6, Figures 7 - 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 and two levels of a non-carbon black loading (0.2 and 0.5%). All carbon black levels have a very low transmission (< 0.3%) while the non-carbon black materials have substantially greater transmission (1-15%).

This investigation shows that color markedly influences laser transmission (Figure 7). 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. A possible exception is the non-carbon black samples for which we have not obtained NIR transmission spectra Scattering is the dominant effect, confirmed by the different effective pathlengths observed for the samples (Figure 7). If absorption at the laser 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 limit their use in such applications.

Combined Effect of Thickness and Color

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 was developed by I. Jones [14]. 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 8). The composition of these nylon 6 based plastics is presented in Table 6. 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 9). 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.

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, white and even non-carbon black) 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 10). The effect depends on impact modifier type and reduces laser transmission by about 50% for natural nylon materials. The extent of the effect is not simply dependent on the level of impact modifier but it is larger than the effect produced by addition of equivalent levels of fiber-glass reinforcement.

A fiber-glass reinforced, impact modified, plastic (33 GF wt. %, 5 IM wt. %) further reduces the laser transmission to about 14 % (Figure 11). 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. This is consistent with the observed changes in effective pathlength.

Effect of Masterbatch and Flame Retardant Additives

Addition of a low level of masterbatch has no effect on laser transmission at 1.06 μm, but the effect of flame retardant is substantial. It is not immediately clear what factors determine the difference in response, but flame retardant addition diminishes transmission by 60-70% relative to natural nylon 6.

Conclusions

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

For the short fiber-glass reinforced (GF) nylon 6 plastics the laser energy transmission decreases monotonically (from 70% to 20%) with increasing fiber-glass content from 0 to 63%. 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%. The above data refer to specimens of 3.2 mm thickness. The conclusions will equally apply to other thicknesses but the actual values will vary be higher or lower depending on the sample thickness relative to 3.2 mm.

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%. Carbon black reduces transmission to extremely low levels (virtually not detectable) but non-carbon black colorants yield transmission levels comparable to green and yellow colorants. 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 behave 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.

This paper presented and discussed results on the optical characteristics (transmittance, absorbance, etc.) for nylon 6 materials of practical importance for laser transmission welding (LTW) technology. This will assist designers to discuss / recommend LTW technology for developing new welding applications and manufacturing welded components based on thermoplastic materials.

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Key Words

Nylon, polyamide, welding, laser, near infra-red, absorption, transmission, fiber-glass, mineral fillers, pigments, colors, melt layer, thickness, butt, shear.

Table 1: Properties of Nylon Materials Required for Laser Welding Applications

Property (Units)	Nylon 6	Nylon 66	Nylon 46
Density ($gm.cm^{-3}$)	1.13	1.14	1.18
Refractive Index (molded, undrawn)	1.53	1.53	-
Moisture (dry as molded, %)	0.2	0.2	0.05
Heat Capacity (J/g °K)	1.5	1.5	1.7
Thermal Conductivity (W/m °K)	0.23	0.24	0.25
Polymer Crystallinity (%)	15 - 45	15 - 55	15 - 55
Polymer Melt Point (°C)	222	262	295

Table 2: Properties of Additives Required for Laser Welding Applications

Property (Units)	Composition (%)	Particle size (length x width, or diam., μm)	Refractive Index
Additive:			
GF	0 – 50	180-320 x 12	1.5-1.6
MF	0 – 40	1-20	1.62–1.65
IM	0 – 30	<10	1.47-1.48

Table 3: Fiber-Glass (GF) Reinforced Capron® (Nylon 6 Based) Plastics

Material Designation	GF, % by weight
8202 HS	0
8230G HS	6
8231G HS	14
8232G HS	25
8233G HS	33
8234G HS	45
BG45G13 HS	63

Table 4: Mineral Filled (MF) And Fiber-Glass (GF) Reinforced Capron® (Nylon 6 Based) Plastics

Material Designation	GF, % by weight	MF, % by weight
8267G HS	15	25
8260 HS	0	40

Table 5: Impact Modified (IM) Capron® (Nylon 6 Based) Plastics

Material Designation	GF, % by weight	IM, % by weight
8350 HS	0	28
8351 HS	0	28
BU50I	0	20
8333G HS	33	5

Table 6: Colored Versions Of Capron 8202 HS (Non-Reinforced, Nylon 6 Based) Plastics

Color or Pigment Version	Specification/ Material Designation	Pigment Content, % 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
Black I	Experimental	0.2
Black II	Experimental	0.5
Green	Experimental	0.5
Red	Experimental	0.5
Yellow	Experimental	1.0
White	Experimental	1.0

Table 7: Additive Filled 8202 HS (Non-Reinforced, Nylon 6 Based) Plastics

Additive	Specification/ Material Designation	Additive Content, % by weight
Natural	Natural	0
Nucleator	MB	10
Fire Retardant	FR I	27
Fire Retardant	FR II	30

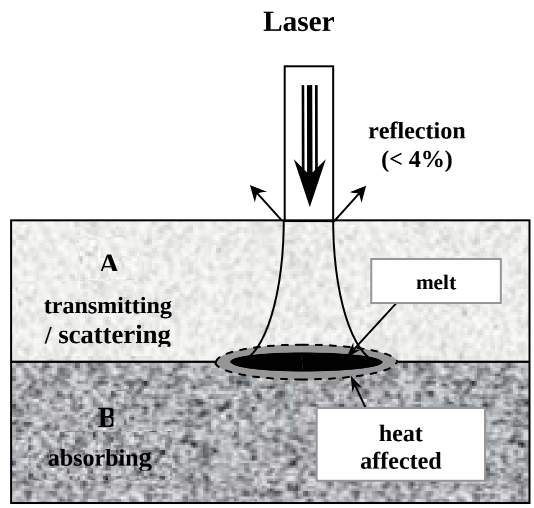

Figure 1: Principle of the laser transmission welding. Part A is a thermoplastic having variable transmission/ scattering. The thermoplastic in part B absorbs the transmitted light at the interfacial region

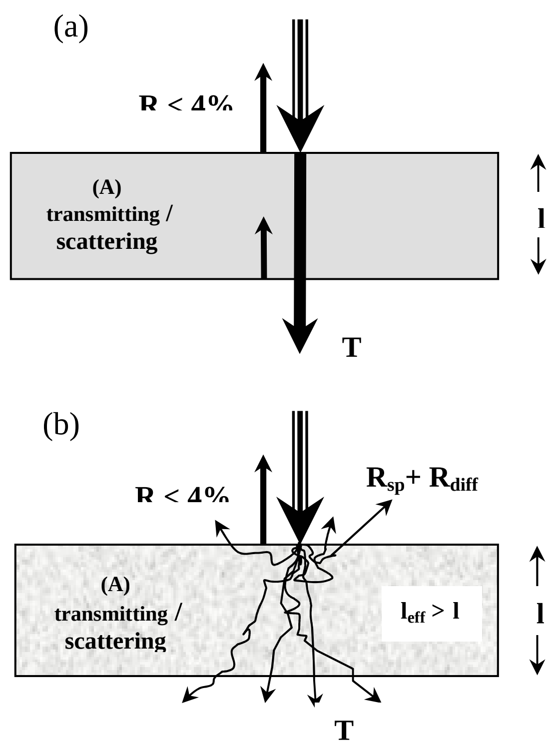

Figure 2: Transmission through plastic samples: (a) homogeneous, glass-like plastics; (b) inhomogeneous, semi-crystalline plastics.

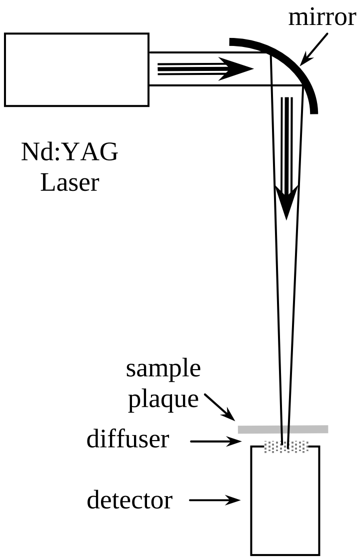

Figure 3: Apparatus for measuring laser transmission at 1.06 µm

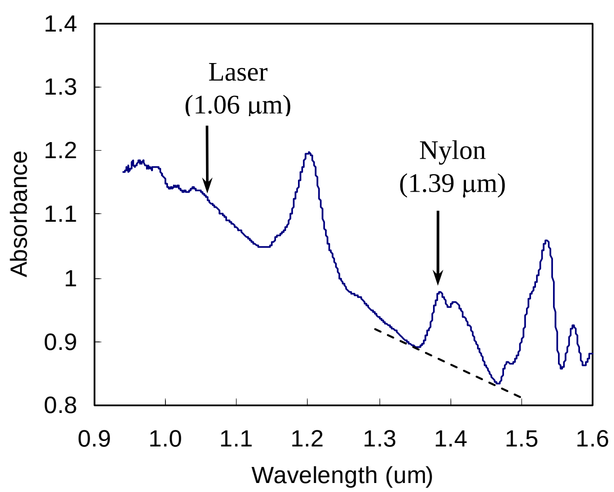

Figure 4: Representative NIR spectrum of a natural nylon 6 plaque (sample thickness = 3.2 µm). The nylon peak absorbance at 1.39 µm is measured from the baseline (---------) drawn from 1.33 to 1.47 µm

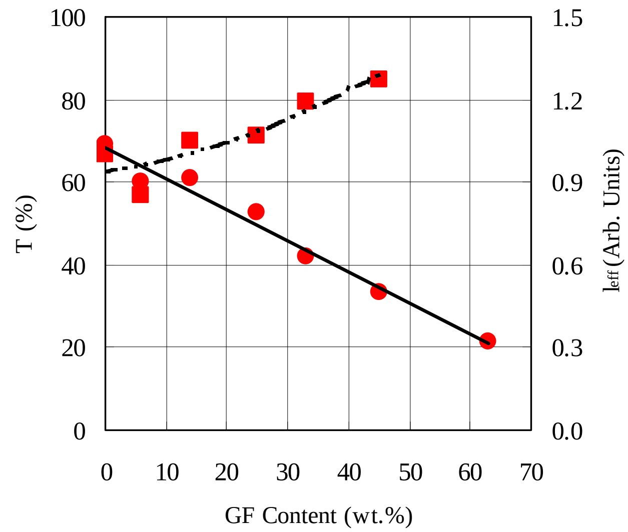

Figure 5: Effect of fiber-glass (GF) content (wt. %) on laser transmission (T) at 1.06 µm compared to effective pathlength (l_{eff}, normalized to 1.0 at 0% GF content). Sample thickness is 3.2 mm.

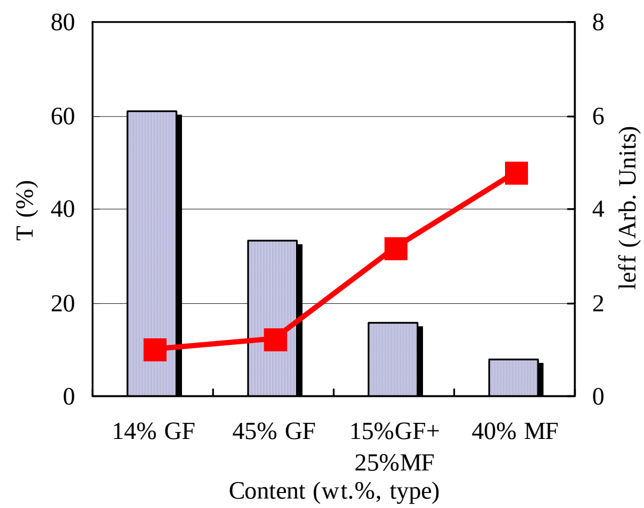

Figure 6: Effect of fiber-glass (GF), mineral filler (MF) and content (wt. %) on laser transmission (T) at 1.06 µm compared to effective pathlength (l_{eff}, normalized to 1.0 at 14% GF content). Sample thickness is 3.2 mm.

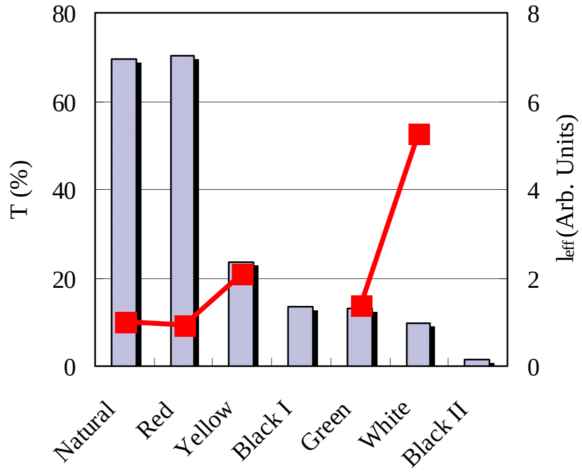

Figure 7: Effect of color version on laser transmission (T) at 1.06 µm compared to effective pathlength ($l_{eff,}$ normalized to 1.0 for Natural sample). Sample thickness is 3.2 mm.

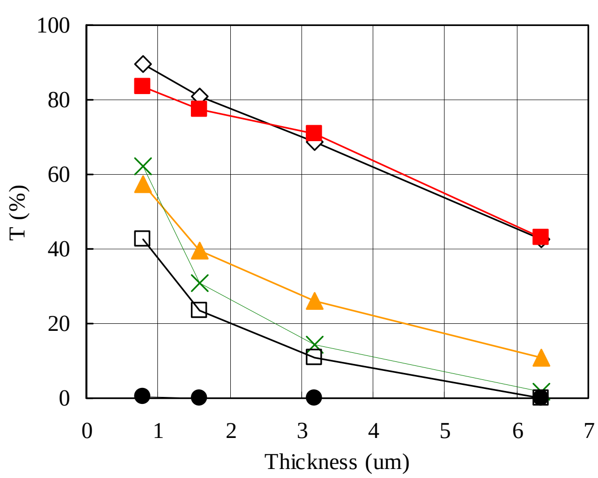

Figure 8: Effect of plaque thickness and color version on laser transmission (T) at 1.06 µm. Legend: natural (◊); red (■); yellow (▯); green (X); white (□); black (●)

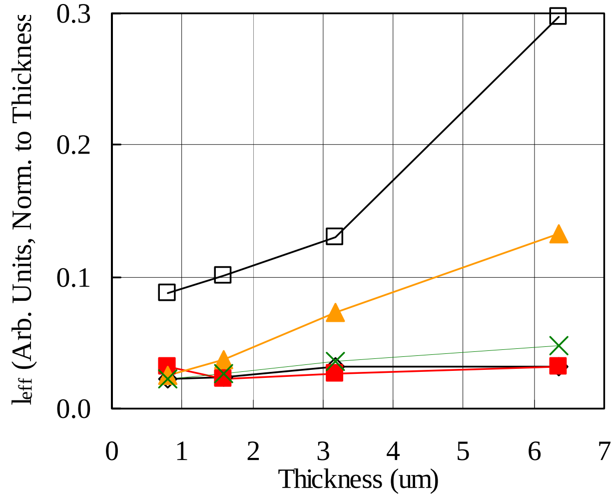

Fig. 9: Effect of plaque thickness and color version on the effective pathlength (l_{eff}, normalized to the thickness) for (natural) nylon 6 materials. Legend: natural (◊); red (■); yellow (▯); green (X); white (□)

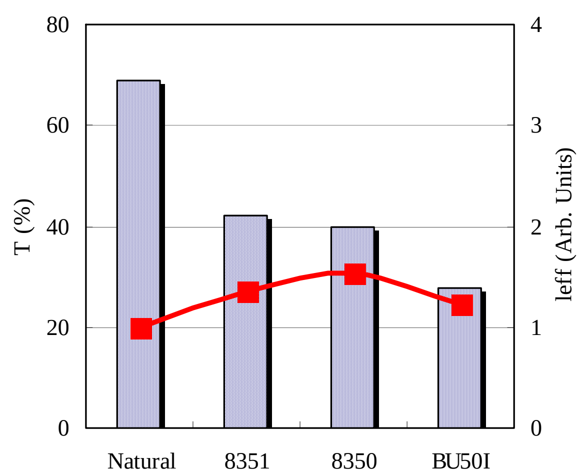

Fig. 10: Effect of impact modifier type (see Table 5) on laser transmission (T) at 1.06 µm compared to effective pathlength (l_{eff}, normalized to 1.0 for Natural sample). Sample thickness is 3.2 mm.

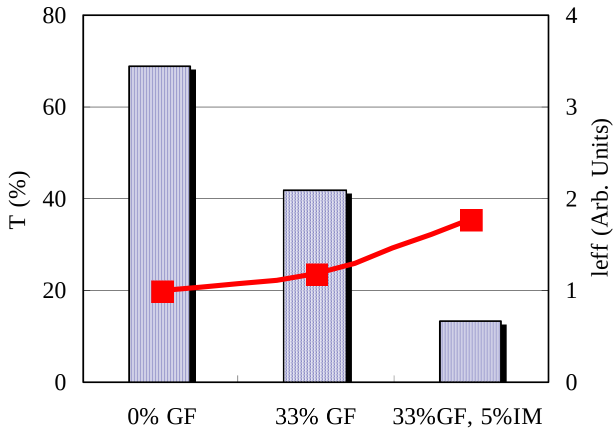

Fig. 11: Combined effect of impact modifier and fiber-glass reinforcement (Table 4) on laser transmission (T) at 1.06 µm compared to effective pathlength (l_{eff}, normalized to 1.0 for Natural sample). Sample thickness is 3.2 mm.

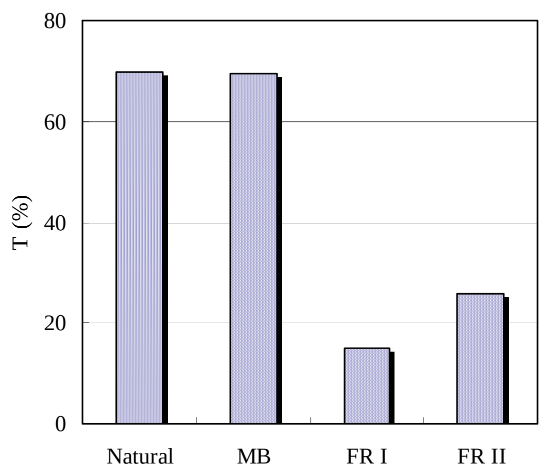

Fig. 12: Effect of maserbatch and flame retardant additives on laser transmission (T) at 1.06 µm. Sample thickness is 3.2 mm, except for FR I and II (1.6 mm).

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