

# LASER TRANSMISSION WELDING OF SEMI-CRYSTALLINE THERMOPLASTICS - PART II: ANALYSIS OF MECHANICAL PERFORMANCE OF WELDED NYLON

## Abstract

Selecting thermoplastics for a wide industrial application (automotive, appliances, lawn & garden, power tools, etc.) strongly depends on the plastic material composition, part design, processing (molding and welding) conditions. The structure of used thermoplastics, mechanical properties and composition (reinforcements, fillers, additives, pigments, etc.) may have the greater influence and need to be characterized for optimum material selection for the laser transmission welding (LTW) application.

To provide a guide to nylon based thermoplastics selection for laser transmission welding (LTW) 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  $\mu\text{m}$ ). The results of an optical characterization of nylon 6 based thermoplastics are discussed in the Part I of this report to ANTEC'2000<sup>1</sup>.

The mechanical performance (tensile strength at room temperature conditions) of nylon welded joints was evaluated in terms of the influence of transmission laser welding technology parameters (laser power, welding speed, laser beam spot sizes, clamp pressure, etc.) and thermoplastic composition (reinforcements, fillers, additives, pigments, etc.).

Technical results of this comprehensive evaluation (optical properties of nylon 6 based plastics and mechanical performance of welded joints) will assist plastic parts designers and technologists in selecting nylon based thermoplastics and developing new products using laser transmission welding (LTW) technology. The purpose

of Part II of this report is to increase understanding within the plastics engineering community regarding the usefulness and possible applicability of laser transmission welding (LTW) technology for nylon made components.

## Introduction

Laser welding technology (LWT) provides a highly attractive method for thermoplastic applications [1-7]. Laser welding of thermoplastic parts is at the initiation stage for wide industrial application [8-10]. Current and potential application areas include automotive (taillight assemblies, fuel line components), electrical and electronic modules (cell phones housings, display windows and connectors) and medical (valves, housings, optical lenses, etc.). [11]. Figure 1 shows a typical application of laser transmission welding (LTW) for polyamide application.

For joining of thermoplastics there are two laser welding methods: a) fusion welding, and b) transmission welding. High power diode (in wavelength range 0.8 to 1.0  $\mu\text{m}$ ) and Nd:YAG lasers were successfully used for welding thermoplastics because of their favorable optical properties in the Near InfraRed [3, 7, 9-11].

Advantages of laser welding technologies (LWT) are mainly in an accurate, non-contact, heat transfer as well as the possibility to optimize welding conditions including temperatures (in the weld interface) and to prevent the possible mechanical and thermal damage of pre-assembled parts. Plastic part design freedom is enhanced because the weld seams may take on virtually any shape and configuration of the joined parts upon welding without concerns about the laser welding process.

Laser transmission welding (LTW) permits an efficient joining of the 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 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 available, allowing welding of long plastic parts where the weld seams reach a length of

<sup>1</sup> Kagan, V. A., Bray, R. B. and Kuhn, W. P., "Laser Transmission Welding of Semi-Crystalline Thermoplastics – Part I: Optical Characterization of Nylon-Based Plastics", - Plastics ... the Magical Solution, Proceedings of the SPE 58<sup>th</sup> Annual Technical Conference and Exhibits (ANTEC'2000)

1 – 2 m (and more) with a reasonable welding cycle time.

## Basics of Laser Transmission Welding (LTW)

Basic principles of laser transmission welding (LTW) and optical properties of semi-crystalline thermoplastics were discussed in Part I of this report to ANTEC'2000. The present study (Part II) focuses on the influence of LTW technology (using a high-power diode laser) and plastic composition on melt-pool formation (Figure 2) and mechanical performance of laser welded joints.

## The Peculiarities of Thermoplastics Heating, Melt-Pool and Welded Joint Formation

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.) [12-16]. The temperature distribution at the weld interface and the melt-pool formation profile for the frictional welding methods is symmetric (for joint welded using similar plastics). Linear vibration welding (LVW) is less sensitive to dimensional tolerances than contact (hot plate / tool) and ultrasonic welding because it is self-adjusting in the bead contact areas [14-16]. It is possible to close a gap up to 5 mm wide (and more), between two joined surfaces with optimized welding conditions (Figure 3).

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 [17]. 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 4 and 5). The following laser transmission welding parameters were changed during this experiment:

- laser power level;
- laser power intensity;
- laser beam scanning rate (welding speed);
- laser beam focus (laser beam size / diameter  $w_{LB}$  at the font of transmitting plastic).

Figure 6 shows the microtomed cross section of a butt joint formed by laser transmission welding (LTW). The melt layer thickness of the transmitting plastic part,  $m_A$ , natural and the absorbing plastic part,  $m_B$ , 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 (see microtomed cross section in Figure 3).

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 [12-15]. 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 7 shows an example of a defect that was created from the laser transmission plastic part side.

## Basic Types of Laser Welding Systems

Three laser types are mostly used for welding of polymer based materials: the CO<sub>2</sub> laser, the Nd:YAG laser and the diode laser [18-19]. These lasers have the following level of efficiency [1, 18]: CO<sub>2</sub> laser – 10%; Nd:YAG laser – 3%; diode laser – 30%. The CO<sub>2</sub> 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 30 W to 40 kW 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 30 W to 4 kW.

For laser transmission welding (LTW) it is also possible to use diode lasers which generate the Near InfraRed (NIR) energy. Typical diode laser systems (Figure 8) have the following technical data [19]:

- Wavelength: 808 ± 10 nm 830 ± 10 nm or to 940 ± 10 nm.
- Output power: from 60 W cw to 4000 W cw.
- Power range: from (1-60) W to (100-2500) W.
- Laser beam quality: min. focus size (86%) from 0.8 x 1.2 mm to 1.8 x 3.6 mm.
- Work distance: from 32 mm to 70 mm (150 mm).

In general diode laser systems are superceding the Nd:YAG laser, due to modular principles of optimized design, and higher efficiency [1-11].

## Mechanical Performance of Laser Transmission Welding (LTW)

Previously we reported to SPE'96, SPE'99 and GPC'99 optimized mechanical performance of linear vibration, orbital vibration and hot plate for welded nylon butt joints [12-13, 15]. 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). 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.) [4-5, 20-21] and they achieved a tensile strength of the butt joint equal to the tensile strength of the base polymer (weld factor  $f_{wm} = 1$ )<sup>2</sup>. 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  $f_{wm} = 0,76$ ) [21]. The AWS G1 standard injection molded specimens were used for welding and testing the butt joints.

Reference [3] evaluated the mechanical performance of several welded plastics (PC, ABS, PP and PS), using the *IRAM<sup>TM</sup>* method (Infrared Assembly Method). Welding using *IRAM<sup>TM</sup>* in transmission mode is based on the wavelength range from 800 to 950 nm. AWS G1 standard injection molded specimens were used for welding and testing of butt joints, as in [20-21]. 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<sup>TM</sup>* welding, [3, 20-21]) joints may be explained in the following ways:

- non optimized pigment content in an absorbing thermoplastic part;
- dimensional non-stability (non-optimized molding conditions and warpage issues) of the AWS G1 standard specimens;
- non fully optimized welding conditions;
- non-identified geometry and sizes of the butt / shear

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<sup>2</sup> Weld factor  $f_{wm}$  = tensile strength of the weld / tensile strength of base polymer (non-reinforced plastic)

joints combined with the influence of the peculiarities of thermoplastics heating, melt-pool and welded joint formation (see Figure 5) for transmission welding (LTW).

## Experimental

### Laser Transmission Welding (LTW) Machine with Complete Robotic System and Processes Control

In this study we used high-power diode laser transmission welding (LTW) system<sup>3</sup> with complete robotic system specially developed for thermoplastic applications [6, 11]. This laser system has the following technical parameters:

- Wavelength:  $808 \pm 10$  nm.
- Output power: 100 W cw.
- Power range: from 20 - 100 W.
- Laser beam quality: min. focus size (86%) - 0.8 mm diameter.
- Work distance: 32 mm – 150mm.

A fiber coupled diode laser system was used to transmit laser energy through the transparent (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 9. This LTW machine can operate in either manual, manual / auto, or fully automated modes.

In the experiments laser transmission welding was performed on injection molded T-type specimens having a butt joint (Figure 4) which allowed transmission welding with the diode laser, and tensile test of the welded butt joints. A universal pneumatic clamping system was used to apply a clamping pressure along the butt joint. These butt joints, were then transmission welded using a robot (Figure 10) to move the focussed laser beam over the T-type specimens.

### Used Plastics and Geometry of Welded Joints

We analyzed the efficiency of laser transmission welding (LTW) technology for five commercial nylon 6 based plastics (Tables 1-4). 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 covers a wide area of a possible applications. At this time we did not evaluate the influence of carbon black content in the absorbing parts (molded from commercially available plastics) and we

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<sup>3</sup> MAGNA, ATC

used recommendations published in [4].

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:

- rectangle shape - 150 mm x 60 mm x 3.2 (or 4.0 mm);
- T-shape - 150 mm x 38 mm x 3.2 (or 4.0 mm). In the local T-shape area the sizes are as follow: width = 6.25 mm, thickness = 3.2 (or 4.8) mm.

Figure 4 shows a schematic of a welded T- type assembly and a machined test specimen (butt joints). 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.

## 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.

For our initial LTW strength studies, we welded 3.2 mm thick, injection molded, rectangular plaques using a lap shear joint configuration. Sizes (length x width) of molded plaque are: 150 mm by 60 mm, approximately. This configuration is often used for laser transmission welding [1-3, 9-10, 18] of amorphous and semi-crystalline thermoplastics. Figures 1 and 6 show principles of the melt pool and joint formation including 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:  $w_{HAZ}$ , see Figure 5). The size (diameter) of the focused laser beam at the front of transmitting plastic  $A$  ( $w_{LB}$ ) and the size (width) of heat affected zone (width of the weld:  $w_{HAZ}$ ) are not the same. The width of the weld ( $w_{HAZ}$ ) depends upon the thermoplastic composition (Table 2). For the short fiber-glass, reinforced nylon 6 plastics the width of the weld ( $w_{HAZ}$ ) 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 (Figures 11 and 12) 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 the plaques 3,2 mm thick;
- non-uniform melt-pool and weld formation along the length of the clamped / pre-joined plaques;
- influence of flexural, peel (for non-symmetrical lap joints) and stress concentration effects.

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 [17].

For the base investigation we used the tensile test (at room temperature, 23 °C) for T-shape butt joints (Figure 4). A minimum of five welded and machined T-shape specimens (20 mm width) was tested using ISO 527 procedures. The weld flash / “bead” was not removed from the weld area. The specimen was loaded until it failed. All tensile test results were used to optimize performance of the laser transmission welding. Samples with high tensile strength were selected (Figure 6) to perform morphology analysis in the weld zone (interface). We also evaluated samples containing material and weld defects, including damage of polymer due to overheating (Figure 7). Tables 1 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 (LTW) technologies.

Data on the efficiency of five welding technologies for 33 GF wt. % nylon 6 plastic is presented in Tables 3 and 4. 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<sup>4</sup>.

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 3).

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<sup>4</sup> Weld factor  $f_{wpl}$  = tensile strength of the weld / tensile strength of reinforced plastic

## Concluding Remarks

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, lawn & garden, power tools, etc. industries.

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.

Laser transmission welding (LTW) was shown to effectively join a variety of nylon plastics (non-reinforced, fiber-glass reinforced, etc.). Comparison studies of linear and orbital vibration (LVW and OVW), hot plate and ultrasonic joining technologies demonstrated that laser transmission welding (LTW) process is efficient for nylon and may be used as alternative to frictional, hot plate and ultrasonic technologies.

### Further investigations are needed to:

- develop mechanical performance data and optimize welding processing conditions for the various colored thermoplastic(s) especially in regard to the influence of composition (types of the pigments / colorants, 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 as an alternative joining method for semi-crystalline thermoplastics. This will allow designers and manufacturers to discuss / recommend LTW technology for developing new welding applications for nylon based plastics.

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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.

Table 1: Influence Of Fiber-Glass Reinforcement On The Tensile Strength (At 23<sup>0</sup>C, Dry As Molded) Of Linear Vibration And Laser Welded Butt Joints (Optimized Processing Conditions)

Wt. %, GF	Tensile Strength of Fiber Glass Reinforced Plastic (MPa)	<b>Vibration Welding Technology</b> Tensile Strength of Weld (MPa)	<b>Laser Welding Technology</b> Tensile Strength of Weld (MPa)
0	82	81	≥ 82
14	125	90.7	N / A*
25	160	90.2	76.9
33	185	83.6	75.4
45	208	80.1	70.4

N/A\* - Data will be presented later

Table 2: 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  $W_{lb} \sim 2,2$  mm

Trade Name of Fiber-Glass Reinforced Plastics	Fiber-Glass (GF), % by weight	Range of the size (maximum width of the heat effective zone $w_{HAZ}$ ) for the lap / shear joints, in mm (Figures 5 and 12)
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

Table 3: Efficiency Of Welding Technologies For Fiber-Glass Reinforced Nylon 6 Based Plastics (33 Wt. % GF, At 23<sup>0</sup>C, Dry As Molded, Optimized Processing Conditions)

Type of the Welding Technology	Weld Factor $f_{wm}$	Weld Factor $f_{wpt}$
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

Table 4: Efficiency OF Laser Transmission Welding (LTW) For Fiber-Glass Reinforced Nylon 6 (Optimized Processing Conditions)

Wt. %, GF	Tensile Strength of Polymer (MPa)	Tensile Strength of GF Plastic (MPa)	Weld Factor $f_{wm}$	Weld Factor $f_{wpt}$
0	82	82	$\geq 1.0$	$\geq 1.0$
14	82	125	N/A	N/A
25	82	160	0.94	0.48
33	82	185	0.92	0.41
45	82	208	0.85	0.34

N/A\* - Data will be presented later



Figure 1: Typical application of laser transmission welding (LTW) for nylon 6 part (30 wt.% GF, door actuator)

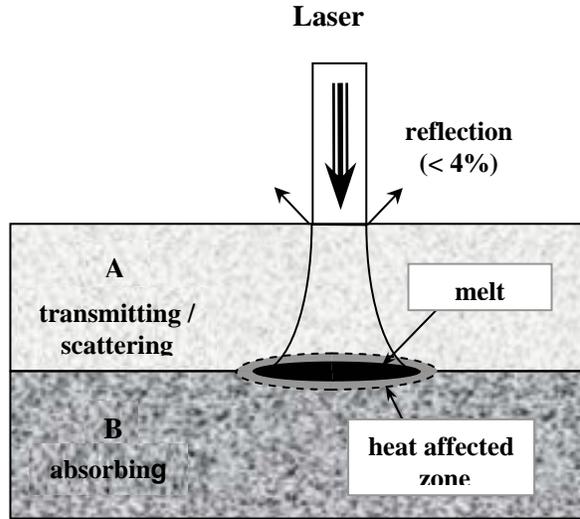


Figure 2: Principle of the laser transmission welding. Part A is a thermoplastic having variable transmission/ scattering. The thermoplastic in part B absorbs the transmitted light at the interfacial region

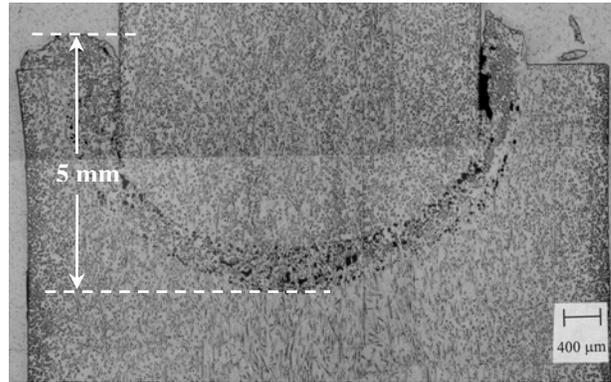


Figure 3: Wide gap adjustment for linear vibration welding (LVW): nylon 6, 33GF wt.% GF (longitudinal oscillations, melt-down = 5 mm)

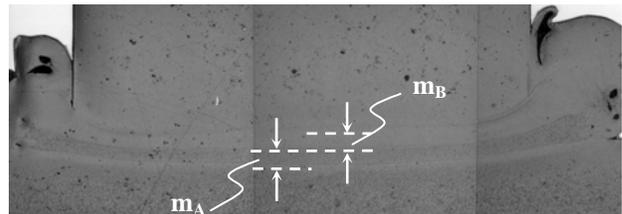


Figure 4: Butt joint structure for laser transmission welding of nylon 6 based plastics. Legend:  $m_A$ , – melt layer thickness of the weld related to laser transmitting plastic;  $m_B$ , – melt layer thickness of the weld related to absorbing plastic

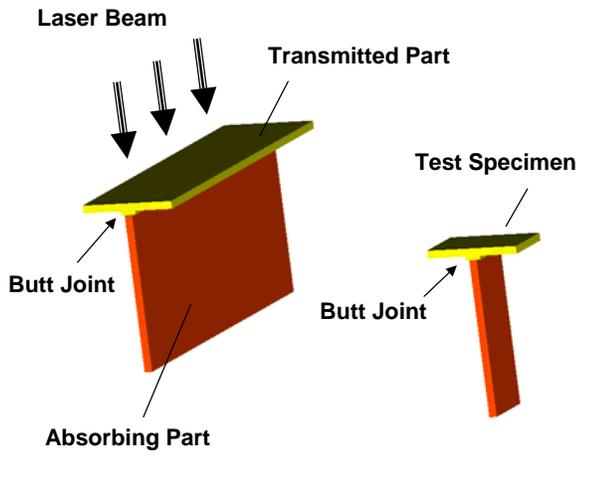


Figure 5: T-type butt joint for the laser transmission welding (LTW)

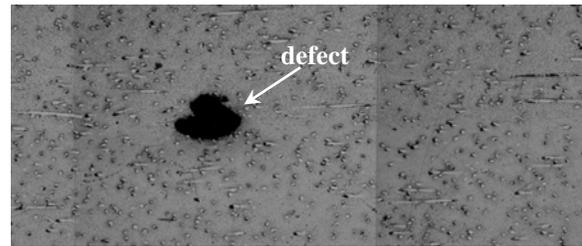


Figure7: Butt joint structure for non-optimized laser transmission welding (LTV) of nylon 6 based plastics

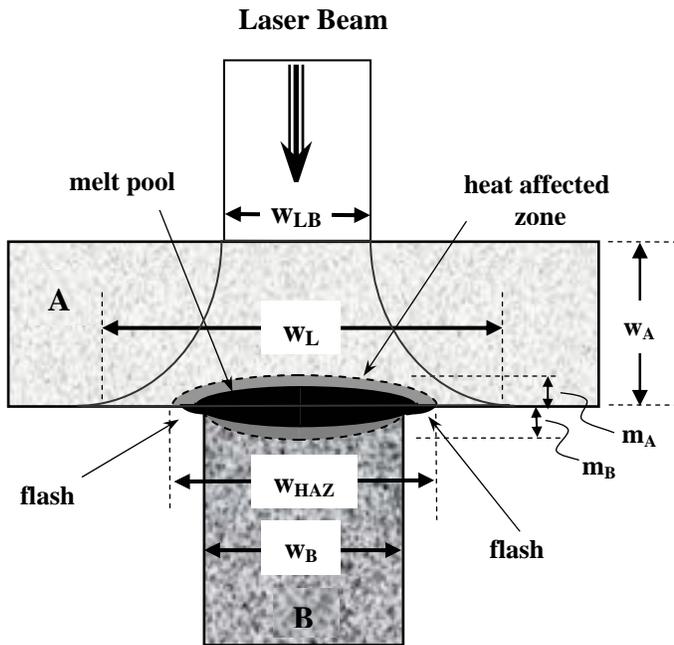


Figure 6: Principles of the butt joint and the formation of the melt pool within the heat affected zone for laser transmission welding. Legend: **A** is a thermoplastic having variable transmission/ scattering; **B** is thermoplastic that absorbs the transmitted light at the interfacial region;  $W_{HAZ}$  = 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 8: Typical high-power diode laser system with compact laser head

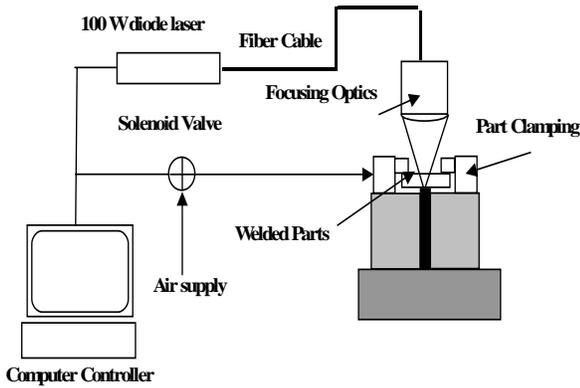


Figure 9: Set-up for laser transmission welding machine

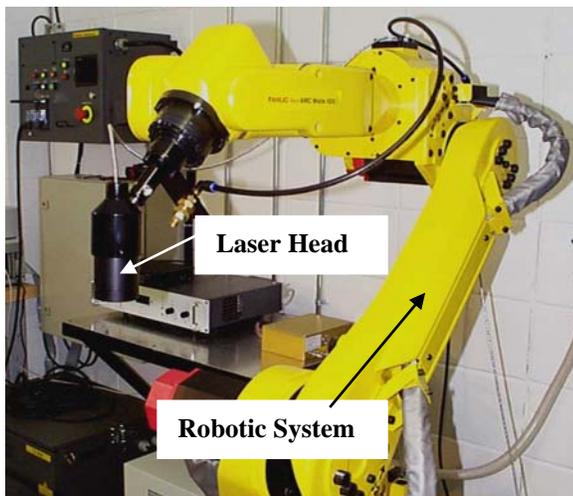


Figure 10: Laser transmission welding (LTW) machine with complete robotic system

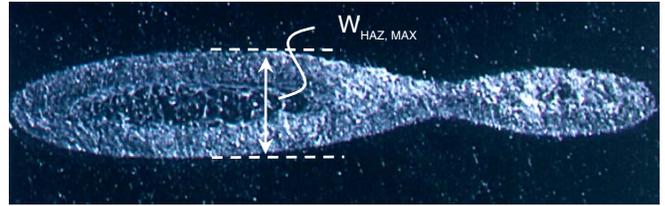


Figure 11: Weld and melt-pool profile for a lap / shear joint (See Table 2)

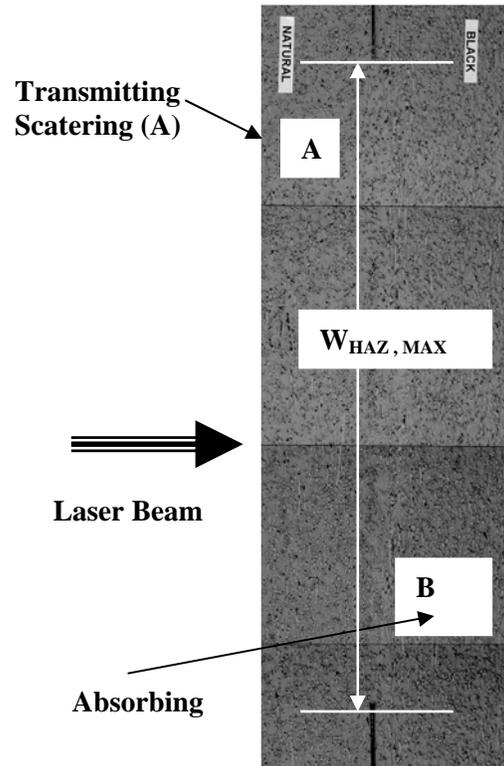


Figure 12: Lap / shear joint structure for laser transmission welding of nylon 6 based plastics. Legend: **A** is a thermoplastic having variable transmission/ scattering; **B** is thermoplastic that absorbs the transmitted light at the interfacial region;  $W_{HAZ, MAX}$  = maximum width of heat affected zone (see Table 2)

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BASF Corporation  
3000 Continental Drive - North  
Mount Olive, New Jersey 07828-1234

[www.basf.com/usa](http://www.basf.com/usa)  
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