

## **Innovations in Laser Welding of Thermoplastics: *This Advanced Technology is Ready to be Commercialized***

### **ABSTRACT**

Previously we reported to the SAE 2000 basics in selection of various colored and un-colored/natural nylon 6 (polyamide – PA 6) based plastics for laser welding technology. Later we presented to Antec<sup>1</sup> 2001 and to SAE 2002 our developments of colored in black through-transmissible grades of PA 6 plastics, which were specially tailored for the specifics of the design and laser welding technology. In this current paper, we will try to enhance the understanding of the engineering community regarding the usefulness and applicability of laser welding technology, developed colored thermoplastics, and its increasing use in various automotive and transportation applications.

### **INTRODUCTION**

Laser welding technology is a modern and innovative method of processing technology for various structural materials including thermoplastics [1-4]. Fundamentals of laser materials processing, including laser welding of various materials, are described in details in [1]. Unfortunately, this comprehensive work presented very limited information on laser welding of thermoplastics including polyamides. At present, this sophisticated method starts to make its first efficient steps into wide engineering applications for automotive plastic made parts such as air intake manifolds (AIM's) [2].

After successful applications in the processing technology for metal [1, 4], lasers are now reaching new targets for various polymers and thermoplastics [2-5]. The laser welding process for assembly of thermoplastics has been in continuous experimental use for the last ten years<sup>2</sup>, yet this technology is still not familiar to many automotive and plastics engineers. Laser welding technology of thermoplastics is relatively new, in comprising to the traditional joining techniques of

plastics, such as ultrasonic, linear and orbital vibration, spin, stir, kinetic, electromagnetic (Emaweld® and SmartBond®), hot plate, hot-gas, hot-air and extrusion welding [3-5]. Every welding technology of plastics is based on the needs to delivery energy to the area of the future joint (weld) and creates melt-pool. This pool after solidification will join separate plastic parts in one solid piece. The small and local energy input laser welding induces less thermal and residual stresses compared to traditional techniques and generates high quality weld.

Selection of plastic for traditional welding methods is based on various physical-mechanical factors and chemistry (composition) of used plastics. In our report to SAE 2000, we presented [6] our basic findings on selection of polyamide based plastic for laser welding technology related to specifics of laser energy transmission and absorption. Recent developments [7-9] were oriented to the development of colored polyamides for laser welding technology, the comprehensive optical characterization over a wide range of infrared (IR) wavelengths, optimized mechanical performance of welded various polyamide and other thermoplastics also. During this study, recommendations were developed for optimizing the non-carbon black pigment loading in various non-reinforced and fiberglass reinforced polyamide 6 grades with high-laser transparency [8].

The latest developments in laser welding, micro and macro technologies of polymers and thermoplastics, related to needs of automotive industries, were widely published and presented in North America and Europe [2-25, 29-30]. The various technical data and recommendations may be obtained from the proceedings of the followings conferences and shows:

- Society of Automotive Engineers (SAE)
- Society of Plastic Engineers (SPE)
- Automotive & Transportation Technology (ATT, UK)
- International Plastic Manifold Forums (ASK – Altmann, Germany)
- Global Powertrain Congress (GPC, Detroit)
- International Congress on Applications of Lasers & Electro-Optics (ICALEO®) sponsored by Laser Institute of America (LIA)
- National Plastic Exhibition (NPE, Chicago)

<sup>1</sup> Antec – is Annual technical conference of the Society of Plastics Engineers (SPE).

<sup>2</sup> The first experiment in application of infrared (IR) radiation to weld polymers and plastic was successfully realized in the 1970's. At the same time, its first patent was issued on laser welding of polymers and plastics.

- K-show (Dusseldorf, Germany)

The following presents our study centered on:

- Analysis of efficiency and basics of laser welding technologies (non-contact, traditional<sup>3</sup> through-transmission, and through-transmission clear-weld<sup>4</sup>) for the design with thermoplastics.
- Information on commercially available laser welding system (machines) and technology providers.
- Analysis of series of comprehensive optical characterizations<sup>5</sup> of colored and non-colored (natural state<sup>6</sup>) polyamides tailored to specific laser welding.
- Potential and current applications of laser welding technology for thermoplastics in various industrial applications including transportation and automotive.

The results of the mechanical<sup>7</sup> performance, optical characterization, developed recommendations for optimized design and processing, will contribute to a better understanding of various laser welding processes, plastic selection, and welded part design to succeed in the success of various automotive applications.

### EFFICIENCY OF LASER PROCESSING OF THERMOPLASTICS

#### REMARKS ON LASER PROCESSING OF PLASTICS

The most important feature of lasers for materials processing is their ability to deliver high values of irradiance to selected area on plastic part, which cannot be matched by any source. This can produce rapid heating in a very small region. The localized nature of the heating and formation of melt-pool leads to many applications of laser in thermoplastic processing. Laser welding is a significant part of the laser processing technology of polymers and thermoplastics, which includes the following typical methods [1, 3-4]:

- Welding
- Rapid prototyping
- Machining, cutting and profiling
- Drilling, perforating and balancing
- Marking and coding
- Local treatment (surface and micro structural modification)
- Bulk curing (adhesive, paint, etc.)

<sup>3</sup>In the case of the traditional through-transmission laser welding one plastic should be transmissible and second need to absorb laser energy.

<sup>4</sup>For clear-weld technology, both (or more) thermoplastics should be laser transmissible.

<sup>5</sup>Optical data published by various authors [5-18, 29-30].

<sup>6</sup>Natural state is color of un-pigmented thermoplastic specimen after injection molding.

<sup>7</sup>Short-term tensile properties of welded butt joints.

### LASER ENERGY SOURCES FOR WELDING OF THERMOPLASTICS

Laser welding process is economically (Figure 1) and technically reasonable advanced joining technology (Table 1) for many thermoplastics. In addition, excimer lasers such as CO<sub>2</sub> and Nd:YAG, widely used for material processing, high power diode laser systems, are taking new areas of welding of thermoplastics.

Table 1. Advantages and limitations of traditional and modern joining methods of polymers and thermoplastics

Type of Welding	Welding Time/Speed	Advantages and Limitations
<i>Frictional</i>		
Friction stir	≈ 3 mm/sec	Very early stage
Spin	1 ~ 15 sec	Design limitation
Linear	1 ~ 10 sec	Linear motion
Orbital		Orbital motions
Ultrasonic	< 1 sec	Weld size limitation
<i>Hot tool (-air, -gas)</i>		
Hot bar	1 ~ 3 sec	Mostly for films
Hot gas/air	30 mm/sec	Manual
Hot plate	< 1200 sec	Material dependant
<i>Electromagnetic</i>		
Laser	Up to 15 m/sec	Material dependant
SmartBond	7 ~ 40 sec	
Emaweld®	10 ~ 90 sec	
Microwave	< 60 sec	
Infrared, non-contact	< 600 sec	
Resistive implant	10~2000 sec	
<i>In-mold and Extrusion</i>		
In-mold	Molding cycle	Advanced tooling
Over-mold		Additional injection molding unit & tool
Extrusion	30 mm/sec	Manual

The high-power diode lasers are very compact and reliable. One important advantage of a diode laser system is a very high efficiency (up to 30%-60%) with power up to 3 kW. These systems have a very low or moderate maintenance expenses [1-2, 4, 13, 21]. At the current time, the system, up to 8 kW, are commercially available with free space and fiber delivery [1].

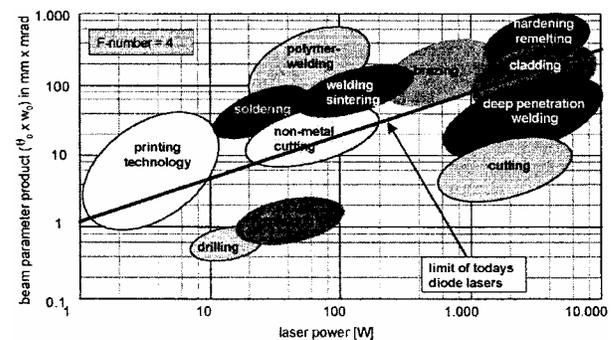


Figure 1. The efficiency of the diode lasers for materials processing technology.

In this report, we are centering our developments, discussions and analysis on laser welding technology for rigid injection molded thermoplastics (mostly for polyamides) utilizing advantages of high power diode systems.

**BASE PRINCIPLES OF LASER WELDING OF POLYMERS AND THERMOPLASTICS**

**Introductory Remarks**

In thermoplastics welding, we need to create heat and melt at joined surfaces for the weld inter-phase formation. The most common plastics welding methods include friction, hot tool, and electromagnetic (Table 1). By using the classification of the electromagnetic welding, it includes the following joining methods:

- Resistive implant
- Inductive implant
- Emaweld®<sup>8</sup>
- SmartBond®
- Dielectric
- Microwave
- Laser/Infrared (IR)

In general, two principles in the joining surfaces heating for a local thermoplastic(s) melting and subsequent welding may be applied for laser welding technology at the current time:

- Non-contact laser welding (Figure 2)
- Through-transmission laser welding (Figures 3-7)

Both laser welding methods have a lot of advantages and possible disadvantages, related to heat generation principles, plastic(s) composition, and the stiffness of joined plastics, part design (thickness at weld area), color version, etc.

Non-Contact Laser Welding

Non-contact laser welding is typically used for joining of rigid thermoplastics. The process of non-contact laser welding (Figure 2), preferably applied for butt joints, is very similar to contact or non-contact hot plate welding [5, 16]. This type of laser welding technology may replace the hot plate or radian (including heating process by the infrared lamps). For hot plate joining technology, the welding of plastic parts results from local material(s) melting layers, and the pressure-induced flow of material, which causes diffusion and interlocking at the weld inter-phase area. Heating and melting of the polymer(s) is caused from the absorbing of energy by thermoplastic parts 1 and 2, made from material “type B” (which has sufficient absorption properties, Figure 2).

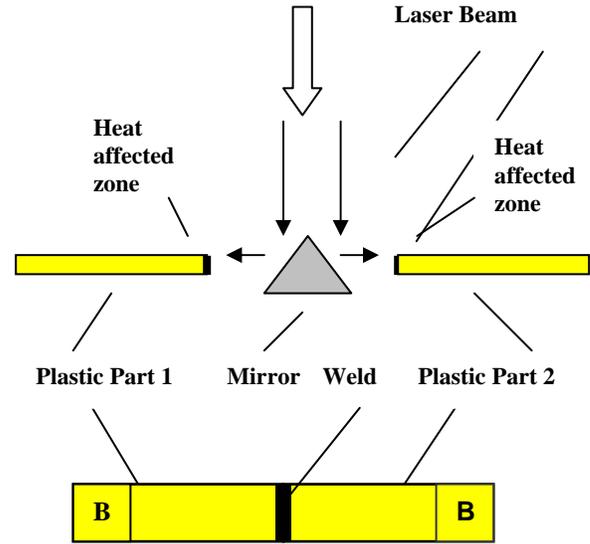


Figure 2. Principles of the butt joint formation for non-contact laser welding. Legend: B plastics that absorb laser energy at the inter-phase of the weld.

A different physical mechanism is used to generate local material(s) melting layers for non-contact welding:

- Conduction
- Radiation
- Convection
- Subsequent contacting (similar to hot plate welding)

Selected material(s) for welded parts by non-contact laser welding technology should provide energy absorption and melting at local areas for inter-phase formation. The non-contact method may be applied for joining of the various colored similar and dissimilar polymers and thermoplastics. It was pointed out [5, 17] that only a limited inter-diffusion is expected at the joint of dissimilar polymers. Because of their difference in thermal properties, one plastic may melt faster than the other one. Sometimes, one of the materials may not even reach its melting point at the interface (at not optimized processing conditions). Due to the temperature gradient across the width of the melt-pool, the flow of the joined plastics is not uniform.

<sup>8</sup> Emaweld® is trade name of welding process from Ashland Chemical, Inc.

## Through-Transmission Welding

Through-transmission welding may be applied for joining of the various plastics and in the following design combinations:

- Rigid to rigid (molded, extruded, etc.)
- Flexible to rigid (films and soft TPE to molded and extruded)
- Flexible to flexible (films, soft TPE, etc.)

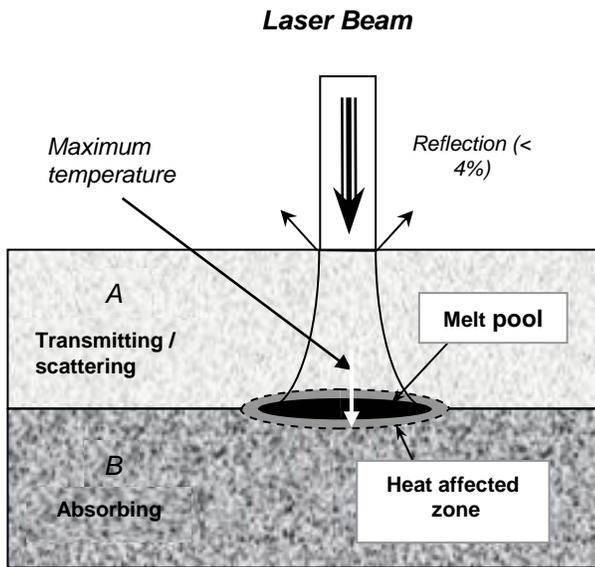


Figure 3. Principles of the butt joint and the formation of the melt pool within the heat affected zone for traditional through-transmission laser welding. Legend: A is laser transmissible plastic; B is a thermoplastic that absorbs the transmitted light at the interfacial region.

## Traditional Through-Transmission Laser Welding

In “traditional” through-transmission welding, the thermoplastic parts to be joined are brought into direct contact prior to welding (Figure 3). The welding process requires two thermoplastic materials (A and B) 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 type pigments) is in contact with an optically dense part (B, typically carbon black filled, or colored with absorbing type pigments). The laser beam is totally absorbed within the surface (interfacial) 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. The heating and melting of the polymer is started from absorbed energy from part B.

The *maximum temperature at weld inter-phase and the center of molten elliptic shape volume (melt-pool)* are located under the heated surface of the absorbing part B (Figure 3). The heat from this area(s) is transferred to the surface of the laser energy transmissible part A.

Both melt layers (A and B) are creating the weld inter-phase. Figure 4 shows potential application of traditional through-transmission laser welding technology in manufacturing of the cover of the automotive gears shift mechanism.

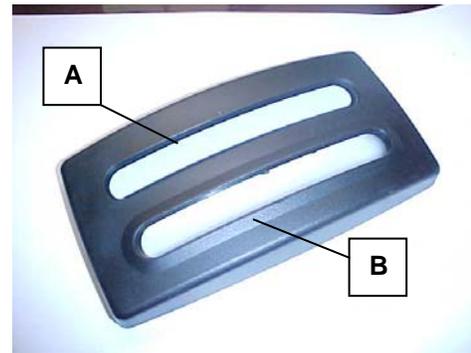


Figure 4. Thermoplastic welded cover of the automotive gears shift mechanism. Legend: A - transparent window; B - colored in black cover molded from plastic that absorb laser energy at the interfacial region.

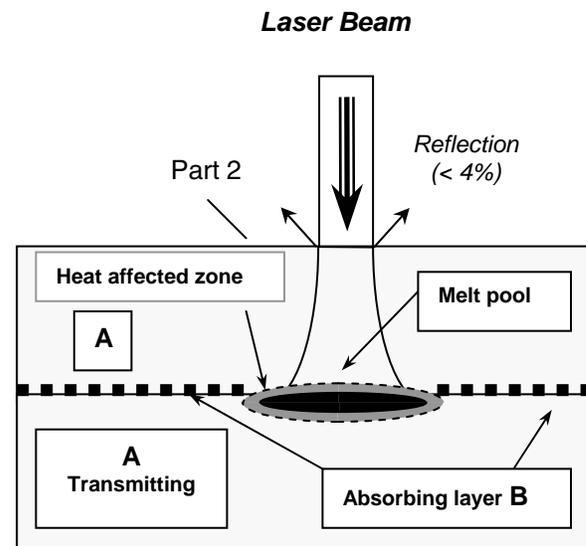


Figure 5. Basic principles of the butt joint and the formation of the melt pool within the heat affected zone for clear welding. Legend: A are laser transmissible plastics; B is an absorbing inter-layer.

## Clear-Weld Laser Method

For clear-welding applications (Figure 5), both joined plastics (A1 and A2) are optically transparent. The laser beam is transmitted through Part 2 with minimal losses and absorbed by layer B, which converts absorbed energy into heat. Direct contact between both parts (A1 and A2) and inter-layer B will help to transfer heat into both the upper (A2) and lower (A1) parts, developing the necessary melt-pool. Both joining technologies (traditional through-transmission and clear-welding), are critically important to achieve a sufficient and consistent

heating of the plastic in the region of the joint during the pre-melt and fusion phases.

This condition will produce a consistent thickness for the weld interface and the desired mechanical performance of the weld. The specifics of the weld formation between parts A1 and A2 (at absorbing inter-layer B) should be taken into account in material selection for the joint design. Previously developed optical data [4-9] on laser energy transmission and absorption is very helpful for the selection of materials A and B (or absorbing inter-layer B) in laser (infrared) welding methods.

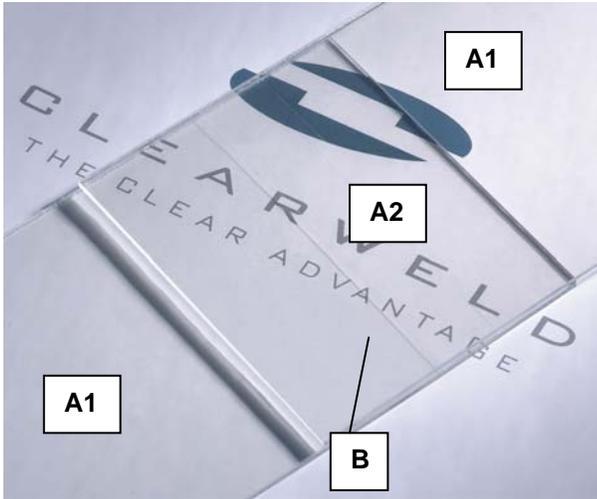


Figure 6. Basic principles and advantages of clear welding for the optical (translucent) applications. Legend: A1 and A2 are thermoplastics, which transmit laser beam. A2 is plastics placed on the top of plastic A1. B is weld (developed by presence of an absorbing inter-layer placed between plastics A1 and A2).

Table 2. Design and technology considerations for welding modes of through-transmission technology

Welding Method	Thickness of melt-pool, $\mu\text{m}$	
	Non-optimized	Optimized
Scanning	$\leq 200-350$	$> 500$
Simultaneous	$\leq 150-300$	$> 300-600$
Quasi-simultaneous	$\leq 100-300$	$> 300-600$
Mask	$\leq 200$	$> 300-500$

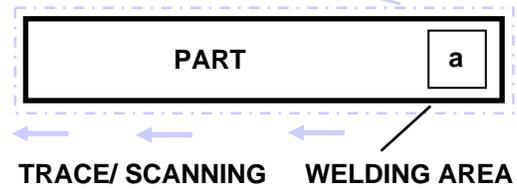
### Basics of through-transmission welding modes

By heat generation, melt layers, and inter-phase formation, through-transmission laser welding methods may be classified into the following groups:

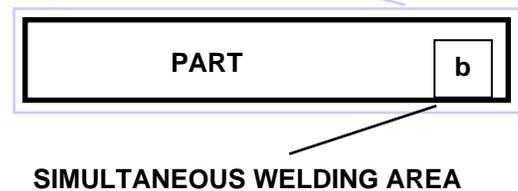
- Scanning (moving) of the laser beam along the weld contour (Figure 7a).
- Simultaneous heat generation at the contour of the weld (Figure 7b).

- Quasi-simultaneous (laser beam guided with the deflection mirrors along the weld contour at the frequency of up to 50 Hz).
- Mask (Figure 7c).

#### Heat Affected Area (Trace / Scanning)



#### Heat Affected Area (Contour)



#### Heat Affected Area (Trace / Scanning)

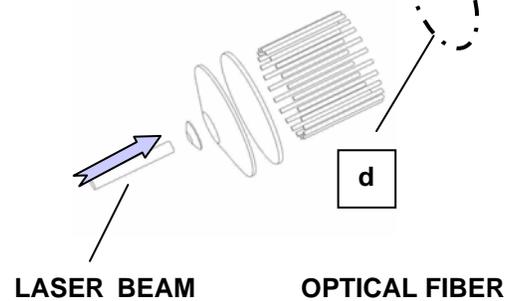
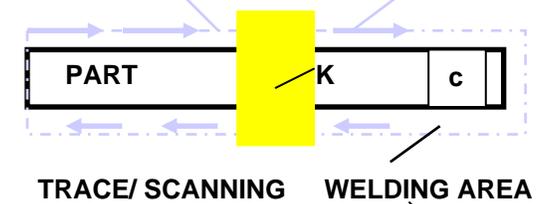


Figure 7. Basic modes of through-transmission laser welding. Legend: A - contour; B - simultaneous; C - mask; D – fibers coupled diode welding.

Welding mode, processing parameters and optical properties of joined plastics might influence the thickness and geometry of developed melt-pool (Table 2). In general, the mechanical performance of welded joint is increased the thicker melt-pool was created. The melt penetration depth may reach over 300  $\mu\text{m}$  for large parts, and less than 250-300  $\mu\text{m}$  for medium and small plastic components (which did not require hermetecy of weld). Commercially available and specially tailored

plastics may be used for optimized processing parameters and desired mechanical performance of welded parts.

Key processing parameters needed for optimized performance of welds

Basic laser beam parameters are summarized in Table 3. Optimized performance of weld requires to managed the following additional processing and design parameters:

- Melt-pool temperature:  $T$ , °C
- Laser power:  $p_L$ , W
- Wavelength:  $\lambda$ , nm
- Laser beam focus spot and profile size(s):  $b_W$ , mm<sup>2</sup> (or mm x mm), or diameter  $d_{focus}$  (mm)
- Welding time:  $t_W$ , sec
- Welding (clamp) pressure:  $p_{CL}$ , MPa
- Welding speed:  $v_W$ , mm/sec
- Width of weld: 0.1 ~ 10 mm
- Thickness of thermoplastic: up to 4 to 6 mm
- Surface conditions of joined/contacted thermoplastic parts (related to laser energy reflection)

Table 3. Parameters describing focused laser beams

Parameter	Symbol (equation)
Beam power	$P$
Width of the portion of the unfocused beam	$D$
Wavelength	$\lambda$
Focal spot diameter	$d_{focus} = \theta_{dif} f = 2\lambda f / D$
Peak Intensity at focus	$I_{focus} = 2P / d^2$

**ADVANTAGES AND LIMITATIONS OF THROUGH-TRANSMISSION WELDING TECHNOLOGY**

Previously, we discussed and illustrated the following basic advantages of through-transmission laser welding:

- Welding of pre-assembled plastic components with the parts in the same orientation and position as the final assembled product
- Absence of vibration of the parts in the welding process (in contrast to ultrasonic and linear welding technologies) that permit welding of sensitive electronic and medical components
- Seam quality and flash (particles) free
- Design freedom:
  - Minimal limitations on the geometry and the size of the plastic parts to be joined
  - Minimal limitation of the weld length and geometry (3-D, straight and curved welds)
  - High optical appearance
- Processing freedom
  - Accurate, non-contact, heat transfer with the possibility of optimizing the welding

temperatures (at the weld inter-phase) during the joining process

- Improved localization of the heat affected zone, shape and sizes of laser beam, and control of melt flash in the joint area
- No visible damage or marking on the external colored surfaces correlated to the joint area
- Easy to automate, short welding cycle time. Rapid welding speeds permitting welding of long and wide parts with acceptable weld times
- Low cost tooling (fixturing)
- High mechanical performance of welded joints for various plastic compositions (unfilled and fiberglass reinforced, and colored/pigmented)

Table 4 summarizes basic advantages and limitations of through-transmission welding.

Table 4. Basic advantages and limitations of the through-transmission welding technology. Legend: By the type of welding: C- contour; SI- simultaneous; QS – quasi-simultaneous; MA – mask; By the size of part: L – large; M - medium S – small; Any – no limitation.

Parameter/Method	C	SI	QS	MA
Laser Type	Diode	+	+	+
	Nd:YAG	+		+
Relative cost <sup>9</sup>	M	M/High	M/High	M
Weld shape	3D	2D		3D
Weld cycle	M/L	S		S/M
Size of plastic part	Any	L		
Length of weld	Any			Any

Unfortunately, through-transmission laser welding has the following limitations, which may be reduced by proper material and welding method selection:

- Material dependent:
  - Require plastics (A and B) with different absorption characteristics for the laser
  - Response to some additives (fillers, impact modifiers and pigments)
- Intimate contact (pre-assembly) required at joint area
- Possible development of the residual stresses at weld inter-phase for highly rigid plastics, when the laser beam is scanning along of the weld contour
- Increased full time cycle for clear-weld technology due to the additional time needed to place absorbing inter-layer

**COMMERCIAL AVAILABILITY OF LASER WELDING SYSTEMS**

<sup>9</sup> Data represents author’s observations and opinions only. Relative cost (equal to “cost of laser welding system/cost of vibration welding”) of the system depends on its size of welded part and power of system).

Since the development of the first laser in 1960 and the use of infrared (IR) radiation to weld polymers and plastic in the 1970's, new types of laser welding machines and systems have been developed over the years (Table 5). During the last five years, several *plastic welding companies presented at SAE, NPE, Assembly Technology, K-Show*, various infrared and laser welding equipment, designed for joining of thermoplastic parts.

Table 5. Commercially available laser welding equipment for plastics and polymers application.

Equipment Manufacturer & Technology Provider	Model of Machine / Laser Welding System
Bielomatik	Laser-Tec
Branson	IRAM™
Fraunhofer Institute of Laser Technology	Dioweld 40
Leister	Modulas
Limonics	Impact
Rofin Sinar	DL
Sonotronic	Focus One

Figure 8 shows a typical design of a fully automated through-transmission welding systems. These systems are medium by size and may be used for joining small and medium plastics components.



Figure 8. Fully automated high-tech welding systems designed for laser protection by current regulations. Legend: **a** – IRAM™ (Branson Ultrasonic); **b** – MODULAS (Leister Process Technologies, Switzerland).

As a rule, these welding systems are of a modular concept and may be customized for various industrial applications and design requirements. The modular concepts allow the integration of the welding machine(s) in fully automated production lines including processing and quality control. Laser welding systems are available in manual, manual & automated mode, or fully automated modes (Figure 8 and Table 5). Laser diode-based systems have two major very important advantages, such as flexibility and cost-efficiency. A

laser power level of 10 to 400 W allows welding speeds as fast as 1000 mm/min. All of these systems are available worldwide for various applications including automotive. The sizes of components to be welded range from micro- parts such as electronic devices to very large such as automotive fluid tanks.

#### ECONOMICAL ASPECTS OF LASER WELDING

Up to 80 welding equipment and plastic part material manufacturers as well as joining technology providers are making the first steps in utilizing laser (infrared) welding technology for various industrial applications including automotive. Basic technical and economical data needed for the performance evaluation of laser material processing systems is presented in Table 6.

Table 6. Basic technical and economical data needed for the performance evaluation of laser material processing systems.

Parameter	Type of Laser System		
	CO <sub>2</sub>	Nd: YAG	Diode
Laser active medium	Gas	Solid state (crystal)	Semi conductor
Max. output power cw, kw	Up to 50	Up to 5	From 0.06 to > 1 (3)
Efficiency, %	5-10	3-5	30-60
Intensity in focus, W/cm <sup>2</sup>	10 <sup>6</sup> -10 <sup>8</sup>	10 <sup>5</sup> -10 <sup>8</sup>	10 <sup>3</sup> -10 <sup>5</sup>
Wavelength, x1.000 nm	10.6	1.064	~800-900
Size/laser head, cm <sup>3</sup> /W	~200	~20-50	~1
Maintenance, hours	1.000	500 (lamps)	None
Space needed	Very large	Large/medium	Small
Price, \$/W	70	180	70

It was mentioned previously [2, 21] that a number of perspective developments and very positive results have sometimes significantly exceeded users expectation. It makes this technology realistic in the areas of dynamic growing markets such as sensors technology, electronics and micro-system engineering<sup>10</sup>. Current and potential application areas for laser welding technology for various semi-crystalline and amorphous include automotive taillight assemblies, fuel line components, electrical and electronic modules; cell phones housings; medical devices, and connectors (Figures 4, 9-12).

When developing a new part for an automotive application, thermoplastic part designers chose from a variety of fiber reinforcements, fillers & impact modifiers and resin systems. In this case, polyamides are

<sup>10</sup> In general for design of these components and systems, polyamides are not materials of the first choice.

frequently utilized in the design of various under-the-hood plastic, interior and exterior components. Knowledge of the principles of laser welded part design with the influence of material properties, processing, joining technology and end-use conditions is the first requirement for designing the safe parts and assembled products.



Figure 9. Automotive fluid reservoir.



Figure 10. Welded thermoplastic fluid reservoir, which requires an optical transparency.

Table 7. Choice of materials for the design and technology considerations of laser (infrared) welding technologies

Welding Method	Availability of Polyamides/Nylon		
	A – Laser Beam Transparent		B – Laser Absorbing
	Comercial	Experiment.	Comercial
Traditional	+	+	+
Clear-weld	+	+	+ <sup>11</sup>
Non-contact	N/A	N/A	+

As for today, only one project in laser welding technology, for under-the-hood application, was reported in year 2001 to K-show [1]. The reason for laser welding is the complexity of the shape of air intake manifold (AIM) for M3 model of BMW [31]. Base two parts were joined using hot plate technology, and six air channels

<sup>11</sup> Developed by Gentex Corporation.

were laser welded to the base part. Some plastic part designers and manufacturers are infrequently alarmed by the high initial costs of a laser (infrared) welding system and cost of specially colored/tailored laser transparent thermoplastics. The portion of specially tailored thermoplastic costs may be about 20 to 30% greater [2, 21]. Factual cost drivers, however, are the subsequent manufacturing cost that sometime exceed 75% of the part (unit) cost. As we showed previously, through-transmission laser welding offers a lot of additional features, which lead to a cost reduction when this advanced method is used properly with good knowledge of material, design and processing technology (Tables 1-2 and 4).



Figure 11. Plastic air intake manifold (potential “dream application of the author’s” for through-transmission laser welding technology). Legend: A – top part molded from laser transparent polyamide 6 colored in black; B – base part colored by carbon black (laser energy absorber).



Figure 12. Display window of electric power tool (translucent window and colored in black cover, by courtesy Leister Process Technologies).

Here we need to be more accurate because, for example, non-colored (natural – “natural state as molded”) polyamide 6 grades are “laser transparent”. By the calculation presented in [21], the cost of laser welding equipment is greater than other welding technologies (such as spin or hot-plate welding). This cost portion related to “capital spending” is generally small and in most manufacturing cases is less than 5%

of the unit cost (this portion will decrease with the growth of production). Table 7 presents data on materials consideration for laser (infrared) welding technology.

#### POLYAMIDE IS MATERIAL OF CHOICE FOR AUTOMOTIVE APPLICATIONS

Polyamides are widely used in design of various components and laser welding may be applied for manufacturing of some of these parts as well. Commercial PA 6 grades will include fiber-glass reinforced (from 6 wt. % to 63 wt. %), mineral filled (from 10 wt. % to 50 wt. %) and impact modified plastics uncolored (natural) and colored in several types of carbon black and various custom colors. Injection molded Capron®<sup>12</sup>, for welded components, have remarkable high modulus, tensile and flexural strength, fatigue, and creep resistance. The composition of plastics should be adjusted to the basic optical properties needed for welded parts design by laser welding criterion.

The following important *plastic(s) compositions, molding tool, plastic part*, interrelations must be considered at the outset by those specifying a polyamide: PA 6 is a family of related plastics, not just a single composition [26-28]. Reinforced polyamide (with 15–40 wt. % fiberglass reinforcements - GF) is commonly used in design of automotive welded fluid reservoirs, air intake manifolds (AIM'S), etc. Fiberglass reinforced and mineral filled polyamide (25–45 wt. % GF/MF) are used in the design of the welded resonators and various engine covers. Automotive PA specifications include various colored PA grades (black, gray, yellow, red, blue, etc.). The biggest demand is for materials pigmented in black.

Colored polyamide is a high performance semi-crystalline thermoplastic with a number of attractive physical and mechanical properties. Demand for colored plastics for welding applications is increasing dramatically. Coloring of polyamide is a separate area of the plastic development and manufacturing because this pigmentation process may vary from simple to very complex. Both short-term and long-term properties (such as resistance to impact, fatigue, creep, heat aging, etc.) of the welded colored plastics may be affected by colorants. The family of colored fiberglass reinforced or reinforced glass and mineral filled polyamide can be considered, and all of these compositions have the following advantages for welded components:

- Fast overall processing cycles and ejectability (part release from molding tool) is excellent.
- Predictable mold and annealing shrinkage. There's a small tendency for warpage following welding.
- High flow and toughness in thin sections, which has an easy fill of complicated shapes.

- Sufficient knit and weld line strength.
- Good mechanical performance of molded and welded parts after several re-molding/regrind cycles (mechanical property losses are minimal, etc.).

#### BASIC OPTICAL PROPERTIES NEEDED FOR COLORED THERMOPLASTICS SELECTION AND DESIGN OF LASER WELDED COMPONENTS

Optimized design for laser welding requires *key optical properties (transmission, absorption, reflectance)* of thermoplastics developed with the influence of material composition, color version, processing technology and end-use conditions (time, temperature, moisture, etc.).

Laser energy transmittance (in %) is equal to

$$T = 100 \frac{I_t}{I_0} \quad (1)$$

Laser energy reflectance (in %) is equal to

$$R = 100 \frac{I_r}{I_0} \quad (2)$$

Laser energy absorption (in %) is equal to

$$A = 100 \frac{I_0 - I_t - I_r}{I_0} \quad (3)$$

where:  $I_t$  - is the laser beam intensity passing through;  $I_0$  - is the laser beam intensity incident;  $I_r$  - is the laser beam intensity reflection.

Figure 13 presents *kinetic of these three optical properties* with the influence of pigment concentration at wavelength 1,064 nm. The effects of transmission are contrary to the effects of absorption; kinetic of reflection is not significant at evaluated pigment concentration range (from 0% to 0.25%).

<sup>12</sup>Capron® - is a registered trademark for BASF Corporation polyamide based plastic products

## Evaluated Polyamides and Color Versions

For this study, we used three types of commercially available polyamide: PA 6, PA 66, and amorphous polyamide. Several grades and color versions of thermoplastics were evaluated experimentally:

- Non-reinforced /non-filled plastics
- - PA 6 (natural state<sup>13</sup>, various colors including black carbon and non-carbon black )
- PA 66 (*natural state only*)
- blends of amorphous polyamide with PA 6 (three versions of the amorphous polyamide content by weight: 0; 30 and 40 wt. %, *natural state only*).
- Short fiber-glass reinforced plastics:
  - PA 6 with the level of GF from 6 wt. % to 63 wt. %, *natural state, carbon black and non-carbon black*
  - PA 66, with the level of GF from 15 wt. % to 45 wt. % GF (*natural state only*)

ISO multipurpose specimens and rectangular plaques were used for the optical characterization of the evaluated plastics at the following five thicknesses (1.6; 2.0; 3.2; 4.0 and 6.25 mm). In parallel to our investigation, we evaluated and analyzed additionally the published optical data [8-10, 12-14, 17-21] also.

## ANALYSIS OF BASIC OPTICAL PROPERTIES OF POLYAMIDE FOR LASER WELDING

Previously, we discussed the importance of optical properties of plastics at near-IR wavelength for laser welding technologies. Development and analysis of comprehensive optical properties should help designers and technologists in the selection of polyamide for laser welding, parts design, and laser technology optimization.

### Absorption of Laser Energy

At IR spectrum (wavelength), the uncolored plastics (color version – natural state) absorbs a very small portion of laser energy because only overtone- or combination-vibration are simulated. Absorption characteristics of five different colored PA 6 materials (at a wide range of wavelengths from 600 to 1500 nm), were discussed in [6, 21]. Over 20% of the laser energy were absorbed by uncolored (natural state) PA 6 (Figure 14).

<sup>13</sup> For clarification of the “color version” of uncolored thermoplastics, which optical properties were evaluated at “natural state as molded”, we will use the term “natural state”.

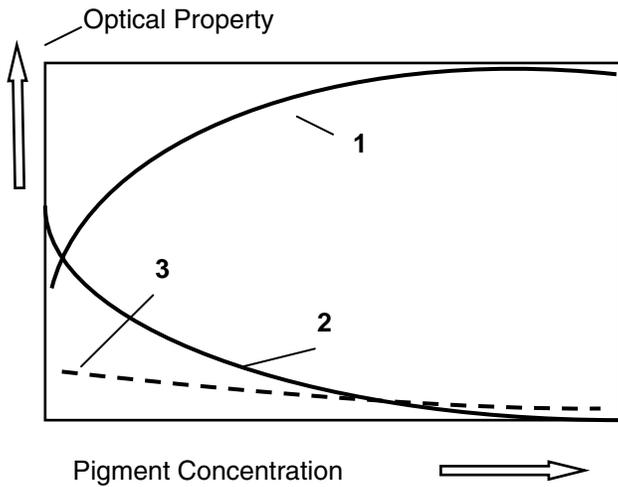


Figure 13. Kinetic of basic optical properties of thermoplastic with pigment concentration. Legend: 1 – absorption; 2 – transmission; 3 – reflection.

Optical testing and evaluation of thermoplastic for laser welding has some similarities with characterization of “optical polymers” and various optical components. Efficiency of non-contact and through-transmission laser welding is strongly dependent on the optical properties of the joined plastic parts and the nature of the laser. In some cases (for an example for “clear welding technology”), we need to take into account additional optical properties of the third substance, which is placed at the area of heat generation for joined surfaces. The following four properties are typical for characterization of optical plastic in design of various optical components and systems for clear-weld technology: - clarity; -haze; - birefringence; - yellowness.

For the laser welding of plastic(s), the following three parameters are very important for modeling and understanding the laser process (through-transmission and non-contact):

1. *Optical properties:*
  - Laser energy transmission ( $T$ )
  - Laser energy absorption ( $A$ )
2. *Plastic(s) composition and material state:*
  - Plastic(s) composition, by wt. % (reinforcement, mineral fillers, impact-modifiers, heat stabilizers)
  - Additive(s) particle shape and sizes
  - Color/pigments (type and content, by wt. %, level of dispersion)
3. *Physical properties (polymer and additives):*
  - Polymer(s) melt point ( $T_m$ ) and crystallization temperature ( $T_{cc}$ )
  - Heat capacity and thermal conductivity
  - Type of microstructure (parameters of crystallinity CI and CSP, etc.)

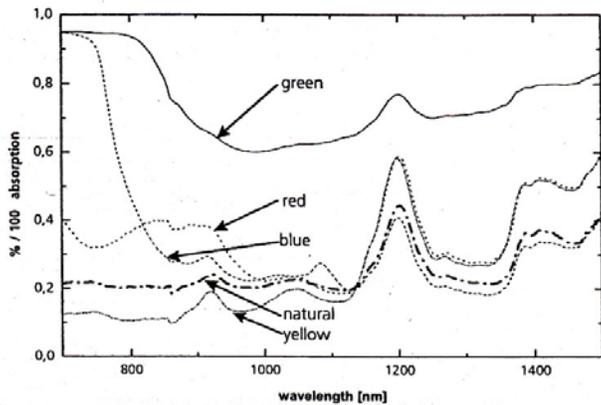


Figure 14. Influence of wavelength on absorption (A) properties for the following versions of colored polyamide: green, red, blue, natural and yellow [21]. Thickness of the specimens is 2 mm.

The additives and pigments may control the absorption properties of the various polyamides. For example, some “green” colorants can increase absorption of polyamide 6 up to 70~80% approximately. The same two green pigments may have the same optical appearance in the visible area, and the absorption in near-IR area will differ very significantly. Many uncolored plastics have a yellow or straw color. This can be seen as a falling-off in the blue area of the light transmission behavior at wavelength  $\approx 400 \text{ nm}$ . A blue toner is added to the polymer to make it appear “as clear”. Both the type of colorants/pigments and the concentration (wt. %) of the colorants play a very important role in the optical properties at near-infrared (near-IR) regions. Fiberglass reinforcement (GF) affects absorption very efficiently; the transmittance is decreasing by  $\approx 2$ -3 times. Absorption increases by 2-3 times for GF range from 15 to 50 wt. % GF (Figure 15). At the same time, for 50-63 wt. % GF polyamide 6, it was observed an increase in *laser energy reflection* from 12% to 31% [5, 19]. Both factors (*absorption and reflection*) will affect the *laser energy transmittance*.

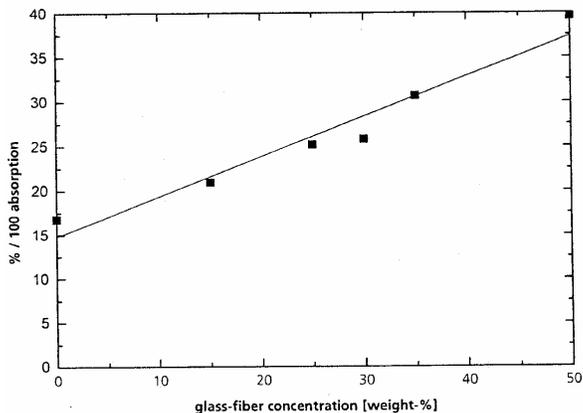


Figure 15. Absorption properties (A) of polyamide with the influence of fiber-glass reinforcement (0-50 wt. GF). Thickness of the specimens is 2 mm. Color version: natural state [21].

## Transmittance of Laser Energy

Some of the published results [5-11, 13, 16, 21] are showing that light transmission of PA may be dramatically reduced by the following additives such as carbon black, pigments, various fillers, reinforcements and foaming agents. Laser energy transmission of semi-crystalline plastics can be reduced also by the increasing the crystallinity and the number of spherulites. The transparency of PA may be increased by the followings two ways: by reducing the crystallization rate and by reducing the spherulitic microstructure.

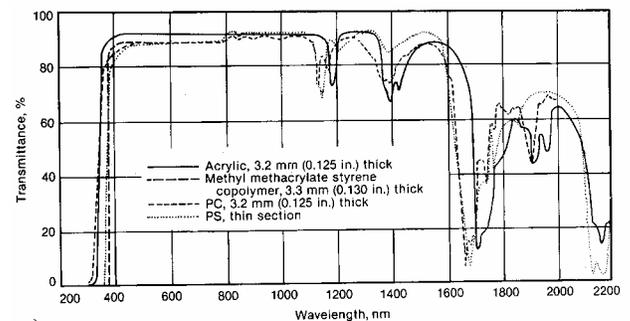
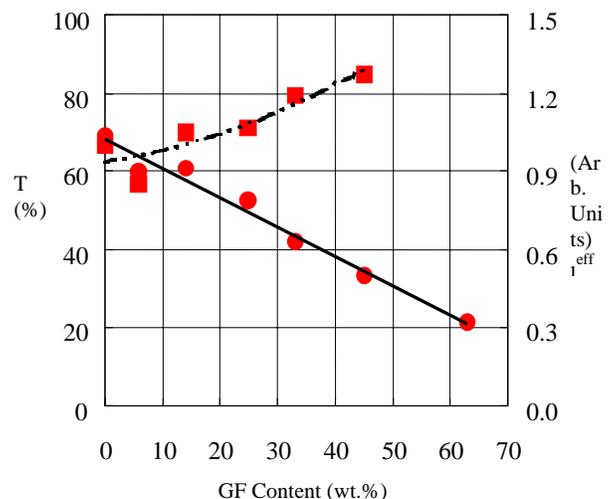


Figure 16. Influence of wavelength on transmittance (T) for optical thermoplastics [28]. Thickness of the specimens is 3.2 mm. Color version: natural state.

The unfilled amorphous PA has the highest light transmission among polyamide  $\sim 86$ -90%, close data was reported [28] for PA 12 ( $\sim 85\%$ ). Highly transmittable optical polymers (amorphous at natural state) are not sensitive to wavelength changes in range from 400 to 1080 nm. The local transmittance *minimum (extremes)* is at 1200, 1400 and 1700 nm approximately (Figure 16). The *maximum transmission* of visible light for optical polymers of any thickness is as follows [27-28]: - un-coated acrylic  $\sim 92\%$ ; - un-coated PC (or PS)  $\sim (89 - 90)\%$ . In the family of various semi-crystalline plastics, a non-filled (non-reinforced) PA has sufficient



transmission properties (Table 8).

Figure 17. Transmittance ( $T$ ) and effective pathlength ( $l_{eff}$ ) at wavelength  $1.06 \mu\text{m}$  of PA 6 with the influence of fiber-glass (GF) content (wt. %). Effective pathlength ( $l_{eff}$ , normalized to 1.0 at 0% GF content). Sample thickness is 3.2 mm. Color version: natural state.

Table 8. Transmission (in %) of laser energy for plastics at various thickness (wavelength =  $1.060 \text{ nm}$ ).

Type of Polymer/Plastic	Thickness = 1 mm	Thickness = 10 mm
PMMA	98.8	88.7
Polyamide (PA)	85.3	20.4
Polyethylene (PE)	80.9	12.1
Polypropylene (PP)	77.1	7.4

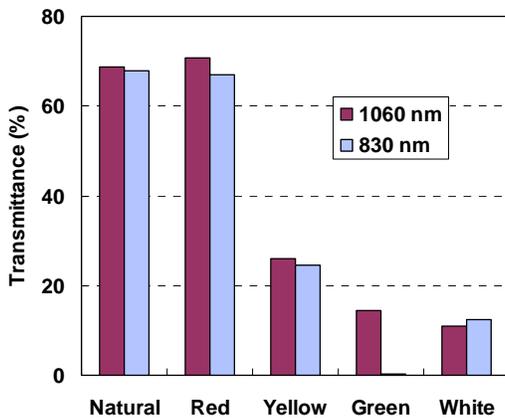


Figure 18. Influence of wavelength on transmittance ( $T$ ) properties for the following versions of colored polyamide. The thickness of the specimens is 3.2 mm.

In the family of various semi-crystalline plastics, a non-filled (non-reinforced) PA has sufficient transmission properties (Table 8). In general, the short fiber-glass reinforced PA 6 (with length of the fibers in average  $\approx 180\text{-}320 \mu\text{m}$  and diameter  $\approx 10\text{-}13 \mu\text{m}$ ), the transmission decreases monotonically with increased short fiber-glass content from 0 to 63 wt. % (Figure 17).

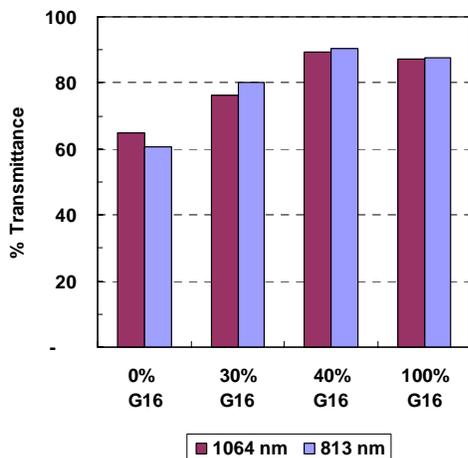


Figure 19. Influence of wavelength on transmittance ( $T$ ) properties for the blends of PA 6 with amorphous PA (Grivory®<sup>14</sup> grade). Thickness of the specimens is 3.2mm. Color version: natural state.

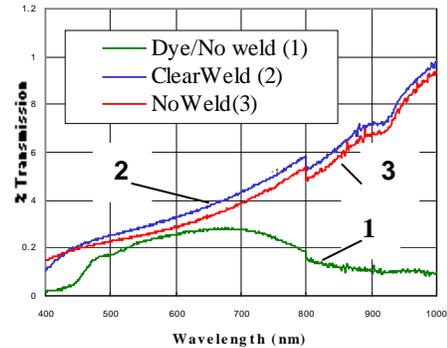


Figure 20. Effects of wavelength on laser on laser transmission for clear welded joints (un-filled PA 6). Wavelength range is from  $400 \text{ nm}$  to  $1000 \text{ nm}$  and transmission range from 0% to 100%.

The similar behavior (influence of fiberglass reinforcements on transmittance) will be typical for PA 66 as well. The decrease in transmission is due to the increase in light scattering. This can be seen in Figure 17, which shows an increase in effective path length {PA absorbency ( $1.39 \mu\text{m}$ )/PA content (wt. %)} as the fiber-glass content increases from 0 to 63 wt. % GF [9, 14].

#### Specific of Laser Energy Transmittance for Clear-Weld

In the case of clear-welding technology, the transmission properties of plastic should satisfy specific needs related to optical performance of end-use application. Figure 20 presents the effects of wavelength on laser transmission for clear welded joints. Wavelength range is from  $400 \text{ nm}$  to  $1000 \text{ nm}$  and transmission range is from 0% to 100%. It is important to note that as results of using special dyes (promoters of local absorbance at future weld area), the transmission of weld is above transmission for the un-welded plastic. Similar effects were observed for fiber-glass reinforced PA.

#### Forward to Laser Welding Process Optimization: Role of Wavelength and Polyamide<sup>15</sup> on Energy Transmittance

Multi-criterion optimization of the mechanical performance of welded joint, produced by through-

<sup>14</sup> Grivory® - is a registered trademark for EMS-CHEMIE AG plastic products.

<sup>15</sup> Produced by various manufacturers

transmission technology, requires managing the following basic processing parameters and materials properties:

- Optical properties of joined thermoplastics with the influence of utilized technology:
  - non-contact laser (infrared) welding
  - through-transmission laser welding (traditional and clear-weld)
- Laser power required for melt-pool formation with the influence of the properties and composition of used thermoplastic(s), joint design (thickness of through-transmissible part **A**) and projected welding time.
- Laser beam focus spot and profile size(s) that correlated to the size of needed width of the weld (melt-pool).
- Melt-pool temperature, which should correlate to type of used thermoplastic(s) and melting point(s) of used plastic(s).
- Welding time and welding speed. Weld time/speed is a function of the first three previously discussed process parameters (laser power, beam spot and melt-pool temperature).
- Welding (clamp) pressure and the thickness of weld inter-phase.

Wavelength is one very important optical property in laser processing technology of colored plastics. Table 9 presents typical wavelength for the base sources of laser energy for welding of thermoplastics. More technical and economical data related to various laser systems are available in Tables 4 and 6. Previously published results on the influence of wavelength on transmittance of various plastics are not consistent, and some of these results are showing an increase in transmittance with wavelength increase, some results are opposite. Below we will discuss the analysis of published results and some of our observations. With decrease of wavelength from 1060 nm to 800 - 830 nm, the transmittance of two colored and natural state non-reinforced/non-filled PA 6 base decreases for white color increased (Figure 18). Transmittance increase effects were observed for blends of amorphous polyamide with PA 6 (Figure 19). With an increase of the amorphous phase in these blends, the transmittance increases up to 25~27%.

Table 9. Typical wavelength for various laser systems.

Parameter	Type of Laser System		
	CO <sub>2</sub>	Nd: YAG	Diode
Wavelength, x1.000 nm	10.6	1.064	~800-900

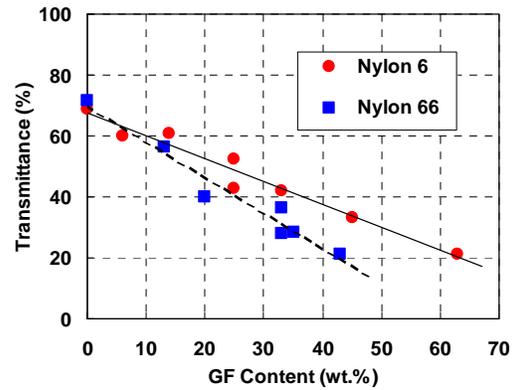


Figure 21. Influence of wavelength (at 830 nm) on transmittance of PA 6 vs. PA 66 based plastics with the influence of fiberglass reinforcement. Thickness of the specimens is 3.2mm. Color version: natural state.

Controversial effects (increasing in transmittance with wavelength increase) were observed for fiberglass reinforced for both evaluated polyamides - PA 6 and PA 66 (Figures 21-22). For optical (PC type) amorphous thermoplastic, the transmission has been unchanged at the 830 to 1064 nm range; the similar results are illustrated by Figure 16 for several optical polymers. At the same time, an increase on wavelength had very little effect on transmittance data. PA 66 is less transmittable (Figures 21-22) in compared with the PA 6 based plastics. This difference increases with high levels of reinforcement (GF ≥ 25 wt. %), and it will affect the level of energy needed for melt-pool preparation and welding time (at the same laser welding parameters).

The type of PA is used in the design of automotive plastic parts depends on the end-use performance, processing technology, etc. There are more than a dozen classes of PA resins, including PA 6, PA 66, etc. Every class has utilized different resins (by molecular weight, extractables, flowability, additives, etc.). Table 10 presents analysis of laser transmission for PA 6 and PA 66 [5, 7, 8-13, 19] with the influence of wavelength and the thickness of specimens.

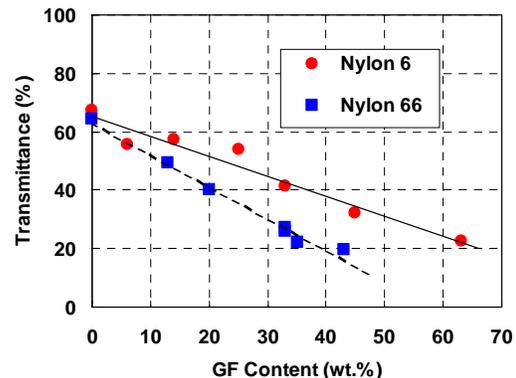


Figure 22. Influence of wavelength (at 1060 nm) on transmittance of PA 6 vs. PA 66 based plastics with the influence of fiberglass reinforcement. Thickness of the specimens is 3.2mm. Color version: natural state.

The range of transmittance with the influence of wavelength is as follow for 30 wt. % reinforced polyamides (thickness of specimen 2.0 mm) is as follows:

- At wavelength equal to 810 – 830 nm:
  - PA 6 - from 31.5% to 51%
  - PA 66 – from 17 to 39.5%
- At wavelength equal to 1064 nm:
  - PA 6 - from 26% to 50%
  - PA 66 – from 15 to 41.5%

Table 10. Laser energy transmission with the influence of type of polyamide and wave-length. Legend: R – experimental data adopted from references; GF – fiberglass reinforcement (in wt.%).

Material			PA 6		PA 66	
R	GF %	T mm	Frequency		Frequency	
			810-830	1064	810-830	1064
11	0	3.2	-	80	-	-
6	0	3.2	64	68	62	-
6	14	3.2	59.5	62	41.5	
26	30	1.6	43	59	35	52
11	30	2.0	51	46	39.5	41.5
11	30	2.0	47	42	34	-
11	30	2.0	34	31	28	22.5
11	30	2.0	31.5	26	17	15
24	30	2.0	39.5	50		
6	33	3.2	29	43		

These results, published by various authors, are confirmed also that PA 66 is less transmittable in compared with the PA 6 based plastics. Accuracy, of some of these results, needs to be discussed with the authors of the investigation. For example, it is a single report, which presented the transmittance of un-filled PA 6 at 80%.

#### CONCLUDING REMARKS ON SPECIFICS OF LASER WELDING AND MATERIALS SELECTION

Laser (infrared) welding of plastics and polymers is a modern joining method with a lot of technological advances for the design and manufacturing of various thermoplastic automotive components.

Recent developments of the high-power diode laser systems and achieved level in process automation make laser (infrared) welding cost effective. Commercial laser welding systems are friendly in-use and cost effective. These systems and technical support is available worldwide from several technology providers. Deep analysis of the specifics of laser (infrared) materials

processing and optical properties of various thermoplastics allow to develop a strategy on materials selection and design for non-contact and through-transmission welding (traditional and clear-weld).

For traditional through-transmission laser welding, the selected plastics should have these different properties:

- one plastic should be through-transmissible
- second plastic should absorb laser energy and provide heating and materials melting at local areas (inter-phase)

For non-contact laser welding, the selected plastic(s) should absorb laser energy and provide heating and material melting at local areas (inter-phase).

Polyamides (PA) are high performance semi-crystalline thermoplastics with a number of very attractive mechanical and technological properties for various laser (infrared) welded automotive plastic parts. Uncolored PA 6 based Capron® grades of plastics, suitable for laser welding, have very high laser through-transmission properties, that leads to improved weldability in various automotive applications.

#### FAMILY OF COLORED BASF CORPORATION<sup>16</sup> FOR LASER WELDING TECHNOLOGY

##### INTRODUCTION REMARKS

Pigments and dyes are different types of colorants. Pigments are incorporated by a dispersion process into the polymer(s), while it is in a liquid phase. A dye dissolves in the polymeric application medium. From a manufacturing point of view, pigments are generally preferred to dyes for the coloration of thermoplastics due of their superior fastness properties, especially migration resistance [26-27]. The main reason for incorporating pigments into plastics is to introduce color, either for aesthetic reasons or because of functional needs, as an example for clear welding. Sometimes, the incorporation of pigments may produce possible problems in thermoplastics, such as the changes of mechanical performance and optical properties (plastics grades colored with carbon black or titanium dioxide - TiO<sub>2</sub> are not suitable for the design of through-transmission part). Pigments are conveniently classified as *organic* or *inorganic*.

<sup>16</sup> In this report we will present data related to laser welding of polyamide/nylon based plastics.



Figure 23. Vibration welded plastic resonator (injection molded from PA 6 colored in black, potential application for through-transmission laser welding technology).

Further important parameters, especially in influencing optical properties of thermoplastics, are particle size and shape, the nature of the particle surface and dispersion. In organic, pigments (titanium dioxide  $\text{TiO}_2$  and carbon black) are usually high refractive index material and highly scattering. In a colorant selected for laser welded thermoplastic parts, the following main reasons related to the nature of near-IR wavelength process should be taken into account:

- Type of proposed laser welding technology (non-contact or through-transmission)
- Requirements of the joined thermoplastic(s) to transmit or absorb laser energy (butt, shear, etc.)
- Optical properties of selected colorants at near-infrared (IR) wavelength

#### ANALYSIS OF OPTICAL PERFORMANCE COLORED POLYAMIDE 6

##### Optical Performance of Un-filled Colored<sup>17</sup> Polyamide

For this evaluation, we used the colored (experimental and commercial available) PA 6 based plastics. Typical mechanical properties of unfilled and fiberglass reinforced PA 6 colored in black (by carbon black) are presented in Table 11. Carbon black colored plastics are typically used for the design of various automotive welding parts when friction or hot tool methods of welded were utilized.

Table 11. Mechanical Properties of PA 6 base plastics (at 23 °C, DAM – dry as molded, colored in black – by carbon black).

Parameter	Fiber-glass content, wt. %		
	0	14	33
Density, gm/ cm <sup>3</sup>	1.13	1.26	1.40
Poisson's Ratio	0.35	0.35	0.35
Tensile Strength, MPa	85.0	134	192
Young Modulus ( $\times 10^3$ ), MPa	3.43	5.96	9.88

<sup>17</sup> Optical performance of colored in black polyamide is discussed separately.

Ultimate Elongation, %	70.0	3.5	3.0
Flexural Strength, MPa	112	180	270
Notched Izod Impact, J/m	55.0	60	115

Transmittance of the following color versions were evaluated (Figure 17) at two wavelengths (830 nm and 1060 nm) typical for high-power diodes: - natural state (as molded); - red; - yellow; - green; - white; - black (carbon black, colorant content is from 0.2 wt. % to 2.0 wt. %) for energy absorbing parts; - black (non carbon black, colorant from 0.25 wt. % to 1.0 wt. %) for energy transmission parts.

All four versions of carbon black (BK) pigmented plastics were found to be un-transmittable for laser energy at the discussed ranges of wavelength [9, 14, 20]. Very low transmittance was found for green and white color version (less than 10%) as well. These plastics may be used for manufacturing of the part **B** (thermoplastics that absorb the laser energy, see Figures 2-4). In general, a high carbon black content (or any other pigment which provide a high absorption constant) may be used in the absorbing part (Figures 9-12, 23). A symmetric/similar temperature distribution and symmetric melt-layers formation can be expected in both thermoplastic parts being welded together applying through-transmission technology.

The details on the influence of a carbon black (BK) on the ratio of the melt-weld (weld inter-phase) thickness for non-reinforced/filled PA 6 as a function of the basic through-transmission laser welding parameters were presented in [16, 21-22]. With the laser scanning rate increase from 4.6 mm/s to 7.7 mm/s carbon black (BK) content of the absorbing plastic part increased from 0.2 wt. % to 1 wt. %. This increase changed the melt thickness ratio ( $L_{A, \text{natural}}/L_{B, \text{BLACK}}$ ) from 0.1 to 1.0 (Figure 24). If the carbon black (BK) 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 ( $L_{A, \text{natural}}$ ) and absorbing/colored ( $L_{B, \text{black}}$ ) plastic parts. Colored in red plastic is highly transmittable (very close to natural state, see Figure 14). The specimens colored in yellow have sufficient transmittance properties (Figures 14 and 18). Colored in blue plastic there should be a transmittance between the red and the natural (Figure 14). Colored in white plastic, there is a very low level of transmittance (Figure 18) at both wavelengths (830 nm and 1060 nm).

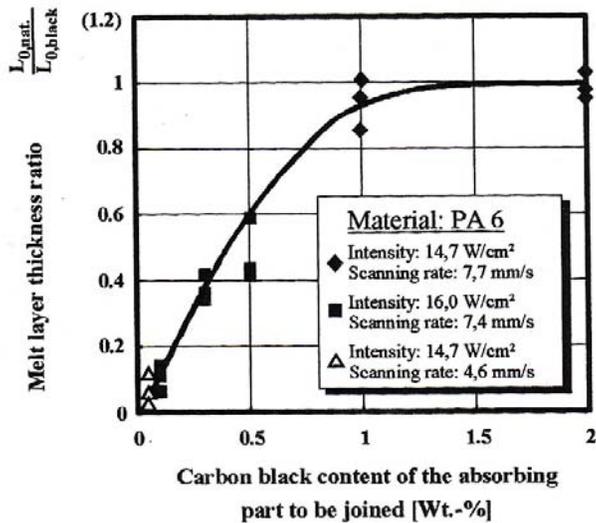


Figure 24. The influence of carbon black content on melt-layers ratio ( $L_{A, \text{natural}} / L_{B, \text{black}}$ ) for polyamide 6 [16].

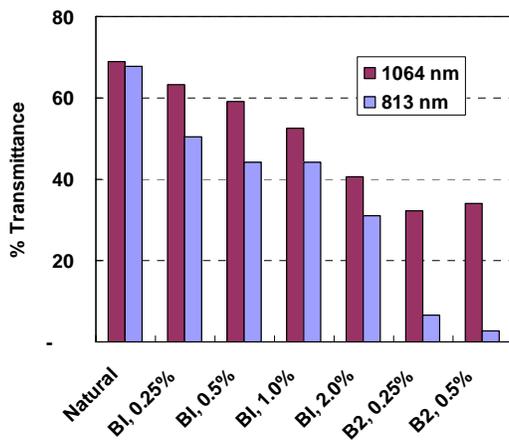


Figure 25. Influence of wavelength (813 and 1064 nm) and the type of colorant and colorant concentration on the transmittance of unfilled PA 6 plastics. Thickness of the specimens is 3.2mm. Color version: Black type B (non-carbon black). B1 and B2 – various versions of used dyes (from “manufacturer 1” and “manufacturer 2”).

Titanium dioxide ( $\text{TiO}_2$ ) is the most important hiding white pigment used in thermoplastics.  $\text{TiO}_2$  will provide a very high degree of opacity and *whiteness* (maximum light scattering with minimum light absorption). We were not able to weld using traditional technology colored in white PA 6 based plastic due to non-ability to deliver needed laser energy at joint area (due to high scattering performance, etc.). In general, the additives and pigments may control the absorption properties of the various polyamides. For example, the same colorants can increase the absorption of polyamide 6 up to 70~80% approximately (for the same thickness of a sample). In addition to the role of pigment content on key optical properties (absorption and transmission), it is

very important to take into account the relation between pigment concentration and depth of laser penetration, which affect to size of melt-pool.

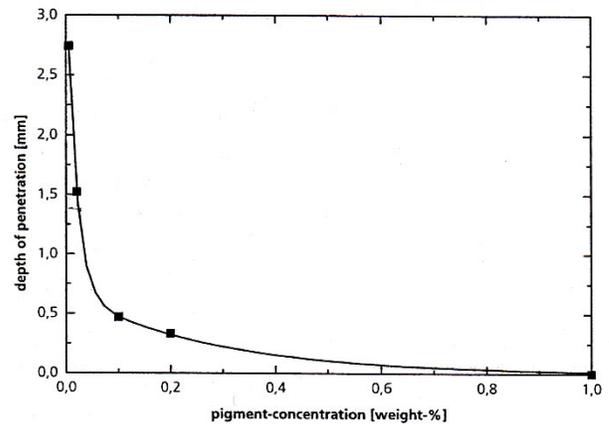


Figure 26. The influence of pigment content on laser energy penetration for polyamide 6. Legend: Thickness of the specimens is 3.2 mm. Color version – green [21].

The analysis of this relation will allow optimize pigment content in thermoplastic (Figure 24). An intensity of color (by optical appearance in the visible area), will influence very significantly on optical properties, such as absorption and transmission in near-IR area (Figures 13-14, 18, 25). All of these results should be applied very carefully for another colored polyamide grades and for amorphous thermoplastics. In [20], were discussed the effects of transmission (absorption) for ABS base colored thermoplastics for non-contact laser (infrared) welding. In summary of this study, the absorption was the strongest for the red samples, weakest for the blue, and decreased as the colors changed from yellow to orange to green. This summary is in some disagreement with some of the results published and developed for polyamides, which are semi-crystalline thermoplastics [Figure 14 and 18]. An efficiency of coloration depends on the type and concentration of the applied pigments (Figure 13, 25-26)

#### Optical Performance of Through-Transmissible Polyamide 6 Plastics Colored in Black (Tailored for Laser Welding)

Coloring/pigmenting in black is very important for many various industrial applications. In general, carbon black is the most important black pigment and is the second most important by the volume of all pigments used in thermoplastic industry [27-28]. Black color is typical for many welded under-the-hood and power train components such as air intake manifolds, resonators, various covers, etc. (Figures 4, 9-12, 23). As a rule, carbon black (BK) pigments exhibit optimized mechanical performance and light fastness at relatively low cost. Properly selected carbon black grades may improve either the electrical conductivity or insulation properties of plastics. Optimized content of carbon black

can maintain temperature profile and thickness of weld-melt from the side of the laser energy absorbing part (B Figures 2-3). For non-contact laser welding (Figure 2), both welded parts (B) may be selected from carbon black (BK) colored plastics, which are non-transmittable, but should be able to absorb laser energy providing material heating and melting at local areas (inter-phase).

Figures 27-28 are showing transmittance data for colored in black un-filled PA 6 plastics (tailored for through-transmission part – laser energy transmitted part A). These PA 6 based plastics are intensively black, and it is very difficult to distinguish them from the similar grades pigmented by carbon black. With the influence of the discussed above requirements, selected thermoplastics for the part A can't be colored using carbon black pigments. We've evaluated an efficiency of three black colorants, which were received from various colorant manufacturers. Presented in Figures 27-28 transmittance data is for *maximum* achieved optical results (*maximum transmittance*) for the part A (to have technical ability to transmit laser energy to the parts, or intimate contact area through thickness of the part A).

approximately four times (in range of thickness from 0.8 mm to 6.25 mm).

Effect of Thickness vs. Concentration on Laser Transmission (813 nm) of Black Colored Plaques

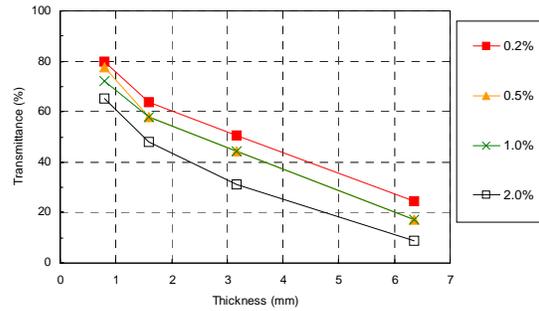


Figure 28. Influence of black pigments content (in wt. %) and thickness of the part (in mm) on laser transmission of un-filled PA 6 colored in black at wavelength 830 nm.

Effect of Thickness vs. Concentration on Laser Transmission (1.06 microns) of Black Colored Plaques

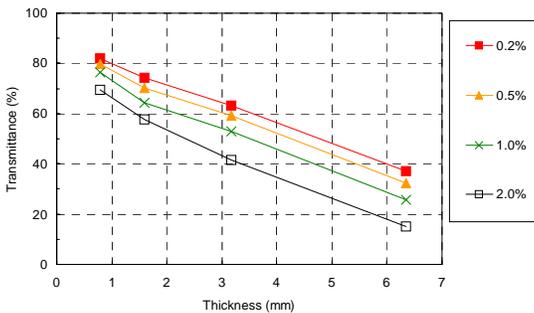


Figure 27. Influence of black pigments content (in wt. %) and thickness of the part (in mm) on laser transmission of un-filled PA 6 colored in black at wavelength 1064 nm. Legend: thickness of the part from 0.8 mm to 6.25 mm; black pigment content from 0.25 wt. % to 2.0 wt. %.

Transmittance data for two grades of fiber-glass-reinforced (14 wt. % and 33 wt. %) PA 6 plastics is presented in Figure 29. With increase of near-infrared wavelength from 830 nm to 1064 nm, transmittance is slightly increasing for both levels of black colorants (0.25 wt. % and 0.5 wt. %). Transmittance of both evaluated PA 6 based plastics was sufficient enough and comparable with the similar data (Figures 17-18, 21-22) developed for natural (non-colored PA 6 and PA 66). The content of the black colorants (0.2 to 2.0 wt. %) negatively affected the transmittance of un-filled PA 6. *Maximum transmittance* was achieved for the lower level of colorant loading (0.2 wt. %). With increase of the thickness of specimens, the transmittance decreases by

These two nylon 6 based fiber-glass reinforced plastics are intensively black, and it is very difficult to distinguish them from the similar grades pigmented by carbon black. The same effects for transmittance were found at evaluated wavelengths (830 nm and 1064 nm). The analysis of the influence of the thickness and wavelength is showing [19] increasing of transmittance for part 2 mm thick (at wavelength range from 830 nm to 1064 nm (Figure 29). At the same time, transmittance of the part 4 mm thick was practically unchanged (for the same range of wavelength). In clear improvement of transmission was observed for all tailored polyamide 6 grades colored for through-transmission parts.

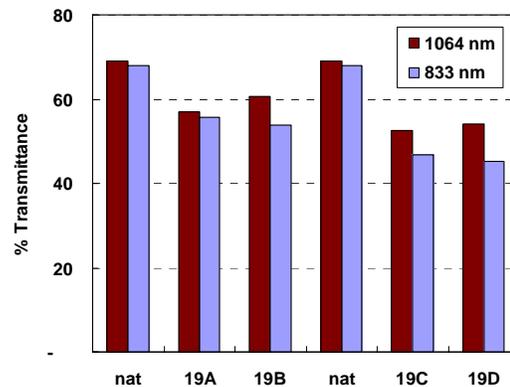


Figure 29. Influence of wavelength (830 and 1064 nm) and fiberglass reinforcement (14 and 33 wt. %) on laser transmission of PA 6 colored in black. Thickness of the specimens is 3.2mm. Color version: black type B (non-carbon black). Legend: plastics series A and B are 14 wt. % GF; plastics series C and D are 33 wt.% GF.

Colored in black PA 6 based Capron® grades through-transmissible plastics suitable for laser welding have

very high laser transmission properties that lead to improved weldability in various automotive applications.

Mechanical Performance of Through-Transmissible Polyamide 6 Plastics Colored in Black (Tailored for Laser Welding)

The following three grades of polyamide 6 (all with heat resistance package – HS) are widely used in various automotive applications:

- PA 6, un-filled (0 wt. % short fiber glass reinforcements).
- PA 6, 14 wt. % short fiber glass reinforced.
- PA 6, 33 wt. % short fiber glass reinforced).

Basic short-term mechanical properties (such as tensile and flexural) needed for plastic parts design of these two nylon 6 grades developed for laser/infra-red welding technologies are presented in Table 12. Used non-carbon black colorants didn't effect the tensile and flexural properties of developed materials. Long-term properties (tensile creep and flexural fatigue) are very similar for non-colored and colored in black (non-carbon black) grades.

Presence of carbon black (BK) in polyamide system may influence (reduce) deformation (ductility) properties and increase strength of these plastics. The similar properties for carbon-black colored grades have been shown in Table 11.

Table 12. Mechanical Properties of fiber-glass reinforced PA 6 (at 23 °C, DAM – dray as molded, specified for the design of laser through-transmission parts – un-colored/natural and black laser transmissible).

Parameter	Color Version		
	GF wt.%	Natural	Black Laser Transmissible
Tensile Strength, MPa	0	82	82.5
	14	128	130
	33	188	190
Young Modulus (x10 <sup>3</sup> ), MPa	0	3.2	3.3
	14	5.6	5.7
	33	9.2	9.6

**MECHANICAL PERFORMANCE OF WELDED POLYAMIDE**

For the base investigation on the efficiency of through-transmission (traditional and clear-weld) technology on mechanical performance of the welded joints, we used specially designed T-shaped (Figure 30). This T-shaped butt joint is very similar (by sizes and shape) to design practices utilized for automotive welded plastic parts such as:

- Fluid reservoirs (Figures 9-10)
- Air intake manifolds (Figure 11)

- Resonators (Figure 23)

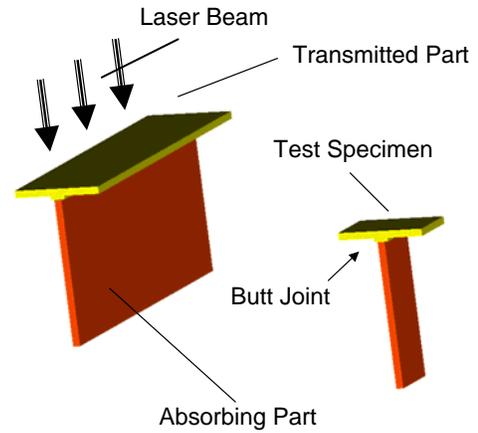


Figure 30. T-type butt joint for the through- transmission laser welding of polyamide

All tensile tests of welded specimens were conducted at room temperature (23°C) in air by ISO requirements. Tables 13-14 summarizes the results of the tensile strength of short fiberglass reinforced polyamide 6 based plastics and welded joints from frictional (linear vibration welding), and the through-transmission welding technologies of T-shaped specimens were performed using previously optimized laser welding processing conditions [9, 17??].

Table 13. Efficiency of traditional through-transmission laser welding for polyamide 6. Legend: The tensile strength (in MPa, at 23°C, Dry As Molded - DAM) for linear vibration and laser welded butt joints.

Wt. %, GF	Tensile Strength (MPa)		
	Thermoplastic	Vibration Welding	Laser Welding
0	82.0	81.0	≥ 82
14	125	90.7	78.3
33	185	83.6	79.4

Table 14. Efficiency of clear welding technology for polyamide 6 grades (at optimized processing conditions).

Wt. %, GF	Tensile Strength of Weld, MPa		
	Clear-weld	Ultrasonic <sup>18</sup>	Hot plate
0	≥ 82	37	82
14	84.3	34	83
33	83.7	32	83

Colored plastics show a sufficient mechanical performance for linear vibration welding technology and the similar results are expected for the through-transmission laser welding. It was found that the

<sup>18</sup> AWS (American Welding Society) specimens with a large energy director.

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

In regards to thermoplastic components welded from PA 6 based plastics, all of these technologies (including laser transmission) are three times more efficient than ultrasonic welding [17, 20].

#### CONCLUDING REMARKS ON ADVANTAGES OF FAMILY BASF CORPORATION TAILORED FOR LASER WELDING TECHNOLOGY

Colored PA 6 based Capron® grades of plastics, suitable for laser welding, have high laser transmission properties that lead to an improved weldability. Developed family of colored PA 6 plastics (un-filled and fiberglass reinforced) have enriched mechanical and technological properties (and may be successfully used for laser welding technologies such as through-transmission (traditional and clear-weld) non-contact.

#### CONCLUSIONS

Laser/infrared welding of plastics and polymers is a modern joining method with many technological advances for design and manufacturing of various automotive components. Recent developments of the high-power diode laser systems and achieved level in process automation make laser/infrared welding cost effective. It makes this technology more realistic at the current and future in various areas of dynamic growing markets.

Colored polyamides/polyamides are high performance semi-crystalline thermoplastics with a number of very attractive mechanical and technological properties for various welded automotive plastic parts.

Developed family of colored polyamide 6 based plastics (un-filled and fiberglass reinforced) have enriched mechanical and technological properties (and may be successfully used for laser welding technologies such as through-transmission (traditional and clear-weld) non-contact.

Selection of thermoplastics for infra-red/laser welding technology from commercially available and experimental grades, depends on the nature of the applied method, material structural (composition), various additives, color version of the joined thermoplastics, and coloring technology used:

Developed results and recommendations will help automotive parts designers, technologist and material developers, in the selection of polyamides for infra-red/laser technology, welded parts design, and laser welding technology optimization.

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## KEY WORDS

Polyamide, nylon, thermoplastic, laser, infra-red, optical, mechanical, strength, reinforcements, welding, joining, fiber-glass, optimization.

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