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Study of Weldability Utilizing Laser Welding for Thermoplastics Modified with Different Additives with Respect to Production Requirement of Injection Moulding

Master thesis

Study programme: N2301- Mechanical Engineering

Study branch: 2301T048 – Engineering Technology and Materials

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Liberec 2018

Technical University of Liberec
Faculty of Mechanical Engineering
Academic year: **2017/2018**

DIPLOMA THESIS ASSIGNMENT

(PROJECT, ART WORK, ART PERFORMANCE)

First name and surname:	**Devang Kanaiyalal Prajapati**
Study program:	**N2301 Mechanical Engineering**
Identification number:	**S15000591**
Specialization:	**Engineering Technology and Materiales**
Topic name:	**Study of weldability of thermoplastic polymers modified with different additives by laser welding**
Assigning department:	**Department of Engineering Technology**

Rules for elaboration:

1. Overview of laser welding techniques. Principles, advantages, disadvantages. Influence of process parameters and material composition on quality of joints.
2. Study of laser welding process in company Magna Exteriors (Bohemia) s.r.o. Proposal of functional tests.
3. Realization of functional tests for chosen materials and adjusted parameters.
4. Evaluation of measurement.
5. Conclusions.

Scope of graphic works: **tables, graphs**

Scope of work report
(scope of dissertation): **approx. 50 p.**

Form of dissertation elaboration: **printed/electronical**

Language of dissertation elaboration: **English**

List of specialized literature:

[1] KLEIN, R. *Laser Welding of Plastic.* **2nd Edition, Published by: Wiley-VCH Verlag& Co. KGaA, Weinheim, Germany, 2011. p. 251. ISBN 978-3-527-40972-3.**
[2] TROUGHTON, M. *Handbook of Plastic Joining.* **2nd Edition, Published by: William Andrew, Nowich, USA, 2008. p. 590. ISBN 978-0-8155-1581-4.**
[3] KATAYAMA, S. *Handbook of Laser Welding Technologies.* **Published by: William Andrew, Nowich, USA, 2013.p. 632.ISBN 978-0-8155-1581-4.**
[4] DAWES, C. *Laser Welding.* **Published by: Abington Publishing, Cambridge, England, 1992. p. 261. ISBN 1 85573 034 0.**

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Date of dissertation assignment: **1 November 2017**

Date of dissertation submission: **1 February 2019**

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Liberec, dated: 1 November 2017

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Annotation:

The work deals with laser welding of polypropylene (PP) matrix based samples with or without chosen additives (carbon black and glass fibre) and investigation of the overall effect on weldability. Furthermore, it evaluates how additives addition affected mechanical properties of welded joints. All the samples were produced by injection moulding technology. Once the samples were welded, they were subjected to tensile testing.

The main challenge was to find appropriate process parameters (laser power and velocity) of the laser machine, so that good weld quality (visual and mechanical) can be achieved. The achieved result shows the impact of carbon black and glass fibre on the weldability.

Keywords:

through transmission laser welding, polypropylene, carbon black, glass fibre.

Acknowledgement:

Foremost, I would like to say special thanks to my honourable professor Ing. Pavel Brdlik PhD. because, he never stopped believing in me during this whole experimentation period. Though there were some obstacles came while experimenting, he was always beside me. So I would like to express my deep gratitude for his generous support.

Besides, it is my privilege to mention the name of my in-charge and supervisor from company Magna, 'Mr. Ondřej Liška'. I would like to thank him for his patience, motivation, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis.

Next, I feel quite grateful and proud to have such a wonderful family. For finishing this thesis successfully, only one sentence from my parents was enough for me: "We are always with you no matter whatever happens". That worked as an unending fuel for me.

I genuinely would like to express my gratitude towards the GOD. I think without his/her blessings and grace, it would not be possible to accomplish my work.

Last but not least, I would like to thank my fellows, who had given me some useful advises: Rushabh Patel, Hardik Prajapati, Anand Bharucha, Nirav Sailor, Rakesh Soni.

This publication was written at the Technical University of Liberec as part of the Student Grant Contest "SGS 21122" with the support of the Specified University Research Grant, as provided by the Ministry of Education, Youth and Sport of the Czech Republic in the year 2018.

Contents

List of abbreviations and symbols

NIR	Near Infrared Region
TTLW	Through Transmission Laser Welding
DC	Direct Current
Nd: YAG laser	Neodymium-*Doped* Yttrium Aluminium Garnet
GaAlAs	Gallium Aluminium Arsenide
GaAsP	Gallium Arsenide Phosphorous
InGaAsP	Indium Gallium Arsenide Phosphorus
α	Amount of absorbed rays
δ	Amount of reflected rays
Υ	Amount of transmitted rays
α_1	Polar surface free energy of material 1
α_2	Polar surface free energy of material 2
Υ_1	Heat expansion co-efficient of material 1 under constant pressure
Υ_2	Heat expansion co-efficient of material 2 under constant pressure
K^+	Scattering constant
N	Number of scattering crystalline phases;
V	Volume of crystalline phases
Λ	Wavelength of radiation
N	Number of scattering crystalline phases
ϱ	Cross-section of scattering particle
PMMA	Poly(Methyl Meth-Acrylate)
PVC	Polyvinylchloride
ABS	Acrylonitrile Butadiene Styrene
HDPE	High Density Polyethylene
PS	Polystyrene
PP	Polypropylene
PA	Polyamide
PC	Polycarbonate
UV	Ultra Violate
ITO	Nano-Indium Tin Oxide
NC	Numerical Control
CNC	Computer Numerical Control
MFI	Melt Flow Index
GF	Glass Fibre
CB	Carbon Black

TP	Transparent Part
AP	Absorption Part
Yb: Fibre	Ytterbium Fibre
CO_2	Carbon dioxide
E_1 and E_2	Energy levels of photon
h	Plank constant
v	Angular frequency
TiO_2	Titanium oxide
SnO_2	Tin oxide

1. Introduction

Manufacturing of plastic parts and their application is continuously growing in all industries. Sometimes the production of complex geometry becomes complicated therefore, it is necessary to make the component in two parts and then join those two plastic parts using conventional methods (hot gas welding, extrusion welding) or non-conventional methods (ultrasonic welding, laser welding). Welding using light sources have been developing rapidly in last 50 years and it is still inclined to new benchmarks and developments. After its inclusion into the industry, conventional joining methods were mostly replaced by these methods because these methods are suitable for mass production [1]. Laser welding method is one of these methods. Laser welding process and its use were initially demonstrated in 1970's. During this period, there was only one laser welding process used, which was direct laser welding by CO_2 laser [1], [2]. Afterward, in 1985, another laser welding method was patented by Toyota, Japan. They welded two plastic parts with a near infrared laser (NIR), which was Nd:YAG laser. This method was named through transmission laser welding (TTLW) [2]. The first TTLW method was patented by using carbon black, as an additive to change the absorption properties of the absorptive part. From 1990, the usage of laser welding as a joining method had already started to increase day by day and in the current scenario, it is one of the most versatile methods for joining two plastic parts. Nowadays, the development is inclined towards increasing weldability of different thermoplastics, so that can be easily welded. If carbon black is applied on the absorptive part as an additive for increasing absorption, the colour of the absorptive part could be changed. So this is the problem of using carbon black as an additive. But still, there is an advantage of using carbon black as an additive because it could evoke the change in the laser welding's process parameters (decrease in the power or increase in the velocity). Laser welding is commonly applied, where the part geometry is flat and easily weldable. But it is difficult to weld uneven geometry rather than a flat one. TTLW is applicable in many fields, like automotive, medical and consumer goods packaging. In the automotive sector, it is used for welding of head and tail light, under hood components and instrument panels [4]. Before laser welding, for joining head and tail lights, hot plate welding was used. But hot plate welding was prone to flash generation in between and caused internal stress also. For these reasons, hot plate welding was replaced with laser welding [5].

In this thesis, the main focus of work was on how to increase the weldability of thermoplastic parts of different thicknesses by using some kind of additives (carbon black, glass fibre). It was also important to figure out how these different additives form the mechanical bonding between specimens. Then, the mechanical quality of weld joint was measured with the tensile testing machine.

2. Theoretical part

Laser welding is one of the most versatile joining methods, which could be utilized for joining a wider range of plastic products. The product thickness can vary from very low (film sheets of 0.01 – 0.1 mm) to a very high thickness (50 mm). Laser welding technique possesses characteristics of high accuracy, high precision and lower distortion, which leads to better performance of components and high weld quality. For keeping high tolerance in the components, generation of laser beam plays a consequential role. So the spot size of laser beam should be very small. Normal white lights produce incoherent beam (figure 1), which results in wider spot size. On the contrary, it is important for laser resonator to create a particular coherent laser beam [6]. For the creation of coherent laser beam, some amount of excitation in the energy state of atoms or electrons is the key thing.

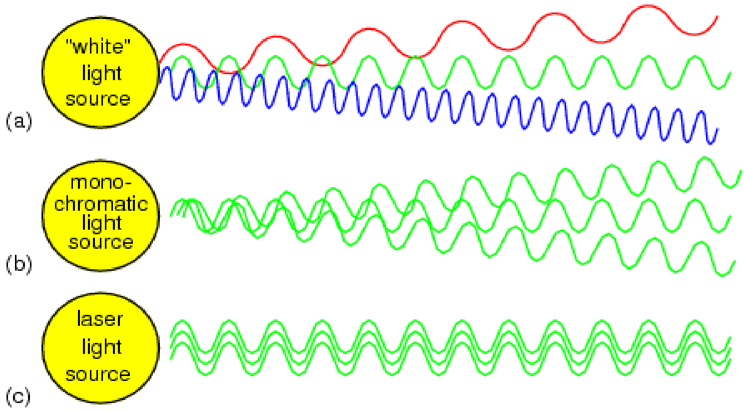

Figure 1 Coherency of laser light [7]

All the molecules and atoms have a certain amount of energy states and energy levels. Amongst them, electrons could peregrinate through these energy levels and transmit their gained energy in terms of photons. For the generation of photons, electrons must travel to and fro from ground level to excited level and vice-versa (figure 2). Predominantly, the electrons lie in the ground state under normal condition. But if the electron is in exhilarated condition somehow with an energy E_2, it could go to the ground level all of a sudden and reduce its energy level to E_1 (figure 2). During reducing the energy level from E_2 to E_1, it liberates photon. This process is called spontaneous emission and this will exhibit fluorescence light [8], [9]. Energy produced by this emission will be:

$$E_2 - E_1 = h\nu; \qquad (1)$$

Where, $E_2 - E_1$ = Energy of photon (J);

h = plank constant = 6.62×10^{-34} (m^2 * kg / s);

ν = angular frequency (rad/s).

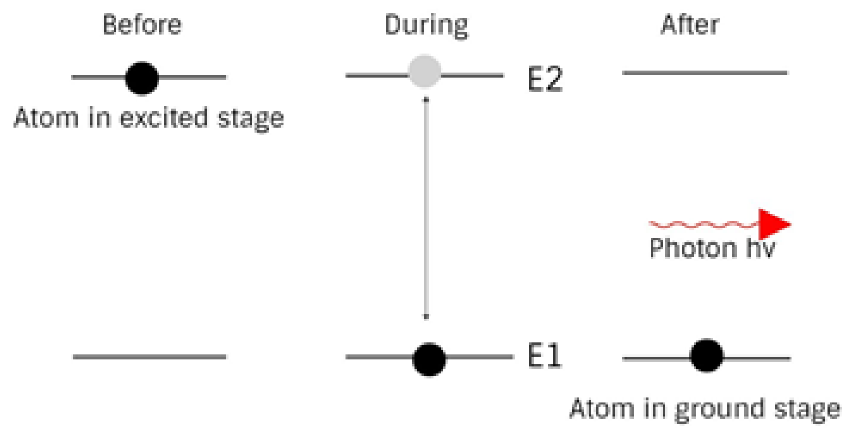

Figure 2 Spontaneous emission

When the electron is at the excited state with energy E_2 and photon is imparted on it from outside source, the electron will relinquish the energy in terms of another photon. Thus, there will be two photons engendered: one is being imparted by photon and another is in pursuance of released energy by an electron. Both of these photons have the same frequency, the identical direction of polarization and homogeneous direction of propagation (figure 3). This process of photons generation is called stimulated emission because the atoms will absorb the incident energy [8], [9]. This is how all the generated photons will be coherent and this is the crucial property needed for the laser to be amplified.

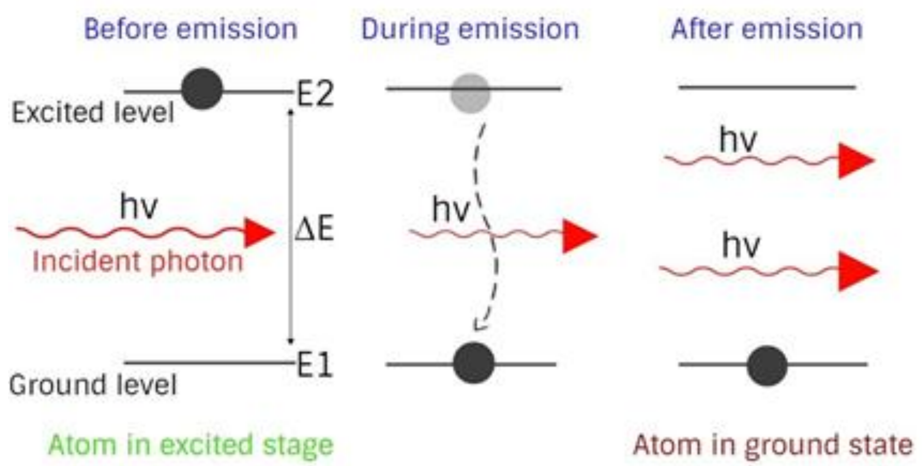

Figure 3 Stimulated emission

Generation of laser beam requires one optical resonator (laser cavity) and one laser gain medium. Laser cavity is comprised of two mirrors from which the laser could be polarized (figure 4). Laser gain medium is made of a laser crystal (pumping source) which is needed for the amplification of laser [8]–[10]. Laser crystal works as a pump so that it can amplify laser (figure 4).

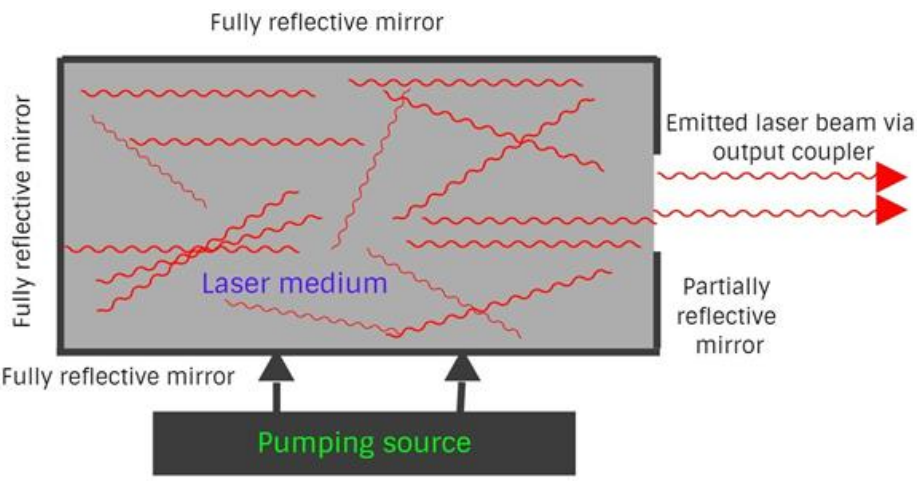

Figure 4 Laser generation device

There are different kind of lasers, which are currently used in practice. Laser generation principle remains kindred for all of them. The only difference between them lies in the place that they use distinct laser pumping sources and active medium [4], [10]. Variants of lasers, which are used in industries are described briefly below:

- **CO_2 laser**

CO_2 laser is effective for generating beam wavelength at about 10,600 nm. The CO_2 laser generator composed of a glass tube with gas inlet and outlet (figure 5). In a glass tube, the gas mixture of nitrogen, helium and carbon dioxide (the highest content) is used. For electrical DC discharge, the tube has anode and cathode locale. The glass tube is sealed off from atmospheric pressure by two Zn-Se windows, which are transparent to CO_2 laser radiation. At the point when the release is occurring between anode and cathode, the coalescence of all of the gases is streamed as a laminar flow [4].

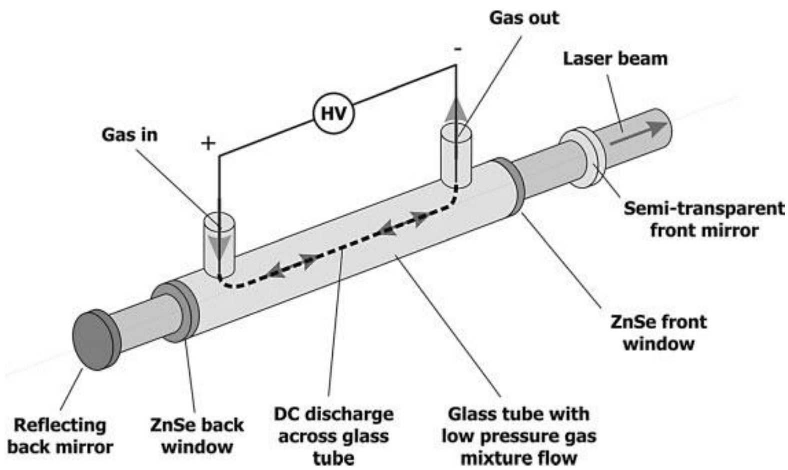

Figure 5 CO_2 laser construction [4]

When the laser power is switched on, it causes electrical discharge amongst anode and cathode. By this phenomena, nitrogen molecules start to vibrate and activate their energy by linear molecular oscillation. These activated nitrogen particles then collide with carbon dioxide molecules, transferring their activation energy to CO_2 particles. Now, these excited CO_2 molecules lower their energy by emission of photon with wavelength of 10,600 nm. After emission of photon, CO_2 particles strike with helium particles and goes to the ground energy level, again getting ready to collide with nitrogen particles. Generated laser could only pass through the semi-transparent front mirror, as the back mirror is consummately opaque. The laser power generated by this system could reach upto 500 W. As the generated power is quite high, the penetration depth of laser beam in material is very low (10 – 100 μm). For this reason, CO_2 laser could not be utilized for thick plastic welding. It is applicable only for joining of thin thermoplastic films [4].

- **Nd:YAG laser**

Nd:YAG is a neodymium-doped Yttrium aluminium garnet solid state laser. Nd:YAG laser commonly produces laser light radiation at 1064 nm wavelength, which comes under near-infrared region (NIR). Some of the Nd:YAG lasers could also deliver laser at some extraordinary wavelengths like 1440 nm, 1320 nm, 1120 nm and 940 nm [11], [12]. The working principle of Nd:YAG laser is demonstrated in Figure 6. Nd:YAG laser rod is placed between two pumping sources in double elliptical cavity. This elliptical cavity is polished like a mirror. Pumping lamps aid to engender photons. These generated photons then target on the Nd:YAG laser rod for amplification. Once these photons are amplified, they are converted into coherent laser beam [4].

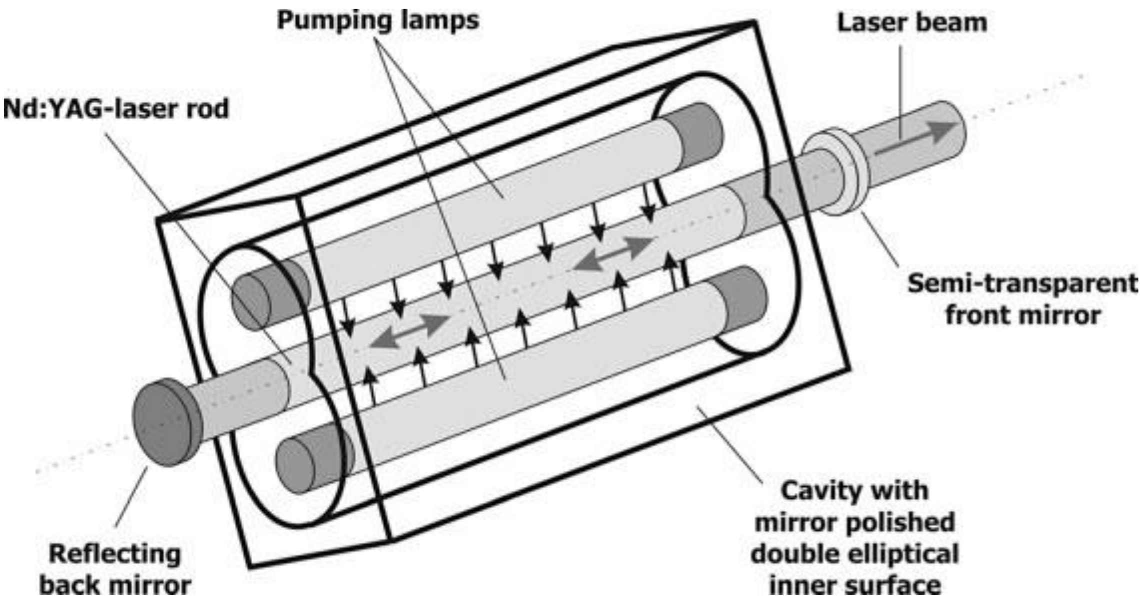

Figure 6 Nd:YAG laser schematic diagram [4]

Before this generated laser beam perforates the parts, it has to travel between two mirrors (figure 6). Both of these mirrors are coated with silver colour. One of the mirrors is thoroughly silvered, while another is partially coloured. The fully coloured mirror will reflect the laser radiation completely. While another mirror, which is partly coloured, will reflect some amount radiation to the target material [4], [7].

Above mentioned lamp pumped Nd:YAG laser has a drawback of poor electrical efficiency (< 4%). Due to low efficiency, any further developments in Nd:YAG lasers had been ceased. Now, the progress is slanted towards the laser diode pumped YAG lasers, which is competent to generate power up to 6-10 kW [2]. Contrasted with a CO_2 laser, Nd:YAG laser has capacity to penetrate deeper in materials, as it can generate lower wavelength (1064 nm). Except for plastic production, Nd:YAG laser could also be used for engraving, etching and welding of metals in medical, aerospace and many else industries [13], [14].

- **Diode laser**

Diode lasers are the most used laser source these days. The root cause behind prodigious applicability of diode laser is that, it could operate in wavelength range from 800 to 2000 nm. Diode laser generates laser power from mW to several kW. For joining plastic components, commonly used diode laser wavelengths are 808 nm, 940 nm and 980 nm since plastic welding with longer wavelength is being investigated [4]. Generation of wavelength depends on the utilized semi-conductors materials (GaAlAs, GaAsP or InGaAsP), which works as an active medium for diode laser.

Diode laser construction contains several diode stacks placed upon each other, as shown in figure 7. Each of the diode bars comprised of their own laser resonator. Laser radiation generated by them is passed through micro-optics to cylindrical and spherical lenses. The shape of the generated laser depends on the arrangement of the micro lenses [4].

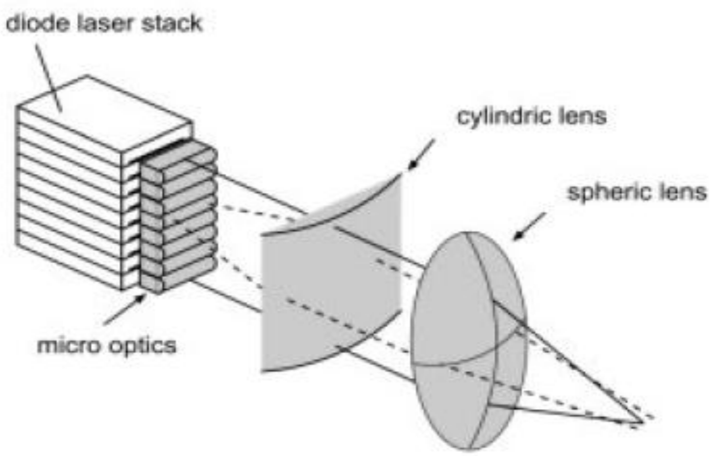

Figure 7 Diode laser generation [4]

For emission of laser with various wavelengths, an electric current must be directly applied to the diodes. Laser generated by diode has lower beam quality than other laser sources like Nd:YAG or fibre laser. This could result in weak spot size on the material. On the contrary, diode laser has lower purchase and running cost, which are noticeable reasons to surmount the problem of lower beam quality [1], [4].

Taking heat into consideration, diode laser is proficient of generating local heat input to the material, which warm ups the part within short time period. Due to this propriety, diode laser source is used for welding plastic products in the fields of packaging, electronics and automotive industries [15]–[17].

- **Fibre laser**

Fibre laser source is capable of generating wavelengths in the range of 1000 – 2100 nm (relies on the utilized active medium). For welding of plastic parts, most used wavelength in industries is proximately about 1100 nm, as it could facilely replace Nd:YAG laser source (1064 nm). Fibre laser has quite similar beam quality as Nd:YAG laser, however it has eminently higher electrical efficiency (up to 30%), which is approximately 7 times higher than Nd:YAG laser source [1], [4].

Fibre laser unit is comprised of glass fibre with very small diameter, which is doped with silica core. This doped silica core works as an active medium for laser generation. Silica core is cladded with two layers: one layer works as waveguide for optical pumping, while another layer ascertains the total reflection of the optical radiation. For optical pumping, diode laser source is directly connected to silica cladding of glass fibre. Now the generated optical radiation will travel along the length of glass fibre for generating laser radiation. For laser radiation pumping, two types of setups could be used (figure 8). End pump configuration has a diode laser directly connected to one of the cessations of glass fibre. Another type is fibre pump configuration, which uses plenty of fibre coupled diode lasers. These in-coupling fibre guides are connected to the cladding of the glass fibre. These fibre guides directly transfer pumping radiation into the cladding [4].

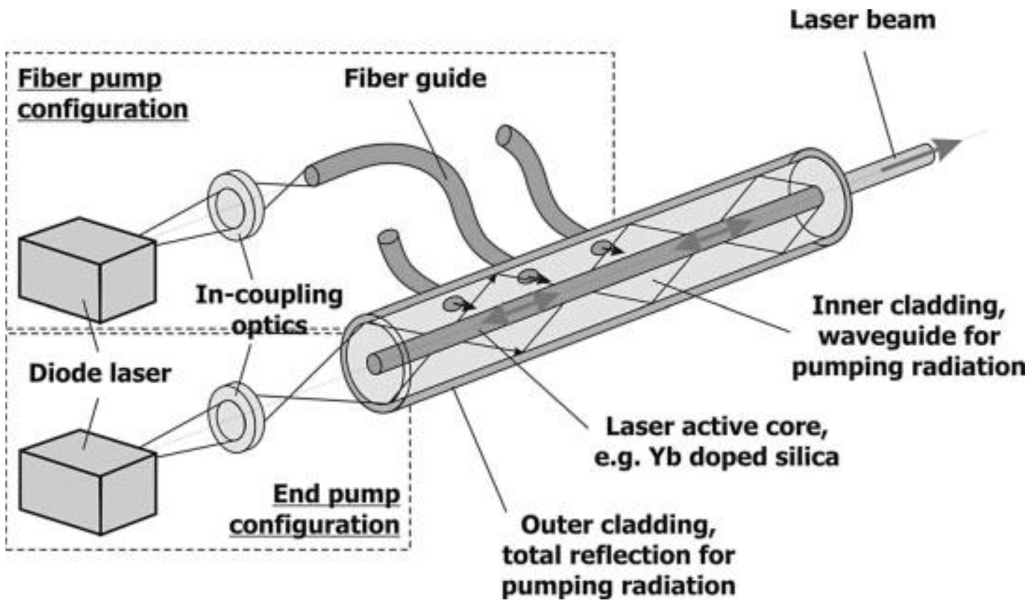

Figure 8 Fibre laser diagram [4]

For joining the plastic materials, usage of fibre laser is continuously increasing due to its high efficiency. Fibre laser is used for very precision welding, thin film joining, large parts and textiles [1].

2.1. Factors affecting laser welding

At the point when a beam of laser strikes on a surface of any products, it has a characteristic tendency to behave in a three ways. The ray could either being absorbed, transmitted or reflected [1]. Corresponding absorption quantity could be counted by following equation [4]:

$$\alpha + \delta + \Upsilon = 100; \quad (2)$$

α = amount of absorbed rays (%);

δ = amount of reflected rays (%);

Υ = amount of transmitted rays (%).

These characteristics are dependent on the several factors [1], [2]:

- Laser wavelength λ;
- Laser beam intensity;
- Clamping pressure;
- Welding time or rate of the laser beam movement.

Laser beam intensity is directly proportional to the generated thermal energy (temperature). If the temperature of a laser beam is sufficiently high then the material at interface could melt effortlessly. Therefore high intensity laser beam could expeditiously cover the entire part geometry. But if the temperature is excessively high, then there could be an issue of material's thermal degradation. On the other hand, if the beam intensity or temperature is too low, then it could be the reason of very low welding productivity, lower weld quality or sometimes even the weld will not be generated. Likewise, if the applied clamping pressure is much higher, then there could be a stoppage of chain dispersion, which could decrease the quality of joints [1]. Despite of this, if the pressure is too low, it could create air gaps, which results in deficient surface wetting. Weld time has nearly similar effect as of the temperature [1], [2]. If the temperature of a laser beam is high, then it takes less time to pass through entire geometry, as the part would be heated rapidly. While if the temperature of laser beam is low, then the interface between two parts would take a longer time to melt. It outcomes in longer weld time. Absorption and transmission of the beam in the material are vigorously affected by wavelength of laser beam, which could affect the weldability. According to this beam wavelength, radiation could be divided into two parts:

- **Short wavelength radiation**: This wavelength is lesser than 350 nm, which comes under ultraviolet beam region. In this radiation region, imparted photon energy is quite high, so that it directly breaks the chemical bonds present in the material. This process is known as photolytic process. For this reason, this beam could be utilized for ablation or for chemically curing the material [1].
- **Long wavelength radiation**: This wavelength is higher than 350 nm and it comes in the infrared region (CO_2 laser, fibre laser). As the radiated wavelength is high, it raises the temperature quickly, which directly involves heating of the surface. This process is known as pyrolytic process. This wavelength interaction causes heat (higher surface absorption and lower transmission) in the material surface so, it is utilized for melting or welding of parts [1].

According to optical characteristics and wavelength of laser beam, laser welding of polymers is divided in two parts: Direct laser welding and through transmission laser welding (TTLW).

2.2. Direct laser welding

The principle of direct laser welding technique is transformation of laser energy on surface of joining parts to heat and creation of ample pressure to join them. Direct laser welding technique could use beam wavelength in range of 2000 – 10,600 nm. The higher efficiency of laser energy transition to surface of material will be achieved by higher applied wavelength. Consequently, the common wavelength used in technical application is 10,600 nm. In direct laser welding, CO_2 laser, fibre laser or Holmium YAG laser could be applied. The CO_2 lasers operate at higher wavelengths than fibre laser or Holmium YAG laser. Therefore it has potential for wider use. Due to low heat conductivity of plastic materials the absorbed heat energy cannot penetrate deeper into material. This is reason why direct laser welding techniques is applicable only to thin thermoplastics like films and sheets [4]. The example of principle the thin film direct laser welding technique is shown in the figure 9.

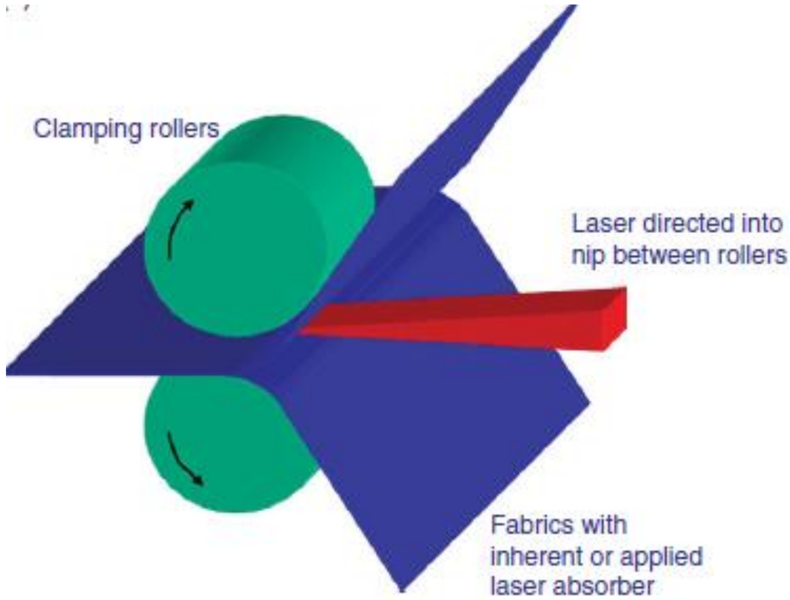

Figure 9 Direct laser welding [2]

At early stages, butt welding of two thick plastic components was performed by using CO_2 laser source. Rather than applying laser beam directly on the surface, one special type of beam bending mirror is used to turn the laser beam on surface (figure 10). When the laser beam heats the surface sufficiently, mirror is taken out and both parts are pressed together to compose a consistent joint. This method was not able to make a colossal impact in industries because of high investment cost [4].

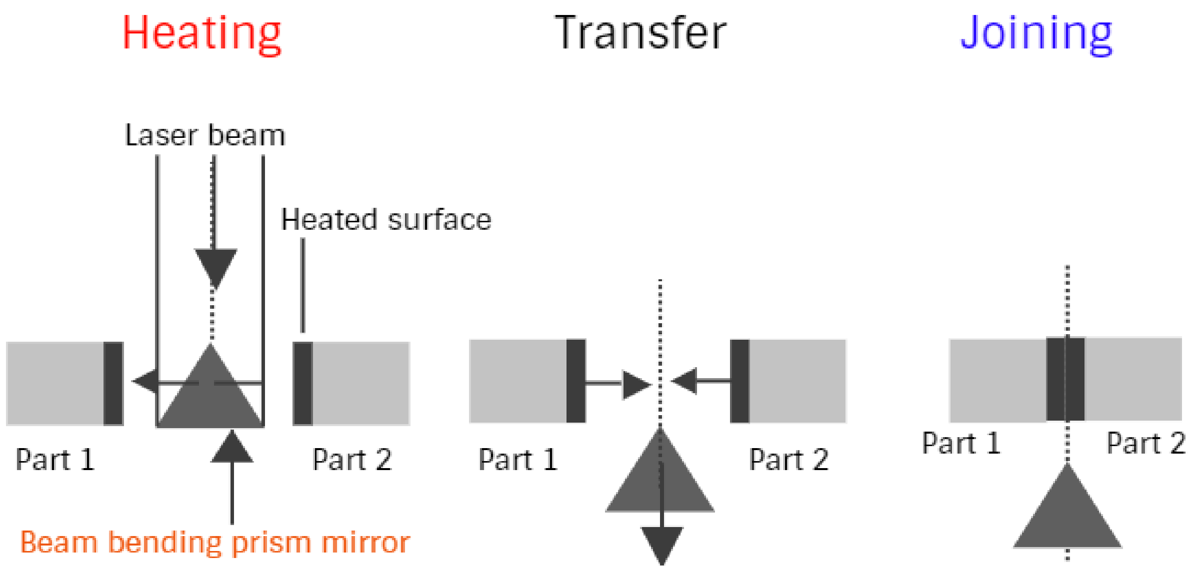

Figure 10 Laser butt welding by CO_2 source

The advantages of direct laser welding could be summarized as follows [1], [18], [19].

- Direct laser welding is a non-contact method, so there is no chance of wear and abrasion as in ultrasonic welding and friction welding;
- By this welding technique, thermal and residual stress in the product will be very less, as the heat affected zone is negligible;
- Process is vibration free because, the heat will be generated by concentrated laser wave and conduction of molecules inside the part;
- There is no chance of flash generation as in hot plate welding because direct laser welding is a non-contact type of technique;
- Bond strength between two parts is very high and stability of welded area is for long term;
- Laser welded part has low rate of rejection due to high precision and accuracy;

Besides having these advantages, direct laser welding technology also has some limitations [1], [18], [19]:

- The beam wavelength, which strikes the surface of the material, is quite high (10.6 μm). Due to this, the generated temperature could also be high and it could cause material degradation;
- Application area of direct laser welding technique is limited to only thin thermoplastic films welding.

2.3. Through transmission laser welding

Through transmission laser welding (TTLW) is a kind of welding procedure, where one of the parts ought to have transmitive property to the laser beam, while another one should be capable to absorb the incident laser beam and transmit it in the form of heat, as schematized in figure 11. Both the parts are firmly in contact with one another by some clamps, which applies adequate welding pressure to them. Laser beam first passes through the transmission part to the absorption part. As the absorption part is doped with some kind of additives, which absorbs the laser beam energy and convert it into melt. As a consequence and due to heat transfer process, transmission part also commences to melt. As mentioned above, both these parts are firmly connected together by some clamping means. Due to this, welding procedure takes place between both the parts [1], [2], [4], [20].

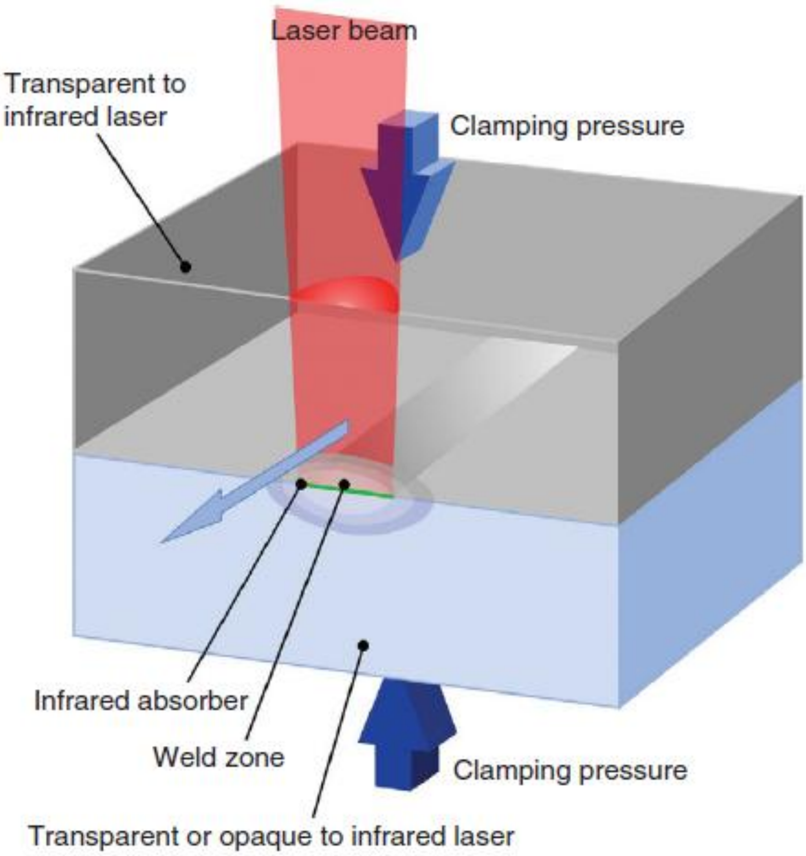

Figure 11 Through transmission laser welding [2]

TTLW method uses laser wavelength in the range of 800 – 1000 nm (NIR radiation). Introduced wavelength region incorporates diode laser, fibre laser and Nd:YAG laser. At this NIR radiation, most of the thermoplastics are able to transmit the incident rays. This could be a complication for absorptive part, because it should absorb the incident rays. For solving this particular issue, some amount of additives (absorbers), which improves absorptivity, should be applied for better welding [4]. There are many types of absorbers available for laser welding. They could be divided into inorganic and organic additives or they could be pigments and solvents. The problem of additives is very vital for quality joints, therefore it will be discussed in separate chapter.

The advantages of transmission laser welding, comparing to another welding techniques, are similar as by direct laser welding. If the two introduced laser welding techniques are compared, the advantages of transmission laser welding are [1], [18], [19]:

- Direct laser welding is limited to the welding of thin films. While by through transmission laser welding, it is possible to make a weld joint in wide range of product thicknesses
- It is quite easy to join complex geometry parts together;

- Laser welded joints has high resistivity towards mechanical loading because the strength of the weld joint is similar as the base material.

Through transmission laser welding also has some of the limitations, which are mentioned below [1], [21]:

- For TTLW, upper part must be transmitive to the laser beam, otherwise it is not possible to create a weld;
- For creation of a weld, the chemical property of bottom part should be absorptive to the rays or else, some of the absorbers must be added to improve absorptivity;
- Surface finishing of joining parts must have higher quality;
- High investment cost;
- Possible occurrence of residual stress at the weld interface for some rigid plastics;
- There is a part thickness limitation i.e. if the transmitive part thickness is quite high, then the laser beam could not reach to the absorptive part. This phenomena could lead towards unsuccessful welding.

Laser welding is advantageous for batch production due to its short cycle time. The high speed of welding, consistency and automated production are reason for its applicability in many branches. For automotive industry, laser joining method is a kind of boon. For an example, this welding method could be used for airbag and camshaft sensor, gear sensor (figure 12 right), display of speedometer (figure 12 left), head light, tail light and fluid reservoir (figure 12 middle) [1], [4], [22]. Another remarkable products, which could be produced by through transmission laser welding are license plates, car keys, door handles and electronic displays. Except automotive industry, laser welding has very widespread application branches like, electronic packaging, textiles, biomedical firm, and food industries [1].

Figure 12 Application in automotive industry [4]

2.4. Materials suitability for laser welding

As explained in previous chapter (chapter 2.3), through transmission laser welding requires two materials from which, one part must be transmitive to the laser beam and another part must absorb the transmitted rays. For quality of the weld to be more durable, several aspects relating to materials must be taken into consideration. The material's properties ought to be adaptable or identical to each other. Some important characteristic of materials, for achieving of good quality of weld joints, are discussed below [4]:

- **Structure**: Both of the joining parts should have identical chemical properties and structure. It is salient characteristic for weld to be occurred. If two joining materials are similar, then the chemical structure, molecular structure (linear or branched), chain length and their distribution should be similar. Otherwise, the differences could lead to insufficient weld strength [4].
- **Thermal properties**: Melting temperature of both the materials should be as similar as possible. If melt temperature of the parts contrasts, then the part would not be in the melt stage, which could lead to no bonding connection. Likewise, heat expansion co-efficient should also be similar for both materials [4].
- **Surface energy**: Also polar surface free energy of both materials should be similar [4].

Besides these properties of materials, there are two fundamental criteria, which must be taken into deliberation before transmission laser welding. First one is that, two thermoplastic materials are laser weldable if another plastic joining methods like, hot plate welding and ultrasonic welding are capable to weld the similar materials [4]. Second criteria verbalizes that through transmission laser welding is only conceivable if the transmitive part has adequate ability to transmit more than 10% of the imparted laser energy to the joint interface [1]. For joining distinct materials, it was explored from experiments that polar surface free energy and heat expansion co-efficient of each of the materials should be under some limits.

$$\frac{\alpha_1}{\alpha_2} > 1.2; \tag{3}$$

α_1 = polar surface free energy of material 1 (J/m$^{2)}$;

α_2 = polar surface free energy of material 2 (J/m$^{2)}$.

$$\frac{\Upsilon_1}{\Upsilon_2} > 2; \tag{4}$$

Υ_1 = heat expansion co-efficient of material 1 under constant pressure (1/°C);

Υ_2 = heat expansion co-efficient of material 2 under constant pressure (1/°C).

2.4.1. Semi crystalline thermoplastics

Semi-crystalline thermoplastics incorporate crystalline phase, as well as amorphous phase. When laser beam goes through these materials, existing crystalline phase will cause some scattering of the beam inside the material [1], [2], [4]. Due to scattering of the laser beam, the beam loses its energy while passing through the material (figure 13). From this statement, it could be said that, the more crystallinity has the material, the more energy would be disoriented at the interface.

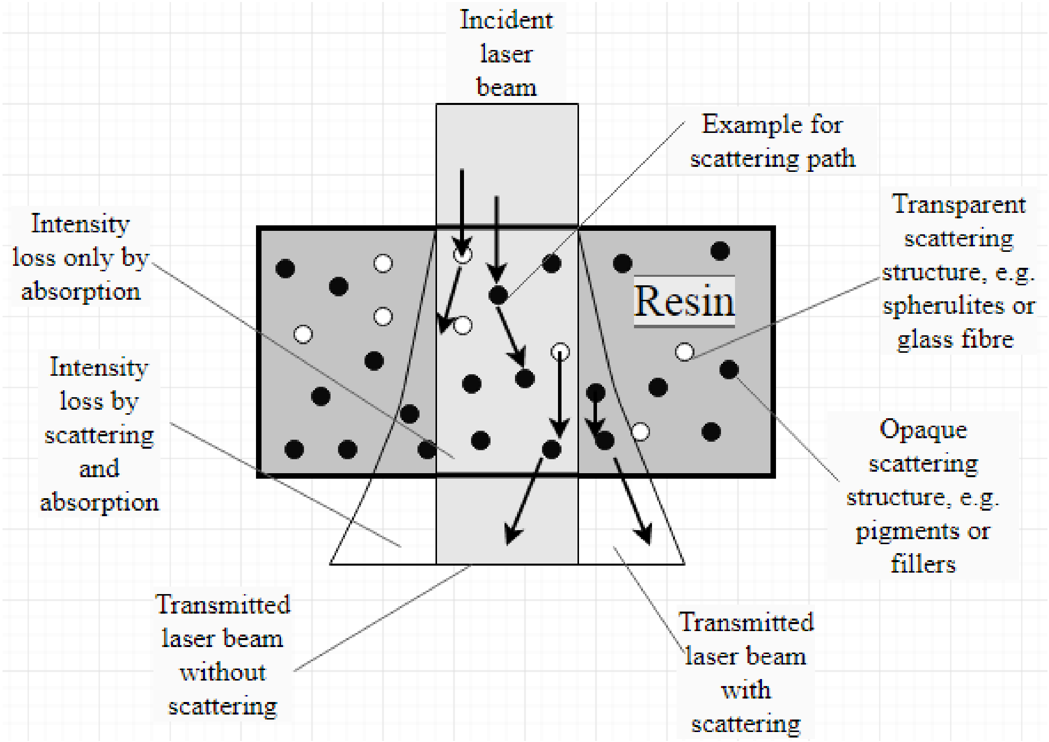

Figure 13 Laser beam scattering through the part

The amount of scattering depends on the shape and size of the spherulites and additives. The laser beam tends to scatter more, if there are more additives or spherulites present in a part. For calculating the amount of scattering, scattering constant is a vital quantity to be find out. Following equation is helpful to quantify scattering constant:

$$K^{+} = -\frac{N * V^{2}}{\lambda^{4}}; \qquad (5)$$

K^{+} = Scattering constant;

N = number of scattering crystalline phases;

V = volume of crystalline phases (mm^3);

Λ = wavelength of radiation (mm).

Scattering constant is dependent on the crystalline lamellas and spherulites (size and structure) as well. It is proportional to spherulites numbers and cross-section of scattering particles i.e. glass fibre, fillers and pigments.

$$K^{+} \propto N * \varrho^{2}; \quad (6)$$

K^{+} = Scattering constant;

N = number of scattering crystalline phases;

ϱ = cross-section of scattering particle (mm^2).

Due to this internal scattering, the laser beam loses its intensity before it could reach at the joint interface. In other words, the transmissibility of laser beam diminishes due to scattering [1], [2], [4]. Table 1 shows the experimented detected values of transmission for some semi-crystalline thermoplastics [23].

Table 1 Transmission property of various thermoplastics with 1mm thickness at wavelength 1060 nm [23]

Type of polymer	Transmission property
PA	85.3%
PE	80.9%
PP	77.1%

In spite of transmission property, the absorption is the second important property for transmission laser welding. The material absorption characteristic is defined with its ability to transform the laser beam into heat. The penetration depth of laser energy is one possible factor which could explain the absorption characteristic. If the penetration depth is higher, than the energy absorbed will be lower. Table 2 shows some examples of penetration depth for selected group of semi-crystalline material. From introduced results it is possible to say that material has significant influence on the penetration depth as well as process parameter such as wavelength also has much higher influence [4].

Table 2 Optical penetration depth of some semi-crystalline in relation with wavelengths [4]

Thermoplastic	a (mm) at 940 nm	a (mm) at 1064 nm	a (mm) at 10600 nm
LDPE	8.49	10.34	0.28
PA6	5.06	5.06	0.040
PP	11.63	12.87	0.19

Below are introduced some typical semi-crystalline materials, which could be utilized for laser welding technology:

- **Polypropylene**:

Polypropylene (PP) is semi-crystalline material with typical content of crystalline phases in range from 50 to 60 %. It is one of the most used material with application in many industries such as packing, building, electronic and also automotive. The reason of its wide applicability is its low density, good chemical as well as electrical properties and low price. The characteristic melting temperature of PP is in the range of 160 – 210 ˚C (depends on the used grade) and decomposition temperature between 336 – 366 ˚C [4]. PP is non polar material. It is reason of low water absorption and difficult bonding agent joining, varnishing and also welding [24]. It is possible to weld polypropylene with techniques like hot plate welding, ultrasonic welding, adhesive bonding, vibration welding and laser welding as well. For laser welding, natural polypropylene has transmission property described in the figure 14.

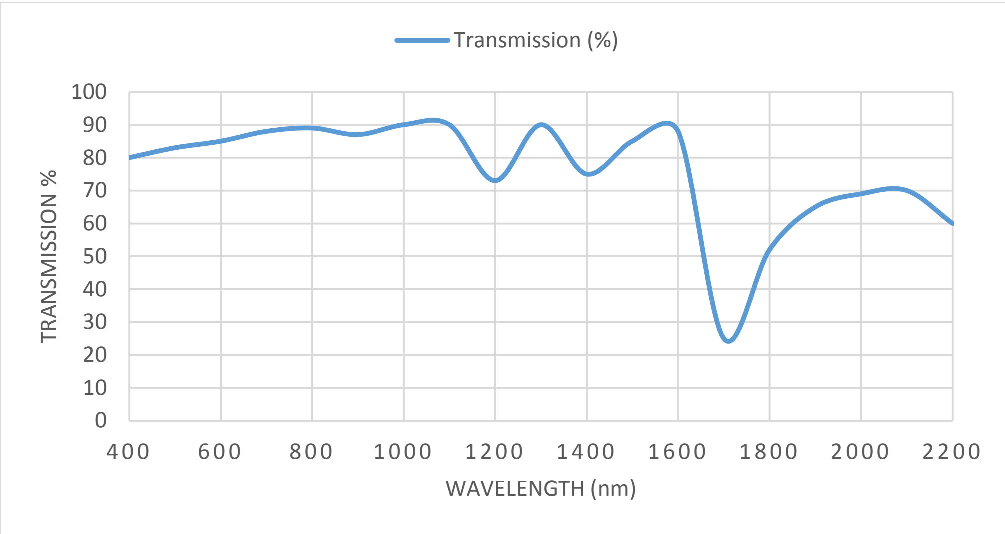

Figure 14 Transmission property of natural PP [4]

From these introduced joining techniques, hot plate welding has quite good quality of weld for PP [1], [25]. Some of the examples of polypropylene laser welding are ink cartridge for printer, car bumpers, and chemical tanks [4], [26].

- **Polyethylene:**

Polyethylene (PE) is commonly used semi-crystalline thermoplastic. PE has melting temperature around 130 -145 ˚C and decomposition temperature in between 360 -390 ˚C. Polyethylene is characterized with crystallization degree in the range of 65 – 80 % [4]. Due to such a high crystallinity, PE is not commonly used for laser welding application like, in automotive or other industry. In some cases, polyethylene is utilized for joining thin plastic films (packaging industry) with the help of CO_2 laser or Nd:YAG laser with shorter wavelength.

- **Polyamide:**

Polyamides are characterised with hydrocarbon bonds. It causes very well mechanical properties which could be even increased by adding glass fibre. Due to this, the material is used for construction applications. Polyamide has typical melting temperature around 220˚C and its decomposition starts at about 327˚C. It has typical crystallization degree in the range of 20

– 45 %. [4]. Polyamides have lower crystallinity than polypropylene, but the hydrocarbon bonds could be the reason of water absorption, which could negatively influence the polymer weldability. Polyamides is possible to weld by different techniques like, heated tool welding, ultrasonic welding, and laser welding [1]. Laser transmissibility of polyamide for part thickness of 1 mm is already mentioned in table 2. Some of the examples of laser welded polyamides are camshaft sensor, fluid reservoir tank and fabrics for air-bags in automobile [4].

2.4.2. Amorphous thermoplastics

Amorphous thermoplastics contain only amorphous phase, unlikely to semi-crystalline material. This is the reason why most of the materials from this group are transparent. The structure of amorphous will cause lower scattering effect and higher transmission (volume absorption) of laser beam than semi-crystalline materials. This will result in lower losing of beam intensity through material thickness [4].

Figure 15 proves the above stated statement. PMMA, which is amorphous in nature, has high degree of transparency compared to any other types of semi-crystalline materials.

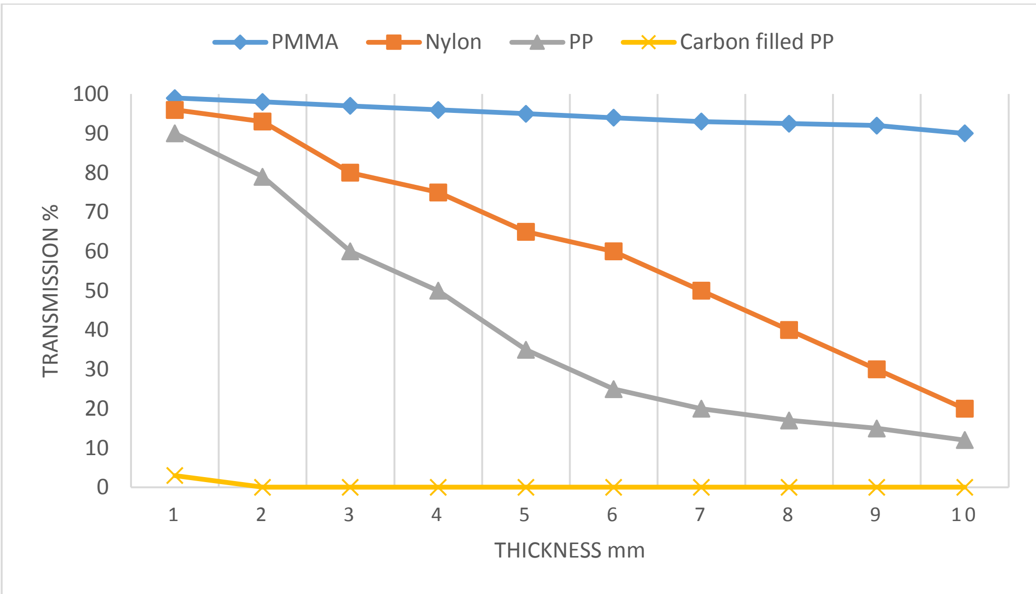

Figure 15 Relation between transmission and thickness of product [4]

Some of the typical amorphous thermoplastics, which could be taken into application for laser welding, are described briefly below:

- **Polycarbonate:**

Polycarbonate (PC) is an amorphous thermoplastic and possesses unique properties of high transparency and high impact strength. As polycarbonate is amorphous in nature, it could easily transmit the laser beam. The laser beam transparency range of PC could be in the range of 91 – 95 % [27]. The characteristic glass transition temperature of PC is about 145 ˚C and its decomposition starts at about 327 ˚C [4]. The optical characteristics (transmission, absorption and reflection) of PC with respect to wavelength of beam is mentioned in figure 16:

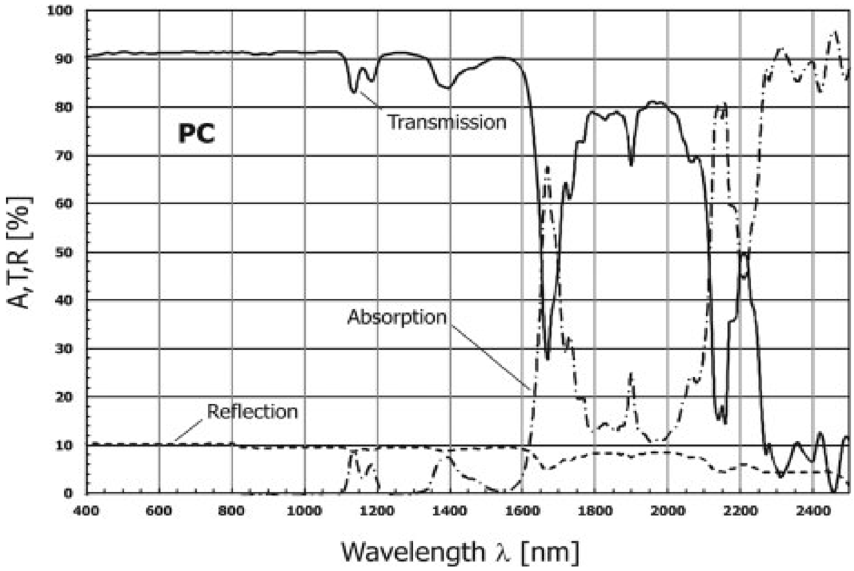

Figure 16 Optical properties of polycarbonate with respect to wavelength [4]

It is possible to weld polycarbonate by different joining techniques like heated tool welding, ultrasonic welding, vibration welding, laser welding and induction welding etc. All of these welding techniques are capable to make a high quality weld of PC. Amongst these, laser welding of polycarbonate is applicable in many fields such as, in automotive industry and medical industry. The examples of polycarbonate welding are heavy duty instruments (pressure gauge) for ships, speedometer for cars and infusion pump in medical [4].

- **Poly-methyl methacrylate:**

Poly-methyl methacrylate (PMMA), also known as acrylic or Plexiglas, is the most transparent thermoplastic in polymer history. It is capable to transmit the light more than 92% [28]. This amorphous thermoplastic is capable to replace polycarbonate in some applications, where high impact strength is not required. PMMA has typical glass transition temperature of 104 ˚C and its decomposition starts at temperature about 226 - 256 ˚C [4]. Figure 17 shows the transmission property of polycarbonate and poly methyl methacrylate with respect to different wavelengths.

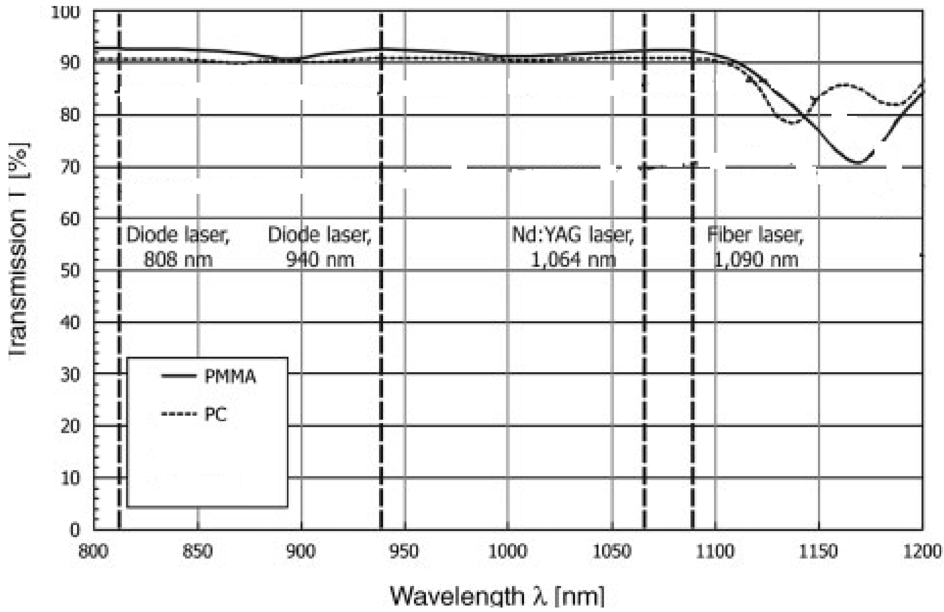

Figure 17 Optical properties of PC and PMMA with respect to wavelength [4]

Due to such a high transparency, PMMA is applicable for laser welding in various applications. For example, PMMA could be utilized for making display of speedometer, oil reservoir and wrist watch.

2.5. Additives

In spite of spherulites in semi-crystalline materials, another reason for beam scattering could be additives such as glass fibres, pigments and fillers [1], [4]. Generously, it is possible to say that, the more the additives are, the more scattering will be and the more beam intensity will be lost. As mentioned above, when the beam strikes any surface, there could be absorption, reflection, refraction, transmission, scattering and polarization. From all of these phenomena, level of reflection and refraction are directly proportional to refractive index of fillers (pigments, talc). When these fillers are compounded with polymer matrix, the ratio of its refractive index to polymer's refractive index has a huge impact on optical properties. When the ratio is near about to one, reflection at the interface (polymer and filler) becomes zero. It means that there is absolute reduction in light scattering and which results in light absorption [29].

In current construction applications, glass fibres are one of the most used reinforcement. The higher content of glass fibres is preferred due to the asked final mechanical properties of product. They are most often combined with PP and PA matrix and their typical content is from 10 to 30 %. According to introduced theory, higher content of glass fibre evoke decrease in the laser weldability (laser beam intensity on the interface). However in some studies [4], [30], it was explored that it is possible to weld material even with 30 % content of glass fibres. From figure 18, it could be discerned that the beam relative diameter or laser beam spot size is increasing with incrementing the glass fibre content.

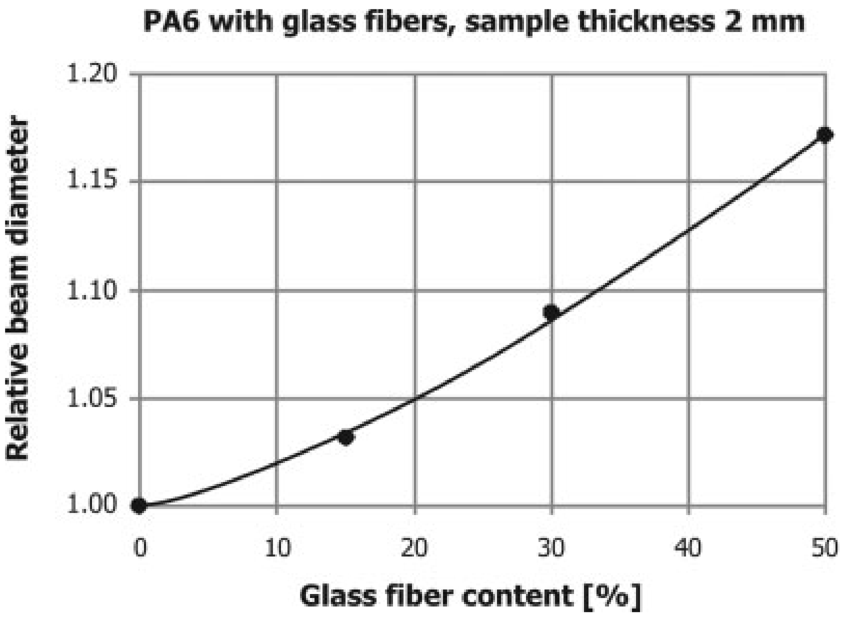

Figure 18 Increase in beam diameter relative to glass fibre content [4]

The other kind of utilized additives are inorganic pigments as for example titanium dioxide (white colour), iron oxide (black colour) or any other kind of metal oxides. These pigments are thermally as well as chemically stable and their characteristic content is from 1 to 2 % [31]. According to refraction index theory described above, this titanium dioxide has refractive index much higher than polymer, so it will cause more internal scattering of beam through material [29]. These standard inorganic pigments do not have any significant influence on the absorption property of polymers [4].

Instead of glass fibre and colorants, fillers (talc, mica, and calcite) are another commonly utilized additives, which could be added into polymer matrix to improve thermal stability and to decrease the shrinkage of plastics. They tend to reduce the economic cost of manufactured product as well. The characteristic content of talc in polymers is around 20% [32], [33]. These fillers also have similar scattering effect as glass fibre and inorganic pigments and have refraction index near to 1.5 [29]. As these fillers are used in higher content, they have generously higher tendency to scatter the laser beam than inorganic pigments. Another reason for internal scattering could be size of the fillers. As the size of these fillers could be varied from µm to nm, they tend to disperse like an individual particles. Due to this reason, the imparted laser beam causes more scattering than absorption [29]. Figure 19 shows the transmission property of polypropylene with various concentration of talc, whose results are compared with natural PP and PP with glass fibre [4]. From figure, it could be easily expressed that transmission of laser beam is highly affected by talcum than glass fibre.

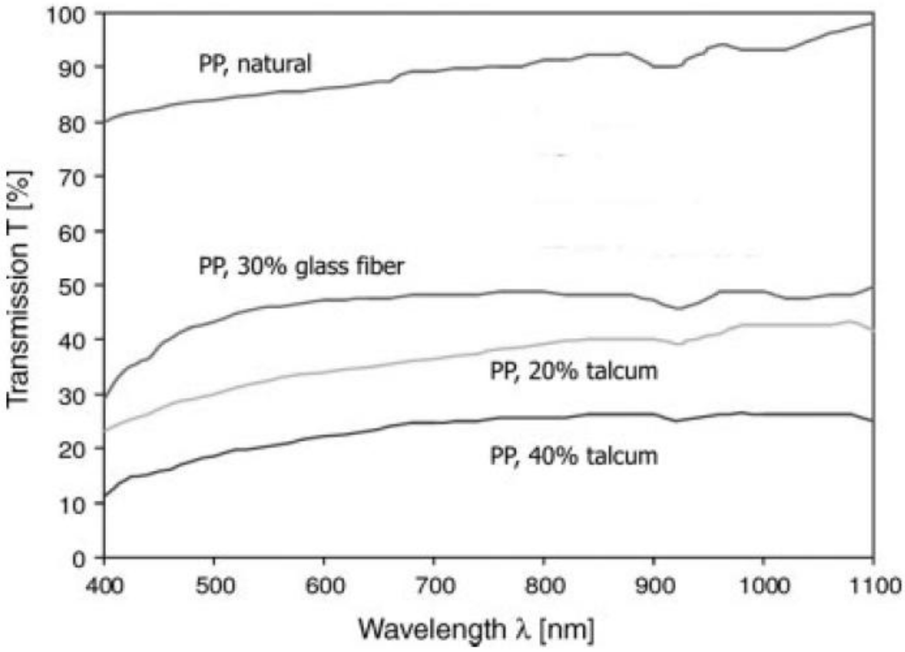

Figure 19 Transmission of PP with talk and glass fibre [4]

As it was introduced, the scattering effect is increased due to higher content of these additives. But it is necessary to mention that inorganic pigments and fillers also have a significant effect to the creation of morphology (heterogeneous nucleation) of semi-crystalline materials, which also influences the losing of beam intensity.

The loss of beam intensity by beam scattering could be approached by increasing the laser power. By increasing the laser power, it is possible to penetrate the beam deeper in the material with less amount of scattering. But if the beam power is increased an extravagant amount, the more heat will be generated at the surface of parts. This could lead to material damage and degradation of material [4].

2.6. Additives to improve absorption

As already stated, for transmission laser welding, some content of absorbers should be applied to the absorptive part of the joint geometry, to enhance the absorption property. These absorptive additives could be carbon black, special kind of inorganic pigments and organic dyes. All of these additives have certain absorption characteristics at some pre-defined wavelength spectrum, which are described below:

2.6.1. Carbon black

As a name proposes, carbon black is mainly compounded of carbon particles. Carbon black is produced by incomplete combustion of hydrocarbons like oil or gases. This conception of incomplete combustion was taken from the production of “soot”, which is produced in similar way as carbon black [4], [34].

The structure of carbon black is distinguished between particles, aggregates and agglomerates. Essential particles are individual particles, which has spherical shape and has diameter from 10 nm to 60 nm. Now, when these individual particles connect each-other by cohesion bond, they turn into aggregate. These aggregates are then loosely packed up-to dimensions of 0.3 μm or more, they are known as agglomerates. Figure 20 demonstrates the complete anatomy of carbon black, how it looks under scanning electron microscopy. The actual construction of carbon black is more perplexed than this [4], [34]. Carbon black is generally utilized in rubber and plastic manufacturing industries as a reinforcing agent. It could be used in tires, inner-liners, tire treads, and food packaging etc [35].

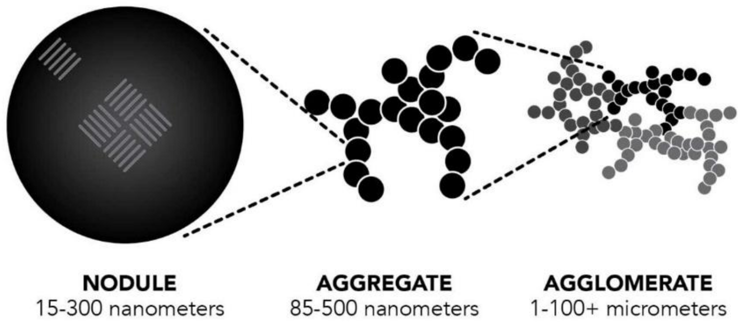

Figure 20 Carbon black anatomy [36]

Carbon black is the most prevalent type of additive utilized for enhancing the absorptivity of polymers. Generally, any other types of additives typically works under only specified wavelength spectrum, but only carbon black has a propensity to operate in entire wavelength spectrum (from UV to NIR) [1], [4]. Figure 21 indicates absorption spectrum of carbon black under different wavelengths. As carbon black has quite good absorption characteristics, it must be applied in some range like from 0.01 to 3% [4].

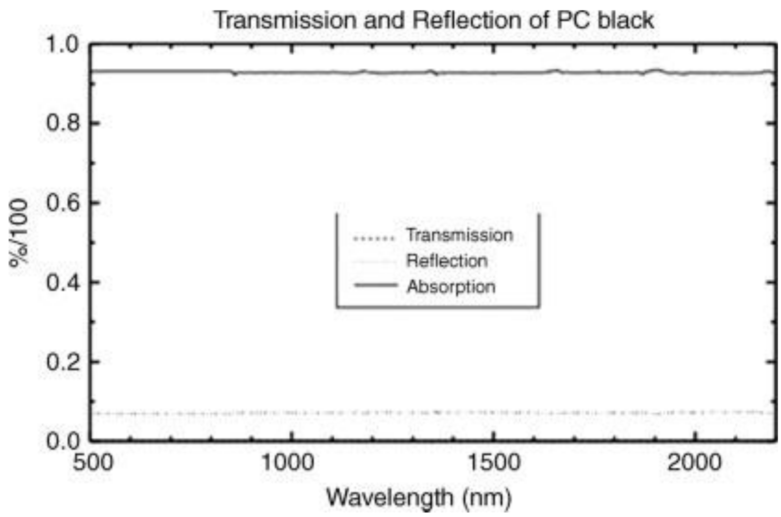

Figure 21 Absorption property of carbon black [4]

As the percentage of carbon black increases into the polymer matrix, optical penetration depth tends to diminish. This optical penetration depth into polymer is limited to some amount like from 10 μm to 100 μm and it additionally relies on the used wavelength. Figure 22 delineates the result of various percentage of carbon black to its optical penetration depth for polypropylene at wavelength of 940 nm [4].

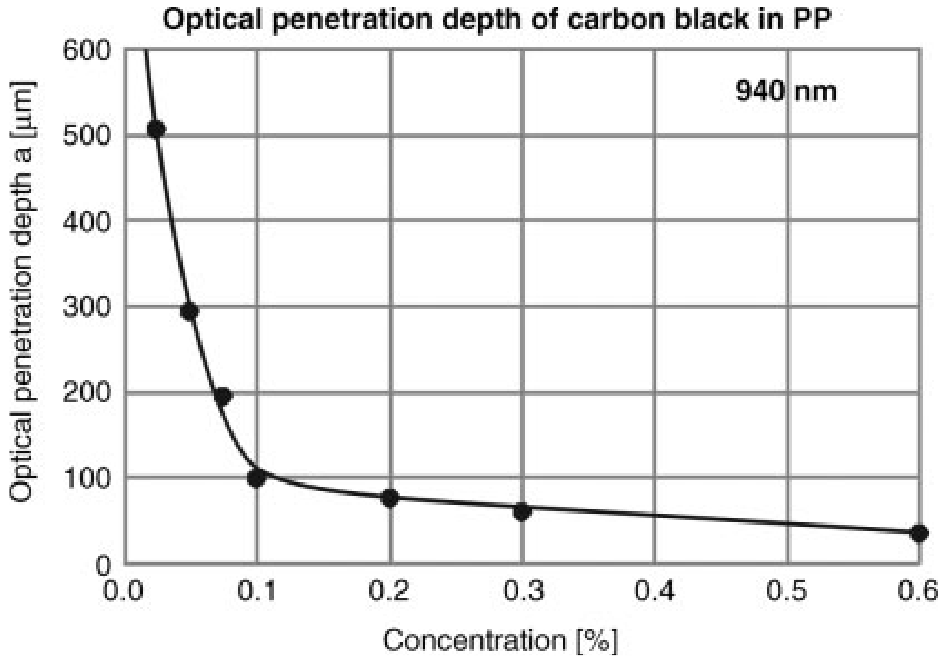

Figure 22 Optical penetration depth vs. various carbon black concentration [4]

As the carbon black is quite economical to produce and it could work in the entire wavelength range, it is the most prevalent additive to be utilized in all kind of industries. However, if carbon black is applied on the absorptive part, it tends to transmute its colour to black. Therefore, there could be an aesthetic problem with carbon black [2], [4]. In integration to this, carbon black could affect the electrical conductivity of the material, which could be significant issue for electrical components to be welded [4].

It is still possible to weld two opaque components though. Carbon black has excellent efficiency towards infrared absorbing capacity so, one of the part should be doped with carbon black to make it dark. It is impractical to dope transmission part of the joint with carbon black because the transmission part must be able to transmit laser beam. For solving this problem, it should be dyed with other suitable dark pigments (red, green). These dyes will still be able to transmit the laser beam. This solution is mostly applied for gear sensor housing for automobiles [37].

2.6.2. Inorganic pigments

As it was introduced above, the absorption property of materials doped with common inorganic pigments (as well as fillers) are not significantly increased. Therefore some special types of additives are necessary to add to increase the absorption properties of absorptive part. The example of the most used additives of these types are Lazerflair®, Fabulase® and Nano-Indium Tin Oxide (ITO) [4].

Lazerflair® pigment has a platelet kind of structure, whose diameter is about 15 µm or less (figure 23). It has multi-layered structure with a core of glimmer, which is coated on both sides by metal oxides (TiO_2 and SnO_2). These multi-layered Lazerflair® pigments have wide range of absorption spectrum i.e. from 900 nm to 2200 nm [4].

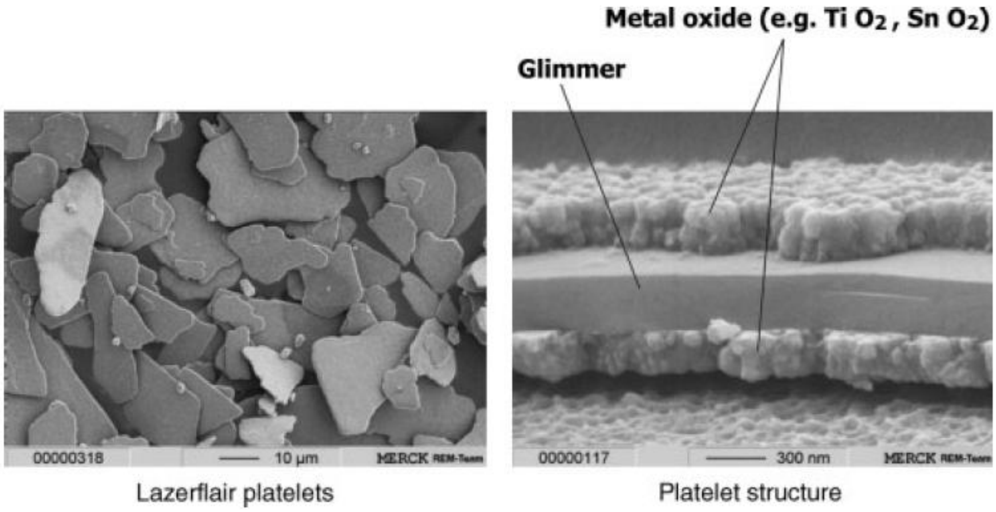

Figure 23 Lazerflair® structure [4]

The concentration of Lazerflair® in the absorbing material should be according to radiated wavelength and it should be in the range of 0.5 – 2% [4]. Lazerflair® pigment does have some internal scattering due to its particle size, even if it is added in some small concentration. If the concentration is high, then it could cause more internal scattering, which results in increased beam diameter. Figure 24 shows the usage of Lazerflair® 825 on Polypropylene material with thickness of 1.5 mm [4].

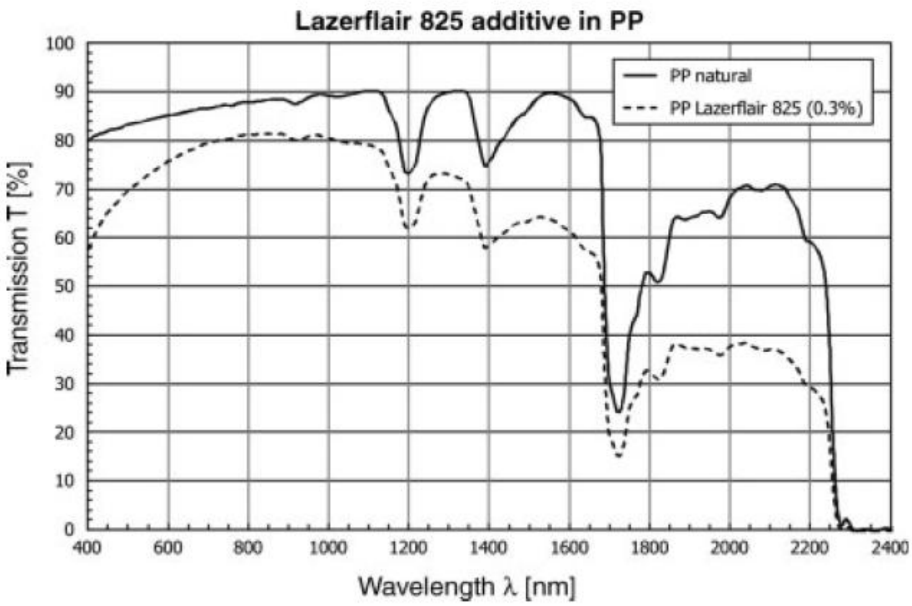

Figure 24 Transmission of Lazerflair® relative to wavelength [4]

Another type of inorganic additive contains copper phosphate, named Fabulase® 322. It tends to have good absorption property under some defined wavelength spectrum (900 to 1500 nm). For Fabulase® 322 to be visible on material under these wavelength, generally slight green colour is added to the resin. The ratio of this added coloration depends on the utilized concentration of Fabulase® 322, which is typically from 0.5 to 2%. Fabulase® 322 are mostly available in pigment size of 0.8 µm to 3 µm. Resembling Lazerflair®, Fabulase® 322 also does some internal scattering and engenders haze to the laser beam [4]. Even though, Fabulase® 322 has better absorption characteristics than Lazerflair® (figure 25).

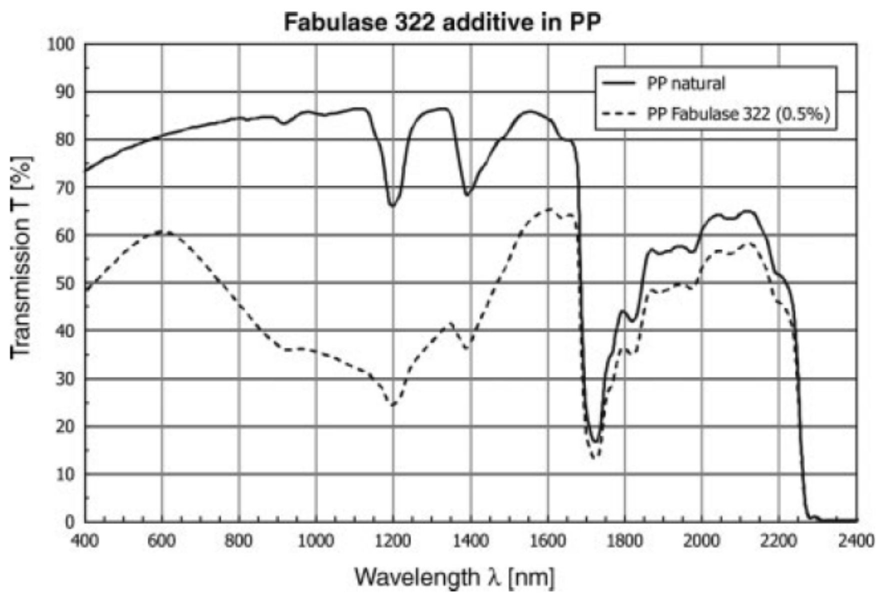

Figure 25 Fabulase® 322 on PP of thickness 2mm [4]

Indium Tin Oxide (ITO) particles are quite small (nanometres) in size and they should be used only in small concentration, unlikely to Fabulase® 322 and Lazerflair®. Generally, Nano-ITO has good absorption characteristics in the defined wavelength range from 1000 to 2000 nm (figure 26). As these particles are very small in size (even smaller than the applied wavelength), they usually disperses finely into the resin. Due to this reason, the imparted laser beam does not tend to create a haze [4]. But if the concentration of ITO is increased in material, the resin colour will turn into slight bluish colour with some hazing effect.

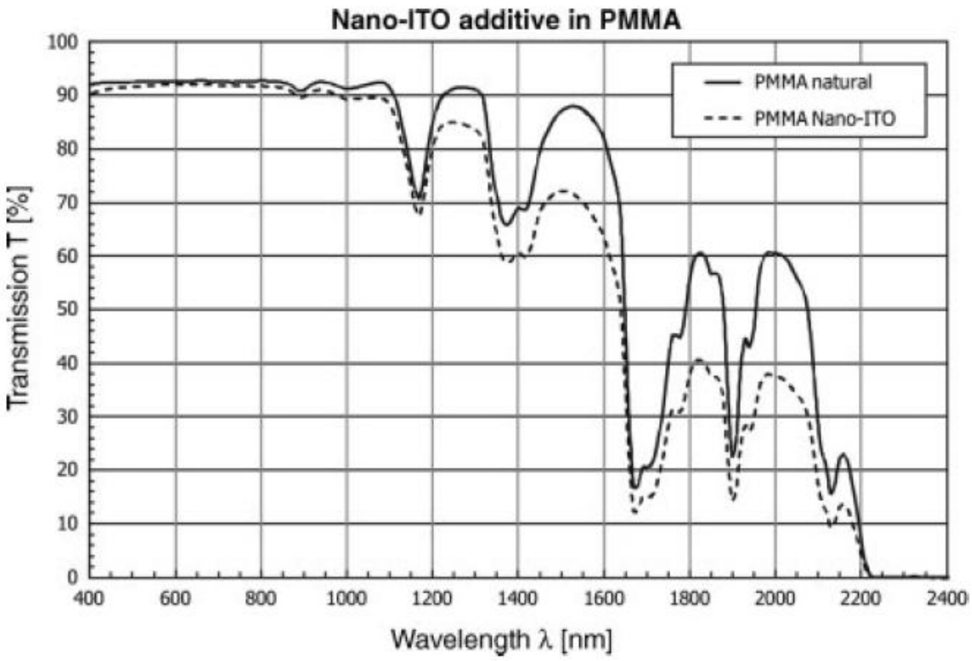

Figure 26 Nano-ITO on PMMA with thickness of 2 mm [4]

2.6.3. Special organic dyes

Special kind of organic dyes such as azo, perionon and perylene are utilized as colorant for plastics, however they do not have any impact on the absorption property of resin. These dyes have disadvantage of being chemically and thermally reactive so, they could not be used for high temperature application of polymers. Adding to this, above introduced organic dyes does not have any absorption characteristics in the NIR wavelength spectrum [4].

In spite of these all, there do exist some of the exceptions like, Clearweld® and Lumogen® dyes. These dyes at least have some absorption peak at particular wavelength or narrow band absorption range in NIR wavelength [1], [4]. Generally, these dyes are subsidiary for transparent thermoplastics like, PMMA and PC. These dyes should be used according to weight percentage 0.001% to 0.2% [4].

These organic dyes are only applied for some particular wavelengths like, Lumogen® IR788 and Clearweld® LWA 208 for 808nm diode lasers or Clearweld® LWA 267 for 940nm diode lasers (figure 27) [4].

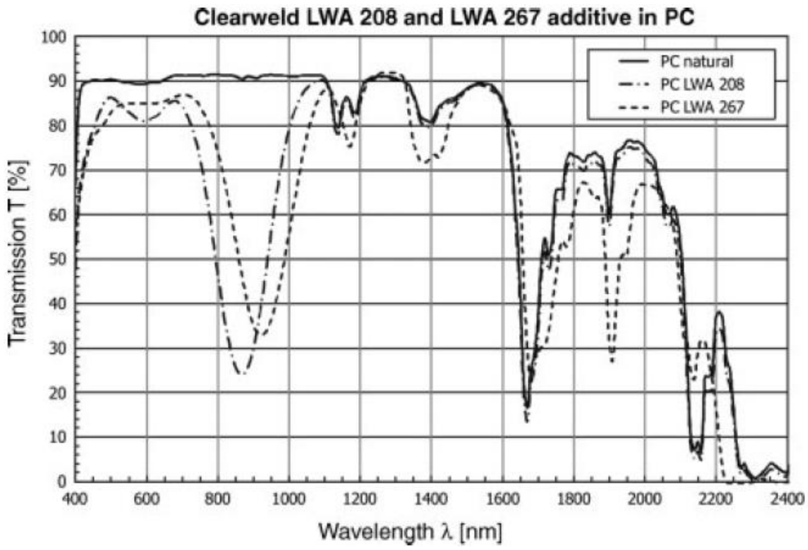

Figure 27 Application of Clearweld® dye on PC [4]

To put all these in a nut-shell, for laser welding of thermoplastics, all the conditions like, used wavelength, material compatibility, demands of coloration, and economic condition, must be satisfied. Usage of absorbing additives should be according to irradiated wavelength. All of these are summarized in the table 3 [4].

Table 3 Absorbing additives according to suitable wavelength and materials [4]

Additive	**Particle size (µm)**	**Absorption range (nm)**	**Thermal stability**	**Chemical stability**	**Visible influence**	**Can be used in**
Inorganic pigments	<0.3	Entire spectrum	500	Excellent	Black coloration	All thermoplastics
Fabulase 322	<5	900-1600	500	Excellent	Slight green coloration with influence to hue	PE, PP, PA
Lazerflair 825	<5	>1000	500	Excellent	Slight green coloration with influence to hue	PE, PP, PA
ITO	<5	>1000	500	Excellent	Transparent colourless	PMMA, PA

Additive	Particle size (µm)	Absorption range (nm)	Thermal stability	Chemical stability	Visible influence	Can be used in
Clearweld A267	-	850-1000	<300	Good	Slight transparent green coloration	PE, PP, PA

2.7. Joint geometry design

For achieving excellent quality of plastic parts using transmission laser welding, three parameters should be taken into account: technical parameters, types of additives (absorber in absorptive part) and joint interface design. Technical parameters (wavelength) and types of absorbers were described above [4]. The remaining term, design of joint interface will be discussed in this chapter. For transmission laser welding, the process demands for making successful weld joints in terms of joint designs are as follows:

- Laser transparent and absorbing parts must be placed in an appropriate manner and should be centred properly;
- Joint interface should be parallel and tight enough to each-other, which could be achieved by some clamping devices;
- The concentrated laser beam should irradiate the joint interface as vertical as possible;
- Surface roughness of both parts should be low i.e. geometric tolerance should be as low as possible. Lower surface roughness results in flat surface and this induces close contact between parts. These close contact between the parts should be provided due to the fact that proper heat conduction between them only takes place when they are in intimate contact;
- For strength criteria, the weld bead size should be equal to nominal wall thickness for unfilled material. For filled materials, it should be 1.25 times higher than wall thickness;
- As for having successful weld joint, intimate contact between the parts is necessary. So the parts should have minimal warpage. It is not recommended to have a ejector pin marks, gate or vent location at the weld joint geometry.
- **Transparent upper part thickness criteria:** In addition, sometimes the minimal thickness criteria should also be taken into consideration. This criteria says that there should be a minimum thickness of the material between laser source and absorbing part. It is because if the part is semi-crystalline and if it is highly filled with some fibres or fillers, the beam tends to scatter more. If the thickness is higher, than the beam could not be able to reach the interface. Therefore, the transmission part thickness should be maximally 2.5 mm for filled

material. For unfilled material, the thickness depends on the transmission rate of that material [38]. Table 4 shows the relation between thickness and transmission ratio for various thermoplastics. As PMMA is amorphous plastic, the transmissibility of it is not affected in a wide range. But for semi-crystalline plastics (PP, PE, PA), the thickness affects more compared to amorphous [23].

Table 4 Transmission of thermoplastics dependent on thickness

Type of polymer	**Transmission at thickness = 1 mm**	**Transmission at thickness = 10 mm**
PMMA	98.8%	88.7%
PA	85.3%	20.4%
PE	80.9%	12.1%
PP	77.1%	7.4%

- **Beam accessibility:** In spite of material thickness, beam accessibility also affects the laser welding process and should be taken into consideration. According to this criteria, the components and clamping tools should be designed to allow sufficient access of the laser beam at weld interface (figure 28). If any of the obstructions (side walls or clamp tools) come in the way of laser beam, they could cause blockage of the beam thoroughly. For countering this problem, the beam accessibility should be measured. For successfully counting beam accessibility, three quantities are required: weld seam width; positional tolerance and dimensional tolerance. Positional tolerance stands for the allowed movement of the part during welding and clamping. Whereas, dimensional tolerance is the measurement of size difference of part before and after welding. Another important parameter is beam cone angle. It should be perpendicular (90˚ ± 15˚) to the surface of part [39].

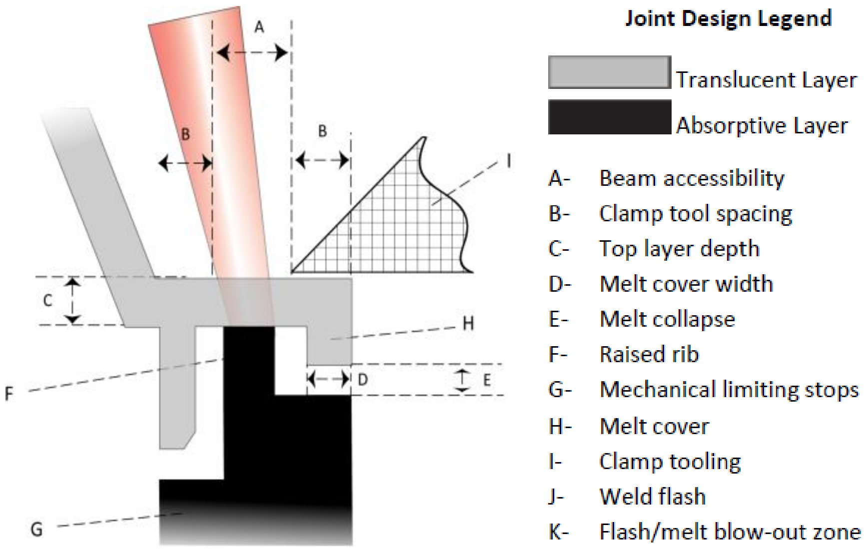

Figure 28 Beam accessibility and melt collapse

- **Melt collapse:** Melt collapse is also known as melt travel distance or joint path. It is the distance the two components move along, when they are melted and pressed together by some clamping forces (figure 28). An ideal range of melt collapse for any material is between 0.1mm to 0.5mm [39]. It could be easily said that melt collapse is dependent on the heat generated at weld interface, time period of heat application and the clamping pressure. It is necessary to balance out all of these three quantities to make a better weld. For example, if the component is taking too much time to make a melt collapse, there could a possibility of component burning and material degradation. For solving out this problem, increase in clamping pressure would give the result in allotted time period [39].

By taking all of these criteria into notice, the possible optimal designs could be as mentioned in figure 29. The joint geometry with square surroundings in figure 29 represents the usage of welding with two distinct wavelengths. Two laser beam absorbing parts are placed upon each other. The wavelength should be selected in such a way that, it will surpass through one absorbing part and absorbed by other [38].

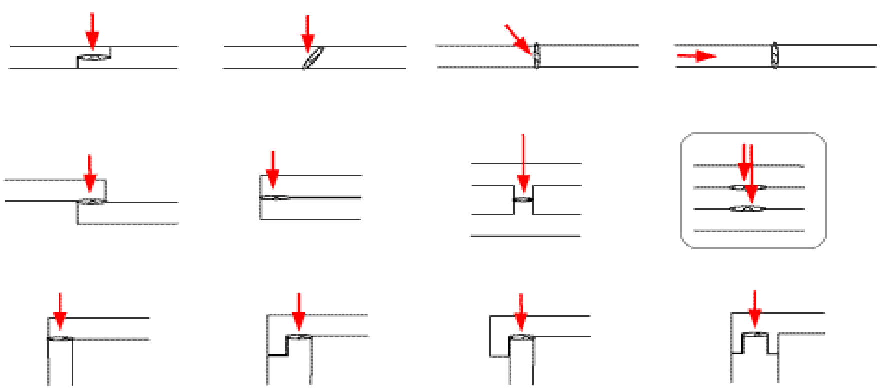

Figure 29 Possible joint designs for transmission laser welding [38]

3. Practical part

The main theme of this experiment was to improvise the weldability of thermoplastic parts of different thicknesses with different concentration of additives (glass fibre and carbon black) using different process parameters (laser power, scanning speed). The samples were produced by common injection moulding process. For joining materials, transmission laser welding technology was utilized. Additionally, for testing these welded samples, tensile test was performed on them.

3.1. Used laser welding machine:

The laser welding station LM05/05 X.W (figure 30) was designed by VÚTS, a.s. and operates on a solid state laser with laser source of Yb:Fibre, which had laser class of 4. The machine was equipped with power supply of 3AC 400V + PE + N and used wavelength was 1064 nm for each experiments. The maximum power generated by machine was 35 W. The laser machine was working on NC programing software.

Figure 30 Laser station LM 05/05X.W

From inside, the laser machine has working table, clamping unit and exhaust for extracting out the fumes generated by laser welding (figure 31).

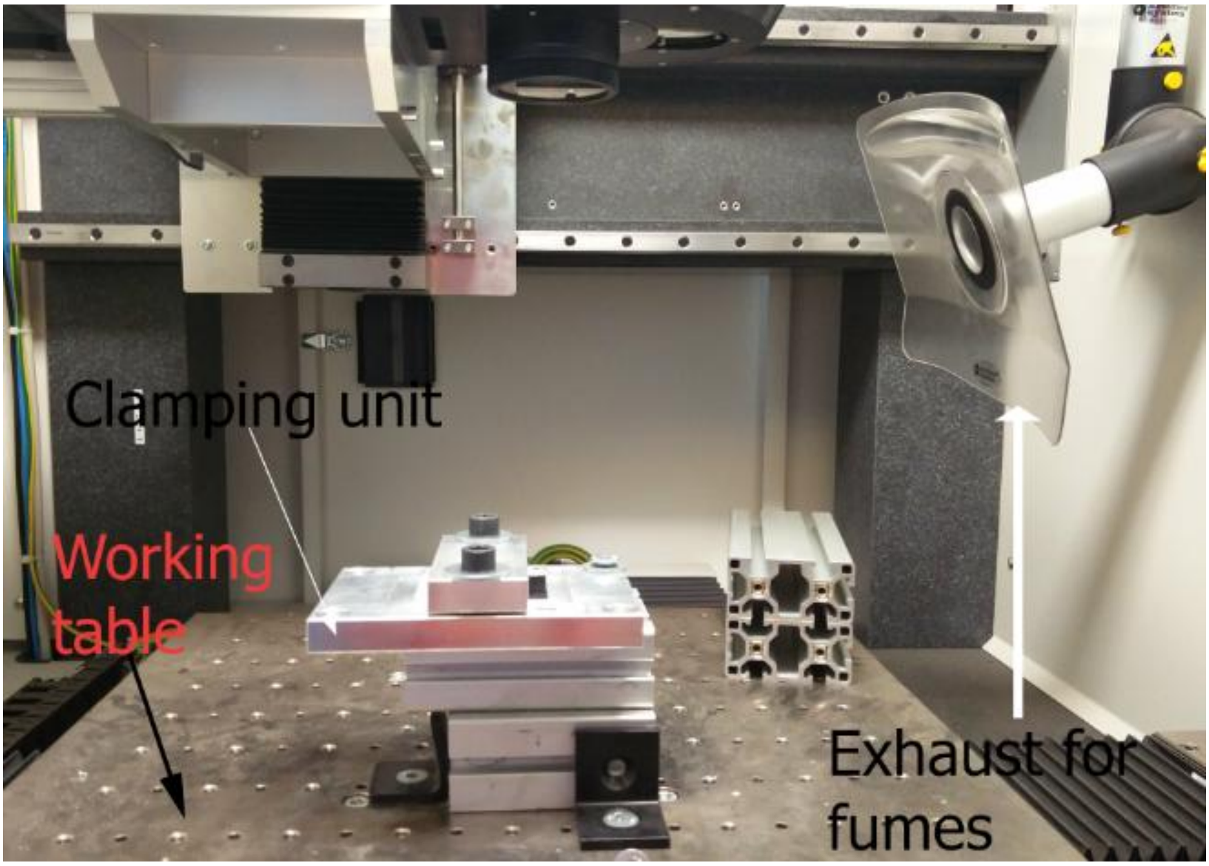

Figure 31 Laser machine configuration

The machine was consisting of “Cross-table” construction for placing work piece (figure 32). The technical data of cross-table is mentioned below:

- Working strokes: X axis: 500 mm; Y axis: 500 mm; Z axis: 200 mm;
- Positioning accuracy: ±30 µm;
- Accuracy of repetition: ±15 µm;
- Maximum feed rate: 20 m/min;
- Acceleration: 3 m/s^2;
- Maximum table load: 15 kg;
- Table length: 1900 mm;
- Table depth 1200 mm;

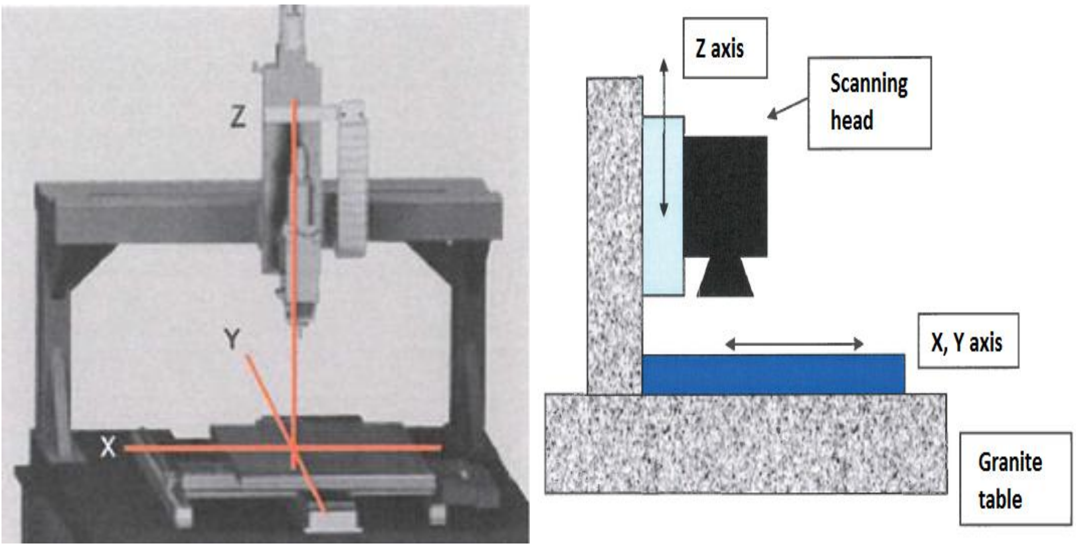

Figure 32 Cross table construction

3.1.1. Control unit

Sinumeric 840D (graphical user interface) is CNC control system for machine tools. By this control system, it is possible to control the laser power and speed. Using this interface, it is possible to do interpolation up-to 3 axis. Sinumeric 840D allows the production of small to large series of work piece. It is also equipped with geometric processor for entering any contours or shape for laser welding. The basic view of Sinumeric 840D control panel is shown in figure 33.

Figure 33 Control panel OP 010C for Sinumeric 840D

3.1.2. Clamping unit

In most of the welding processes, it is certain to have a clamping unit to make sure that there is no air gap between the parts and the parts remain in intimate contact, which aids in perfect welding process. It either could be hydraulic, pneumatic or manual. In our case, the clamping was done manually. As it is visible from figure 34, the clamping unit was consisting of clamp plate, table and bolts.

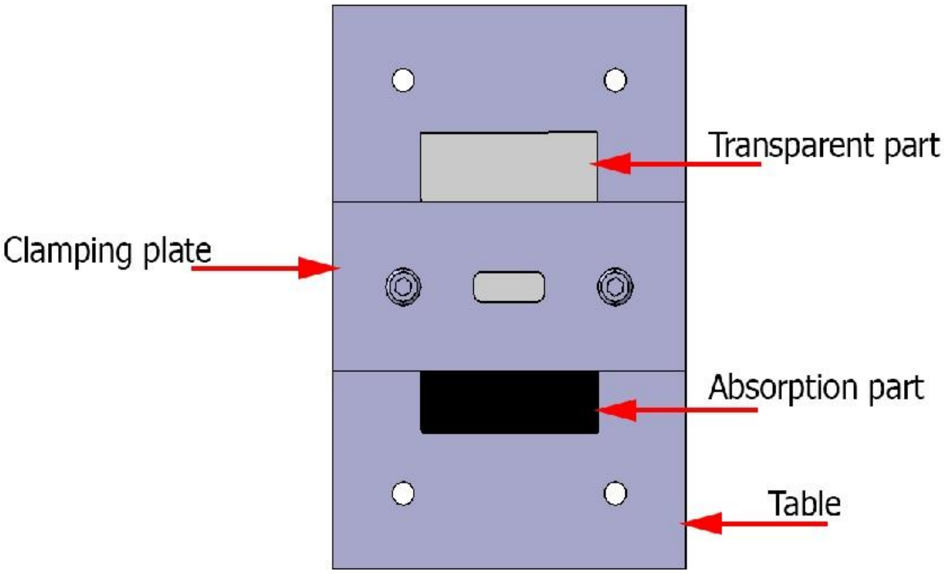

Figure 34 Clamping unit (a)

The transparent and absorption parts were placed in-between the table and clamping plate. This geometry was tightened by two bolts using Hex keys or Allen keys (figure 35). The whole clamping unit is more clearly visible in figure 35.

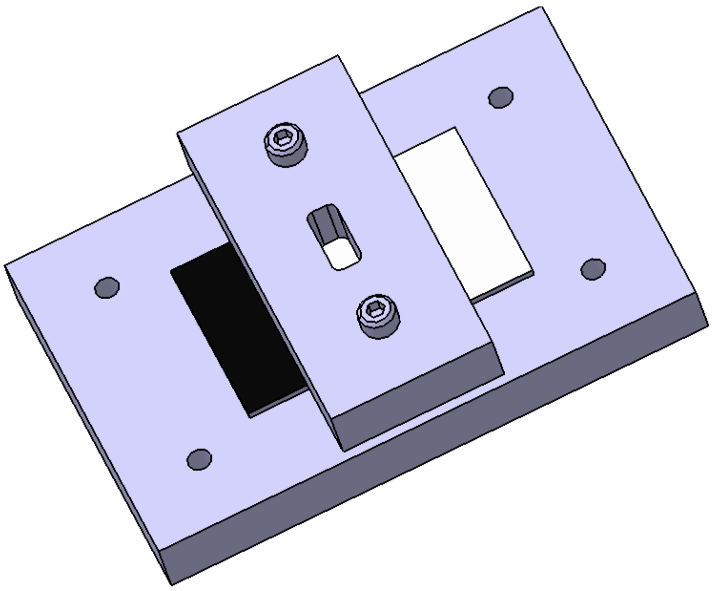

Figure 35 Clamping unit (b)

3.2. Test specimen production

3.2.1. Material specification

For performing experiment, three different kind of polypropylenes were used. The name of the first supplier group is Sabic CX03 81 and it is a homo-polymer. This Sabic CX03 81 is highly crystalline in nature and it is commercially applicable in the field of automotive [1]. Material datasheet for polypropylene with grade Sabic CX03 81 is mentioned in table 5.

Table 5 Technical datasheet of PP Sabic CX03 81[1]

Properties	Value	Test standard
Melt flow index MFI	10 g/10 min	ISO 1133
Melt flow temperature	230 ˚C	-
Yield stress	23 MPa	ISO 527-1/2
Stress at break	21 MPa	ISO 527-1/2
Strain at break	>50%	ISO 527-1/2
Density	905 kg/m^3	ISO 1183

The second supplier group is Braskem Developmental DH742.01 which is also a homo-polymer. This polypropylene resin has a very good balance of physical properties. Moreover, this material was designed for easy processing, low cycle time and good dimensional stability. The material datasheet is mentioned in the table 6 below.

Table 6 Technical datasheet of PP Braskem DH742.01

Properties	Value	Test standard
Melt flow index MFI	12 g/10 min	ISO 1133
Density	900 kg/m^3	ISO 1183
Flexural modulus	1700 MPa	ISO 178

The third material used for experiment was Scolefin® 53 G 10-0. It is homo-polypropylene filled with 30% glass fibre (GF). The main idea of using this material was to examine the effect of glass fibre on the laser welding operation. The material datasheet of Scolefin® 53 G 10-0 is mentioned in the table 7.

Table 7 Technical datasheet of PP Scolefin® 53 G 10-0

Properties	Value	Test standard
Melt flow index MFI	15 g/10 min	ISO 1133
Yield stress	90 MPa	ISO 527-1/-2
Tensile modulus	6800 MPa	ISO 527
Tensile strength	90 MPa	ISO 527
Density	1120 kg/m^3	ISO 1183

For investigating the influence of concentration of glass fibre on laser weldability and on tensile test, the materials Braskem Developmental DH742.01 and Scolefin® 53 G 10-0 were mixed. As the goal of this thesis is about improvising the weldability, the additive carbon black was added in some proportion to the absorption material as well.

3.2.2. Test specimens

All the test samples were produced by injection moulding technology. The produced size of the specimens was 360 * 150 mm (figure 36). These specimens were further cut manually by hand-cutter and after that, the required test specimen size was kept to 40 * 40 mm (figure 37) for all the samples.

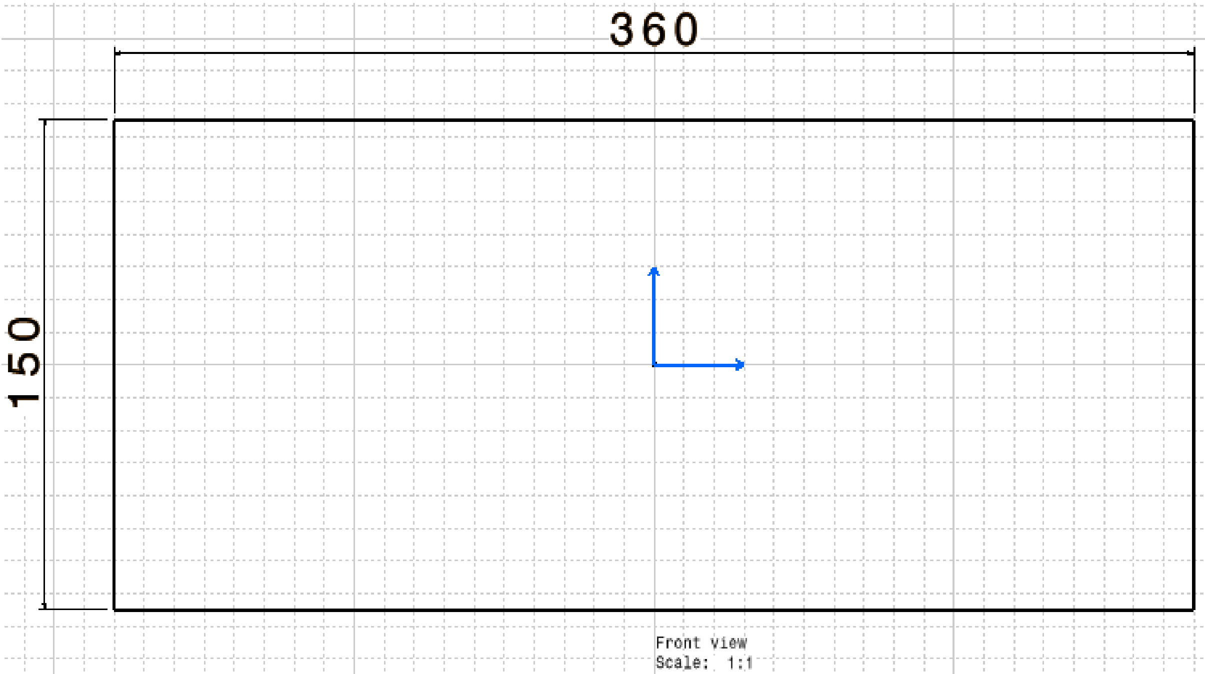

Figure 36 Actual specimen from machine

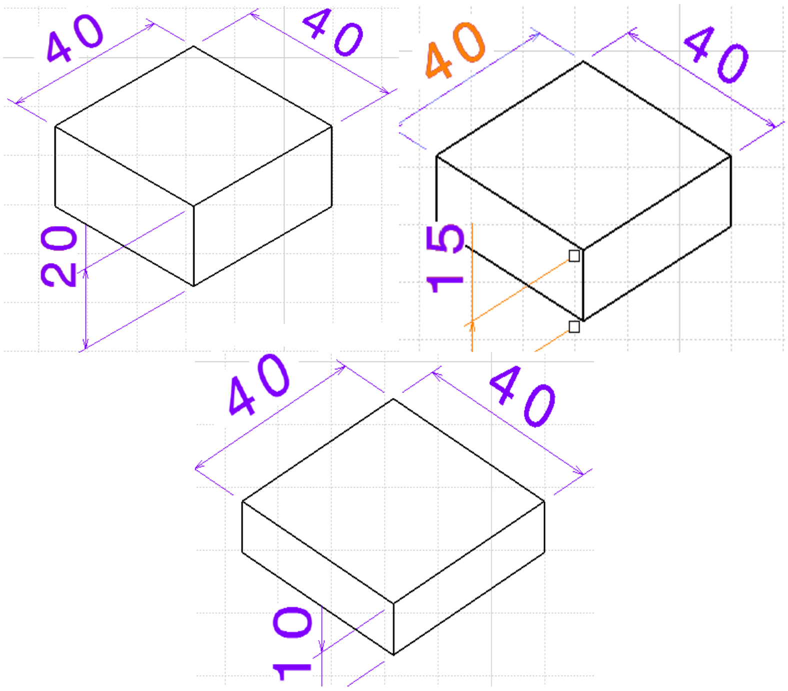

Figure 37 Required dimensions after cutting with variant thickness

3.2.3. Injection process

As mentioned above, every test specimens were produced by injection moulding technology using machine ENGEL VC 1800/300. For the material Sabic CX03 81 with and without carbon black, following process parameters were being set in the machine for production of samples (table 8).

Table 8 Process parameters for Sabic CX03 81

Property	Value
Melt temperature	230 °C
Injection speed	25 mm/s
Holding pressure time	10 s
Cycle time	30 s
Back pressure	10 bar
Clamping force	400 kN

The following table 9 shows the preliminary operation done for producing the samples and table 10 illustrates the used process parameters for the production of samples from material Braskem Developmental DH742.01 and Scolefin® 53 G 10-0 with carbon black and glass fibre.

Table 9 Preliminary operation done on Braskem Developmental DH742.01 and Scolefin® 53 G 10-0

Property	Value
Drying time	3 hours
Drying temperature	90 °C

Table 10 Process parameters for Braskem Developmental DH742.01 and Scolefin® 53 G 10-0

Property	Value
Melt temperature	250 °C
Injection time	2.4 s
Injection pressure	180 bar
Injection speed	65 mm/s
Back pressure	5 bar
Holding pressure	120-130 bar
Holding pressure time	8 s
Cooling time	35 s
Back pressure	10 bar
Clamping force	3000 kN

3.2.4. Sample combinations for experiment

During first trial of an experiment, both the parts were of similar grades (Sabic CX03 81). Their combinations were possible by several ways: sample thickness, amount of carbon black, laser power and laser scanning speed. So to begin with, the samples were combined with each other by different thickness. Main aim for performing this experiment was to make sure that there is no problem in the clamping while using such high thicknesses. In the figure 38 below, it is possible to see the various combinations made for performing an experiment. One attempted combination was with transparent and absorption part thickness 3 mm, which was quite high.

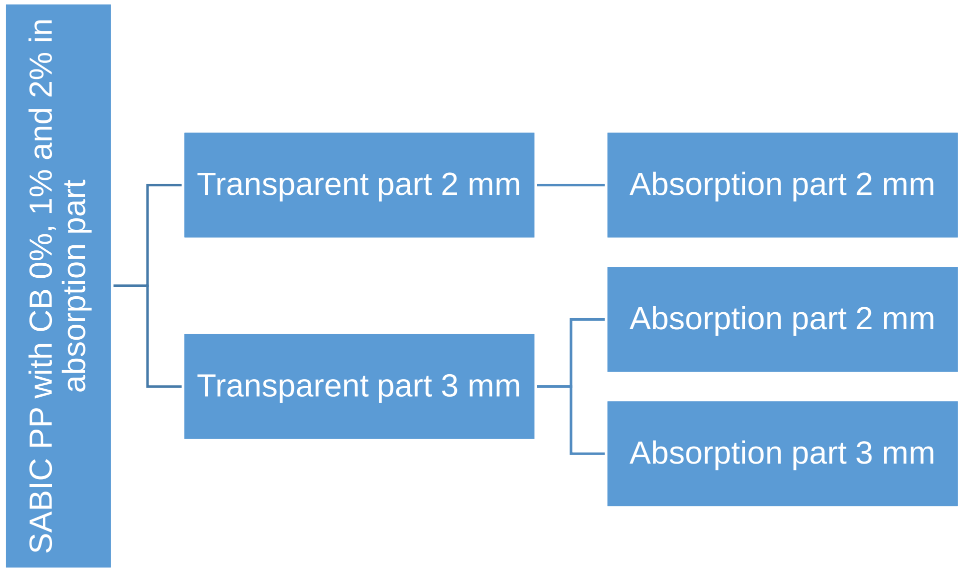

Figure 38 Combination of samples for specimens with Sabic CX03 81

As per theory, it is also important to dope absorption part with some amount of absorbers (carbon black) for enhancing weldability, which literally means that it is not possible to weld samples without doping carbon black on the absorptive part. Even though for proving the theory, experiments were done without carbon black on absorption part. The results of all of the mentioned conditions are described in the next chapter of evaluation.

For next experimentation, the chosen materials were Braskem Developmental DH742.01 and Scolefin® 53 G 10-0. In this case, the absorption part was blended with different amounts of carbon black (1% and 2%) and also with glass fibre, as the idea was to investigate the effect of glass fibre on the weldability and achieving good weld quality.Taking the results of the previous experiment into consideration, the amount of thicknesses were changed for achieving better result. Samples combinations for 1% carbon black with 0%, 10% and 30% of glass fibre could be seen from the figure 39. In this category, the first experiment was done only with 1% carbon black (CB) and without any glass fibre (GF) in an absorption part. This experiment was followed by 1% CB with 10% GF and 1% CB with 30% GF respectively.

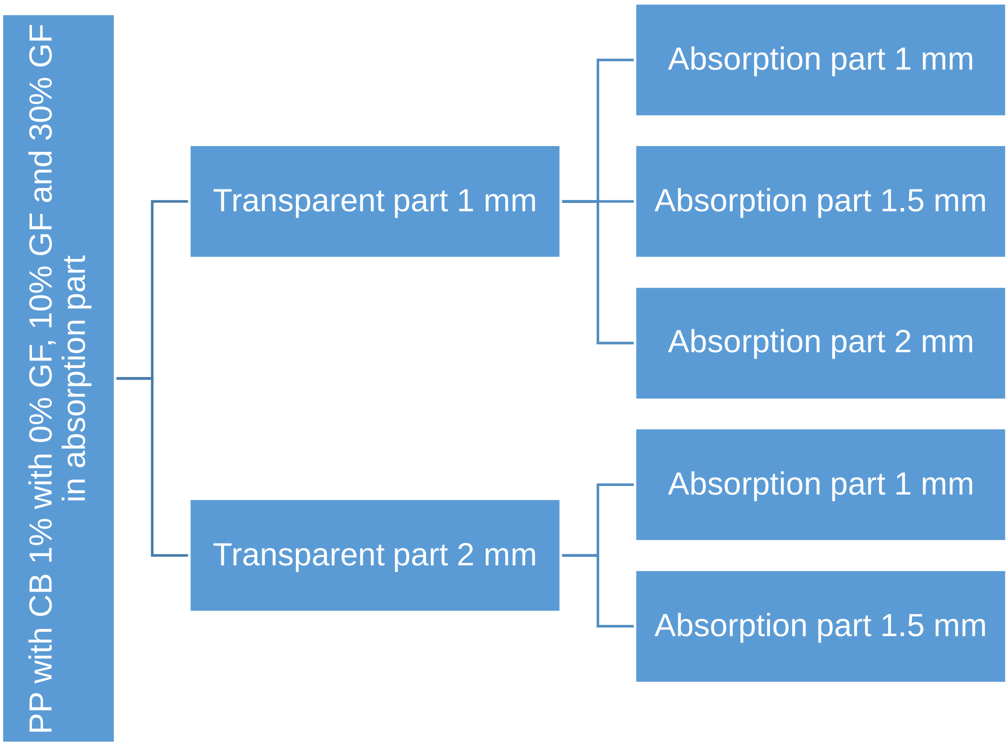

Figure 39 Combination of samples for second experiment

The above mentioned or similar kind of hierarchy applied for the specimens' combinations with carbon black 2% figure 40.

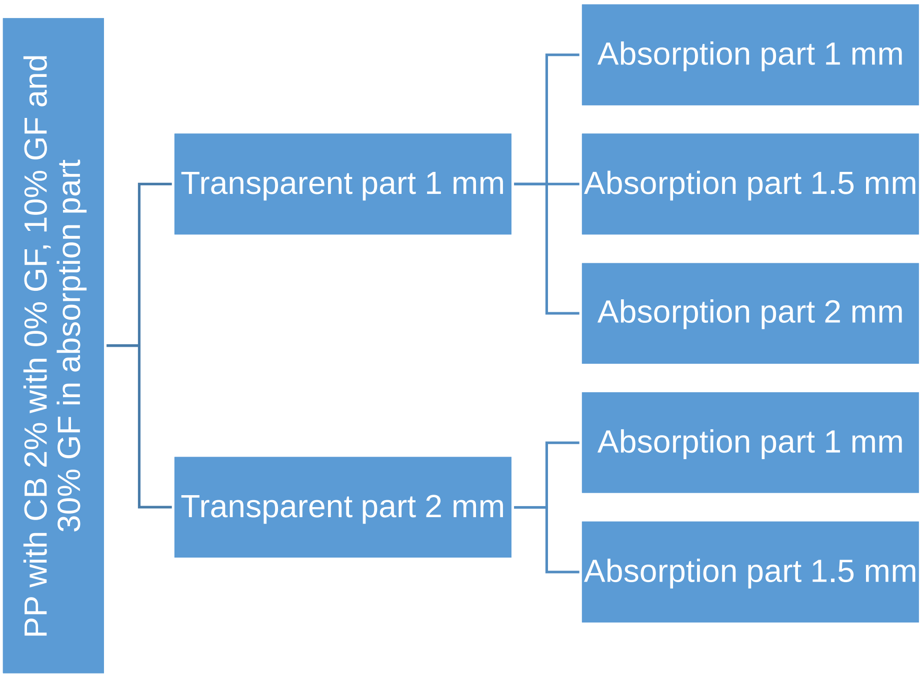

Figure 40 Combination of samples for third experiment

3.3. Welding process

3.3.1. Welding of PP for all the conditions

As mentioned previously, specimens with grade Sabic CX03 81 was only used to check any problem occurrence. The further discussion about this experiment is done in the preceding chapter of evaluation.

Now, the mentioned hierarchy in the chart (figure 41) above was started with transparent and absorption part thickness of 1 mm. In this case, absorption part sample was doped with 1% and 2% of carbon black. The machine was capable to take total maximum power of 35 W and the setting in the machine was according to the percentage i.e. 50% of power means 50% of 35 W. Therefore, the value of power will be written like this in percentage. If the laser power is high or beam velocity is low, then it could cause burning of the samples. On the contrary, if the laser power is quite low or beam velocity is high, then it could result in no welding or partial welding between specimens. Therefore to achieve better welding, it is essential to have good combination of laser power and beam velocity.

For welding the specimens, numerous experiments were performed on each of the specimens to achieve good quality of weld. In some cases, the specimens were not able to weld due to some lacking in process parameters (power and velocity). While in some cases, the specimens were burnt due to high power or lower velocity. So to find the best solution out of them, the tremendous efforts were made. The table 11 below describes the range of laser power and laser velocity for each cases. In the table, TP means transmission part and AP is absorption part. For example, when the transmission and absorption part thickness was 1 mm with 1% CB and 0% GF, the experimented range of power was 48 – 50% and range of velocity was 900 – 940 mm/s and likewise for all the other experiments.

Table 11 Range of laser power and laser velocity used in each cases

Carbon black and glass fibre	**Thickness of both parts**	**Experimented range of power**	**Experimented range of velocity**	**Optimum value of power**	**Optimum value of velocity**
1% CB and 0% GF	TP 1 mm AP 1 mm	48 -50 %	900 – 940 mm/s	48%	900 mm/s
2% CB and 0% GF	TP 1 mm AP 1 mm	48 -50 %	930 – 970 mm/s	48%	950 mm/s
1% CB and 0% GF	TP 1.5 mm AP 1 mm	48 -50 %	900 – 940 mm/s	50%	900 mm/s

Carbon black and glass fibre	**Thickness of both parts**	**Experimented range of power**	**Experimented range of velocity**	**Optimum value of power**	**Optimum value of velocity**
2% CB and 0% GF	TP 1.5 mm AP 1 mm	48 -50 %	950 – 1000 mm/s	50%	1000 mm/s
1% CB and 0% GF	TP 2 mm AP 1 mm	48 -50 %	900 – 920 mm/s	53%	920 mm/s
2% CB and 0% GF	TP 2 mm AP 1 mm	48 -50 %	950 – 1000 mm/s	50%	970 mm/s
1% CB and 0% GF	TP 2 mm AP 1.5 mm	48 -50 %	900 – 920 mm/s	53%	920 mm/s
2% CB and 0% GF	TP 2 mm AP 1.5 mm	48 -50 %	900 – 920 mm/s	50%	970 mm/s
1% CB and 10% GF	TP 1 mm AP 1 mm	48 -50 %	900 – 1000 mm/s	48%	950 mm/s
2% CB and 10% GF	TP 1 mm AP 1 mm	48 -50 %	900 – 1000 mm/s	48%	950 mm/s
1% CB and 10% GF	TP 1.5 mm AP 1 mm	48 -50 %	920 – 1000 mm/s	50%	960 mm/s
2% CB and 10% GF	TP 1.5 mm AP 1 mm	48 -50 %	950 – 1000 mm/s	50%	980 mm/s
1% CB and 10% GF	TP 2 mm AP 1 mm	50 -53 %	920 – 1000 mm/s	53%	960 mm/s
2% CB and 10% GF	TP 2 mm AP 1 mm	48 -53 %	950 – 1000 mm/s	50%	950 mm/s
1% CB and 10% GF	TP 2 mm AP 1.5 mm	53 %	920 – 960 mm/s	53%	960 mm/s
2% CB and 10% GF	TP 2 mm AP 1.5 mm	50 -53 %	950 – 980 mm/s	50%	960 mm/s

Carbon black and glass fibre	**Thickness of both parts**	**Experimented range of power**	**Experimented range of velocity**	**Optimum value of power**	**Optimum value of velocity**
1% CB and 30% GF	TP 1 mm AP 1 mm	48 -50 %	900 – 930 mm/s	48%	930 mm/s
2% CB and 30% GF	TP 1 mm AP 1 mm	48 %	900 – 1000 mm/s	48%	950 mm/s
1% CB and 30% GF	TP 1.5 mm AP 1 mm	49 %	920 – 960 mm/s	49%	920 mm/s
2% CB and 30% GF	TP 1.5 mm AP 1 mm	48 -50 %	940 – 980 mm/s	50%	940 mm/s
1% CB and 30% GF	TP 2 mm AP 1 mm	53 %	920 – 1000 mm/s	53%	940 mm/s
2% CB and 30% GF	TP 2 mm AP 1 mm	54 %	930 – 980 mm/s	54%	930 mm/s
1% CB and 30% GF	TP 2 mm AP 1.5 mm	53 %	920 - 940 mm/s	53%	940 mm/s
2% CB and 30% GF	TP 2 mm AP 1.5 mm	54 %	930 – 980 mm/s	54%	930 mm/s

4. Evaluation and discussion

In this chapter of evaluation, there will be discussion about how the optimal process parameters were achieved for each case of laser welding. While making the attempts to get good weld quality, many of the specimens were burnt at a contour area or sometimes, there was not at all bonding between samples. So there will be discussion about the quality of accomplished weld.

4.1. Welding of PP samples

For the first experiment, the taken samples were: transparent part 2 mm and absorption part 2 mm without carbon black. The material was PP Sabic CX03 81. For welding the mentioned combination, each and every possible combinations of laser power and velocity were used, but there was a negative result each time. The parts were unable to be welded, as the carbon black was missing in the absorption part. Hence, it proved the theory that it is not possible to weld samples without any kind of additives.

After an unsuccessful attempt to weld samples without carbon black, the next attempts were made with 1% carbon black. The transmission and absorption part thickness were kept similar, which was 2 mm. For getting some accurate result, five specimens of each groups were welded. After some attempts, the first specimen was welded with parameters: power 60% and velocity 1200 mm/s. So it was obvious that all the specimens in this group must be welded with these parameters, but there was some adverse result. Rest of the four samples were not welded with the same parameter's setting, rather they had to be welded with some different parameters.

To explain this reason, clamping of the specimens was done with Allen keys or manually (figure 41). Due to this, there might be uneven clamping force to the specimens.

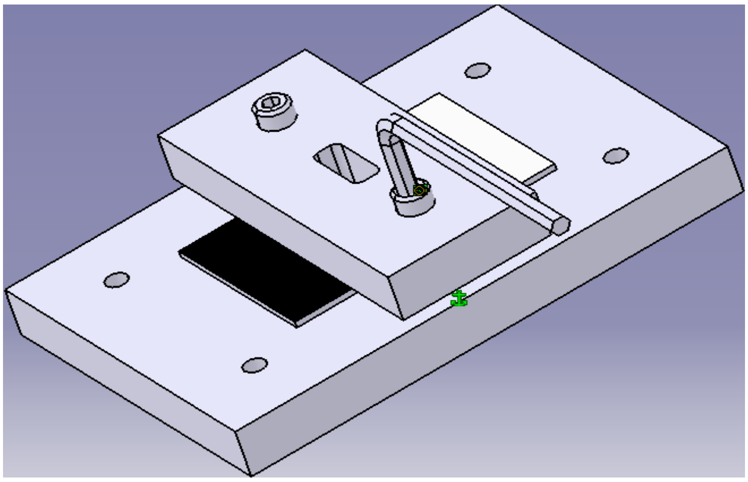

Figure 41 Clamping in first experiment

To make sure that the problem is due to the uneven distribution of force, the transmission part thickness was changed to 3 mm and absorption part thickness was kept to 2 mm with 1% carbon black. As a result, the similar situation like in previous case appeared.

So after performing these experiments, it was sure that there is some problem in the clamping unit and it needed to be solved. So as a solution of this problem, torque wrench was used for clamping the specimens. One more problem might be the thickness of specimens. The combined thickness of them was very high that it was a bit difficult to mount them. So as a solution, the specimens with lower thicknesses were injected with grades Braskem Developmental DH742.01 and Scolefin® 53 G 10-0. Moreover, the recent trend in automotive industry is to make automotive parts as light as possible so that the overall weight of the car reduces and it eventually results in lower fuel consumption and lower CO_2 emission. Below all the experiments are done with optimized clamping (torque wrench).

4.2. Welding of PP without glass fibre with optimized clamping

For the first evaluation with optimized clamping, absorption part was doped with 1% of carbon black and 0% of glass fibre. Both transmission and absorption parts were of 1 mm thickness. For welding, the first trial was made with the combination: laser power 48% and beam velocity 940 mm/s, which resulted in improper welding or there was no welding at all between parts (figure 42).

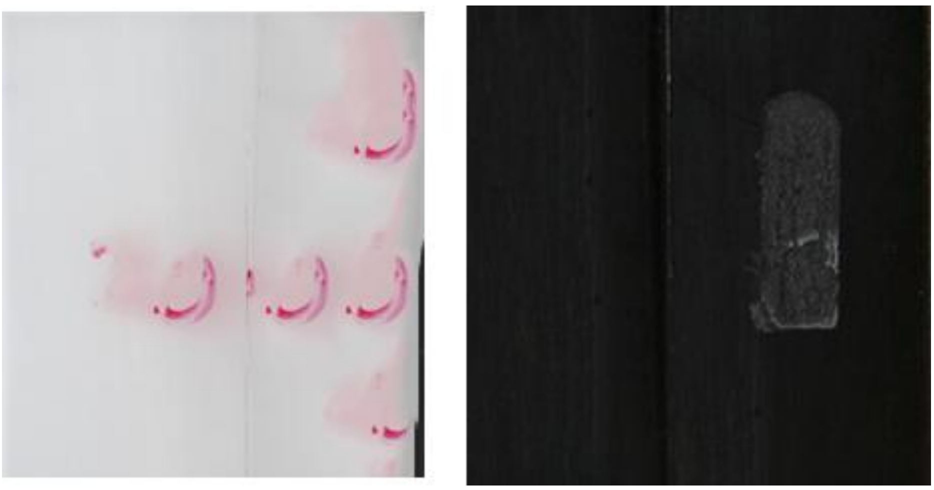

Figure 42 No welding between specimens

So after it, the beam velocity was reduced to 920 mm/s. This time, the part were welded but only partially. After that, the laser power was increased to 50% and beam velocity was again reduced to 900 mm/s. For this case, the welded area was burnt to about 40% (figure 43).

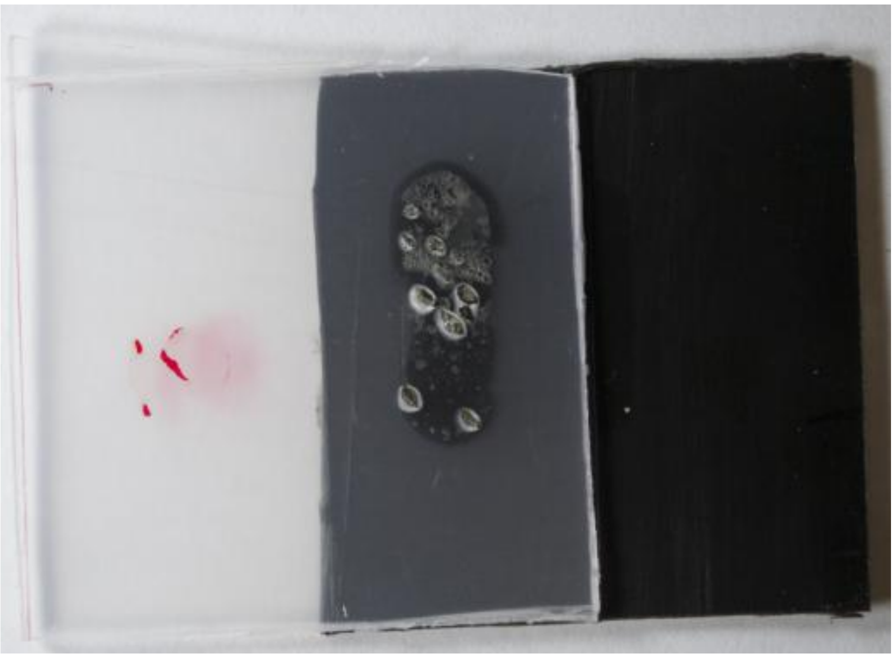

Figure 43 Burning of contour area

After three consecutive failures, one more attempt was made with laser power 48% and beam velocity 900 mm/s. For these parameters, there was observed some satisfactory result of welding (figure 44).

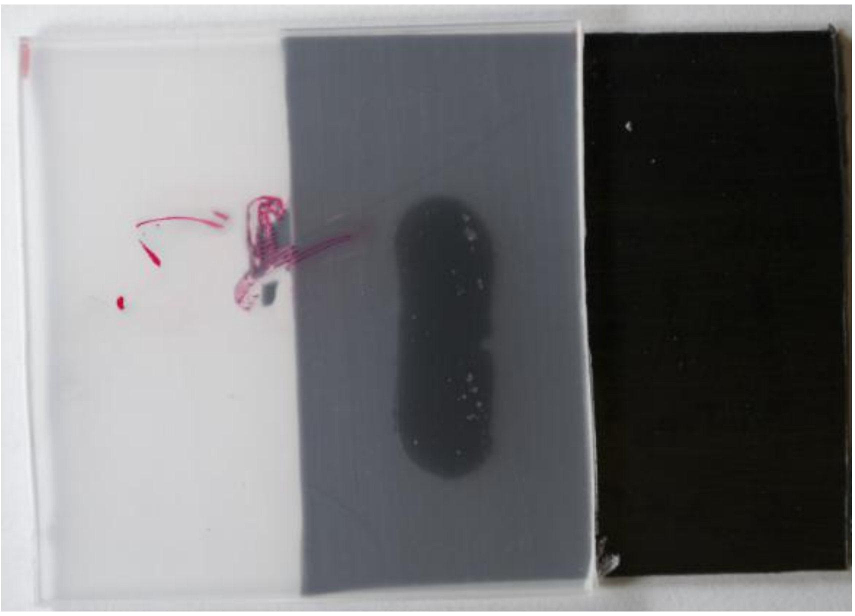

Figure 44 Perfect welding

Therefore all the specimens were welded with 48% of power and with the velocity of 900 mm/s (table 12). Now, it is obvious that for the similar thicknesses, if the amount of carbon black is increased in the absorption part, then either the laser power should be decreased or velocity should be increased. It is because, if the amount of carbon black is more, the specimen tends to absorb more energy and convert it into melt. The same thing was happened in the following case.

When the concentration of carbon black was increased to 2% for same thicknesses, optimal laser velocity was increased from 900 mm/s to 950 mm/s (table 12). The performed trials in this case are mentioned in the table 12.

When the transmission part thickness increases, it causes more distraction of laser beam into material. As a result, the beam tends to reduce its intensity on its way towards absorption part. So it is obvious to either increase the laser power or decrease the beam velocity. When the transmission part thickness was increased to 1.5 mm, the optimal process parameters were 50% laser power and 900 mm/s beam velocity. So compared to TP thickness of 1 mm, laser power was increased by 2%. When the similar thicker specimens with 2% carbon black were evaluated, beam velocity was increased by 100 mm/s, as the carbon black helps to absorb the energy. The most favourable process parameters were: laser power 50% and beam velocity 1000 mm/s (table 12).

When the thickness of transmission part was changed to 2 mm for CB 1% and 2%, the similar theory of beam distraction applies here also. So for compensating it, the laser power was increased from 50% to 53% (for CB 1%) for the velocity of 940 mm/s. Now when the amount of carbon black was increased to 2%, the value of laser power was decreased and beam velocity was increased. The most appropriate process parameters were: laser power 50% and beam velocity 970 mm/s.

As a last experiment in this group, the absorption part thickness was changed to 1.5 mm, whereas, the thickness of transmission part was still 2 mm, the same as previous experiment. So the laser power and beam velocity should be similar because, there is no change in the transmission part thickness. So the laser beam should not be affected by absorption part thickness and should be independent to it. Similar kind of theory applies for specimens with CB 2% (table 12).

In the tables below: N1 means, for the utilized power and velocity setting, specimens were not welded at all. N2 means the specimens were welded at some extent than N1, but for used parameters setting, they were welded partially. It means that the specimens were separated manually.

B1 and B2 tells about the amount of the weld burning area. For used power and velocity, if the burning marks on contour area are between 50 – 80 %, then it is mentioned with B1. When the burning marks were lesser than B1 (around 30%), hence not acceptable, it is mentioned with B2.

Table 12 Process parameter adjustment for specimens without glass fibre

				Velocity of laser						
Part	**Thickness**	**Carbon black**	**Glass fibre**	**900**	**920**	**940**	**960**	**980**	**1000**	**Power**
Transmission	1	-	-	**829.49**	N2	N1				48%
Absorption	1	1%	-	B1						50%
										53%
Transmission	1.5	-	-	N2						48%
Absorption	1	1%	-	**932.54**	N1					50%
				B1						53%
Transmission	2	-	-							48%
Absorption	1	1%	-							50%
				B1	B2	**946.62**	N1			53%
Transmission	2	-	-							48%
Absorption	1.5	1%	-			N2				50%
					B1	**1125.69**	N1			53%
Part	**Thickness**	**Carbon black**	**Glass fibre**	**900**	**930**	**950**	**970**	**980**	**1000**	**Power**
Transmission	1	-	-		B2	**902.23**	N1			48%
Absorption	1	2%	-		B1					50%
										53%
Transmission	1.5	-	-						N1	48%
Absorption	1	2%	-			B1	B2		**902.04**	50%
										53%
Transmission	2	-	-							48%
Absorption	1	2%	-			N1	**1007.62**	B2		50%
								B1		53%
Transmission	2	-	-							48%
Absorption	1.5	2%	-		N1	N2	**1204.24**			50%
					B1					53%

4.3. Evaluation of PP with 10% glass fibre

In the chapter 4.2, absorption part was only doped with carbon black, but in this part of experiment, the absorption part was also mixed with 10% of glass fibre. Similar hierarchy of experiments had been proceeded in every group. So the first experiment was performed on transmission and absorption part thickness of 1 mm with carbon black 1%. As glass fibre were present in the absorption part, they could also help in enhancing the weldability. So to prove it, the first trial was made with power 50% and velocity 920 mm/s, which resulted into full burning of the welding contour. Then, the power was reduced to 48%, but still there were some burning marks. After that, the laser velocity was increased to 980 mm/s with 48% power, which gave a result of partial welding between specimens. Then, as a final trial, laser power of 48% and velocity of 950 mm/s was implemented. This combination gave the best result of welding (table 13). From table 12, it can be seen that, when the similar thickness were experimented without glass fibre, the optimal parameters were: laser power 48% and velocity 900 mm/s. While here, the velocity was 950 mm/s and used power was 48%. So it can be stated that glass fibre helps in enhancing the process. When the similar combination of thickness was experimented with carbon black 2%, it was observed that the proper combination of parameters was similar as parameters with carbon black 1%. The used parameters for welding were: laser power 48% and velocity 950 mm/s.

Once the first stage is completed, the transmission part thickness was changed to 1.5 mm. Rest of the things were similar (carbon black 1% and glass fibre 10%). So as the transmission part thickness was increased, firstly the laser power was increased to 50% and to maintain proper combination, velocity was also increased to 1000 mm/s. As a result, the parts were not welded. So to solve this, laser velocity was decreased to 920 mm/s and it gave the result of burning marks. Again the adjustments were made with laser power of 48% with 920 mm/s velocity but still, the sample was burnt partially. So the velocity was increased to 960 mm/s with power of 48% and it gave result of no bonding between samples. Then, the power was increased to 50% and this combination gave satisfactory result. In a case, when the absorption part was without glass fibre, applied velocity was 900 mm/s. While in present scenario, the velocity was increased to 960 mm/s. This means that glass fibre helps in reducing the cycle time by increasing the velocity. When the amount of carbon black was increased to 2%, the weld contour area was burnt by using 48% power and 960 mm/s velocity. So when the velocity was increased to 980 mm/s, again the contour area was slightly burnt. So afterwards, the laser speed was increased to 1000 mm/s and power to 50%, which gave a result of no bonding between samples. Then, laser velocity was reduced to 980 mm/s and there was perfect welding of samples (table 13). If the parameter setting is compared, it can be seen that for CB 1%, beam velocity was 960 mm/s, while for carbon black 2%, it was 980 mm/s. In both the cases, laser power was similar (50%). So it is possible to say that increase in the amount of carbon black helps in increasing the productivity of welding process.

Table 13 Process parameter adjustment for specimens with 10% glass fibre

				Velocity of laser						
Part	**Thickness**	**Carbon black**	**Glass fibre**	**900**	**920**	**950**	**960**	**980**	**1000**	**Power**
Transmission	1	-	-	-	B2	**838.63**	-	N1	-	48%
Absorption	1	1%	10%	-	B1	-	-	-	-	50%
				-	-	-	-	-	-	53%
Transmission	1.5	-	-	-	B2	-	N2	-	-	48%
Absorption	1	1%	10%	-	B1	-	**993.4**	-	N1	50%
				-		-		-	-	53%
Transmission	2	-	-	-		-		-	-	48%
Absorption	1	1%	10%	-		-	-	N1	-	50%
				-	B1	-	**1063.41**	-	-	53%
Transmission	2	-	-	-		-		-	-	48%
Absorption	1.5	1%	10%	-		-		-	-	50%
				-	B1	-	**1160.18**	-	-	53%
Part	**Thickness**	**Carbon black**	**Glass fibre**	**900**	**930**	**950**	**960**	**980**	**1000**	**Power**
Transmission	1	-	-	-	B2	**906.08**	-	N1	-	48%
Absorption	1	2%	10%	-	B1	-	-	-	-	50%
				-	-	-	-	-	-	53%
Transmission	1.5	-	-	-	-	-	B1	B2	-	48%
Absorption	1	2%	10%	-	-	-	-	**911.78**	N1	50%
				-	-	-	-	-	-	53%
Transmission	2	-	-	-	-	N1	-	-	-	48%
Absorption	1	2%	10%	-	-	**1102.5**	-	N2	-	50%
				-	-	B1	-	-	-	53%
Transmission	2	-	-	-	-	-	-	-	-	48%
Absorption	1.5	2%	10%	-	-	-	**1204.24**	N1	-	50%
				-	-	-	B1	-	-	53%

For the next experiment, the transmission part was changed to 2 mm where absorption part thickness was 1 mm with 1% of carbon black. As the thickness was still increased, for the first attempt, the used combination was: laser power 50% and velocity 980 mm/s. But there was partial welding of the specimen. The specimen was separated manually. So as a consequence, the laser power was increased to 53% and velocity was reduced to 920 mm/s, but it imparted some burn marks on specimen. So for final, the laser velocity was increased to 960 mm/s and laser power was 53%. This was perfect combination of parameters for this case. When the absorption part was without glass fibre, the suitable parameters were: power 53% and velocity 940 mm/s, whereas in the present case, due to glass fibre, the velocity was increased to 960 mm/s. This increment in velocity shows the improvement in the process due to the presence of glass fibre. After this, the amount of carbon black was increased to 2%. And for this experiment, the utilized process parameters were: laser power 50% and laser velocity 950 mm/s (table 13). It can be seen that, in an experiment with carbon black 2%, there is an increase in the velocity than it was in experiment with carbon black 1%. So again, this phenomena proves that if the amount of carbon black is raised, it helps improving the welding process. When the transmission part thickness was 1.5 mm, used velocity was 980 mm/s, whereas here, the velocity was 950 mm/s. So it could be stated that increase in the transmission part thickness takes more time to weld and thus, it affects economically.

As a last experiment in this stage, absorption part thickness was increased to 1.5 mm, while transmission part thickness was unchanged. As there is no change in the transmission part thickness, the utilized process parameters were similar as in previous case for carbon black 1% and 2% (table 13). In the case of specimens without glass fibre and with carbon black 1%, laser velocity was 940 mm/s. When in present scenario, used velocity was 960 mm/s. So due to this increase in the velocity, it is possible to say that glass fibre helps in lowering the cycle time. If the parameters for carbon black 1% and 2% are compared, it can be seen that for CB 1%, used parameters were: laser power 53% and velocity 960 mm/s. While for CB 2%, laser power was 50% and velocity was 960 mm/s. This decrease in the power value is due to glass fibre.

4.4. Evaluation of PP with 30% glass fibre

In the previous case, the absorption part was doped with carbon black and 10% of glass fibre. Therefore, as a last part of an experiment, absorption part was added with 30% of glass fibre and of course, with carbon black. According to the presumption, as the concentration of glass fibre increases, it would result in higher melting of absorption part. Thus, increase in glass fibre content should aid in weldability for laser welding process. For the first trial, transmission and absorption part thickness was 1 mm with 1% of carbon black. At the beginning, the process parameters were: laser power 50% and beam velocity 900 mm/s. As a result, the welding contour area was burnt more than 50%. So the laser power was reduced to 48% but still, there were some amount of burning marks. Therefore, to avoid these burn marks, laser velocity was increased to 960 mm/s. But there was no welding between specimens. The, the velocity was changed to 930 mm/s with 48% power. This time, the quality of weld was better. When there was no glass fibre present in an absorption part, used velocity for welding was 900 mm/s, while in this case, it is 930 mm/s. So it could be said that glass fibre helps in improving the process parameters. The parameters were improved because the glass fibre aids in the beam energy separation, which results in easier melting of the specimen. After that, the amount of carbon black was increased to 2%. In this case, the first attempt was done with 48% power and 980 mm/s velocity, but it resulted in no bonding between samples. So the velocity was reduced to 950 mm/s and the specimens were welded this time (table 14). So when the specimen was doped with 1% of CB, used velocity was 930 mm/s, whereas with 2% of CB, used velocity was 950 mm/s. These values show that carbon black helps in improvising the weldability as well as process parameters.

For the next case, transmission part thickness was increased to 1.5 mm. As the thickness was increased, it was necessary to adjust the process parameters accordingly. For carbon black 1%, the first used parameters were: 53% power and 930 mm/s speed. But the outcome was slight burning of contour area. So as a next trial, laser power was set to 50% and velocity was 960 mm/s. This time, the result was opposite than previous case. There was no welding occurred between samples. So the laser velocity was reduced to 930 mm/s and the result was better compared to last one. When the transmission part thickness was 1 mm, at that time used power was 48%, while in the present situation, power was 50%. This increase in the power was due to the increase in the thickness of transmission part. As the amount of carbon black was increased to 2%, the first used parameter was: laser power 48% and speed 950 mm/s. But the samples were not welded. Then, the laser power was set to 50% and velocity was kept to 980 mm/s. But this time, the result was even worse. The samples were easily separated manually. So as a last trial, the velocity was set to 950 mm/s with 50% power. By this parameter's setting, the bonding between specimens was better. When the amount of carbon black was 1%, used laser velocity was 930 mm/s, but in this case with carbon black 2%, laser velocity was 950 mm/s. This increase in the velocity shows the effect of carbon black in the specimen. To add up, the effect of increase in the thickness could be seen from the table 15. When the thickness of transmission part for CB 2% was 1 mm, used laser power was 48% and velocity was 950 mm/s. While for the present case with 1.5 mm transmission part, used power was 50% with the similar velocity. So this parameter setting proves that for higher value of thickness, either the power should increase or velocity should go down.

Table 14 Process parameter adjustment for specimen with 30% glass fibre

				Velocity of laser						
Part	**Thickness**	**Carbon black**	**Glass fibre**	**900**	**930**	**950**	**960**	**980**	**1000**	**Power**
Transmission	1	-	-	B2	**1054.16**	-	N1	-	-	48%
Absorption	1	1%	30%	B1	-	-	-	-	-	50%
				-	-	-	-	-	-	53%
Transmission	1.5	-	-	-	-	-	-	-	-	48%
Absorption	1	1%	30%	-	**1109.62**	-	N1	-	-	50%
				-	B1	-	-	-	-	53%
Transmission	2	-	-	-		-		-	-	48%
Absorption	1	1%	30%	-	-	-		-	-	50%
				-	B1	**1109.44**	-	N1	-	53%
Transmission	2	-	-	-	-	-	-	-	-	48%
Absorption	1.5	1%	30%	-	-	-	-	-	-	50%
				-	-	**1147.89**	-	-	-	53%

Part	**Thickness**	**Carbon black**	**Glass fibre**	**900**	**930**	**950**	**960**	**980**	**1000**	**Power**
Transmission	1	-	-	-	-	**574.36**	-	N1	-	48%
Absorption	1	2%	30%	-	-	-	-	-	-	50%
				-	-	-	-	-	-	53%
Transmission	1.5	-	-	-	-	N1	-	-	-	48%
Absorption	1	2%	30%	-	-	**781.70**	-	N2	-	50%
				-	-	-	-	-	-	53%
Transmission	2	-	-	-	-	-	-	-	-	48%
Absorption	1	2%	30%	-	-	-	-	-	-	50%
				B1	**835**	-	N1	-	-	53%
Transmission	2	-	-	-	-	-	-	-	-	48%
Absorption	1.5	2%	30%	-	**947.85**	-	-	-	-	50%
				-	-	-	-	-	-	53%

For next experiment, the transmission part thickness was increased to 2 mm. For carbon black content of 1%, the first used parameters were: 53% power and 930 mm/s laser speed. This resulted in high numbers of burning marks. So the laser velocity was increased to 980 mm/s and it gave completely opposite result. This time the samples were easily separated manually. So as a solution, laser velocity was reduced to 950 mm/s. This combination gave some good result and the specimens were welded perfectly. When the same experiment was made without glass fibre, used velocity was 940 mm/s. So it could be stated that there is some notable difference in the process parameters, when the specimens were doped with glass fibre. When the doping of carbon black was increased to 2%, settled parameters were: laser power 53% and velocity 930 mm/s.

For the last scenario, absorption part thickness was increased from 1 mm to 1.5 mm. As mentioned in previous experiments, this absorption part thickness has no significant effect on the laser weldability (table 14). Therefore, the process parameters for CB 1% was similar as they were for absorption part 1 mm (power 53% and velocity 950 mm/s). Also, the parameters' setting for CB 2% was similar as they were for absorption part 1 mm (power 50% and velocity 930 mm/s).

4.5. Evaluation by breaking force

Quality of welding could be assured by many aspects, but the most common are performed by checking visual and mechanical properties. Discussion about quality of weld by visual means (burning marks and partial welding) is already done in previous chapter. Therefore in this part, the mechanical quality of weld joint was made. To check the quality of weld, the evaluation was done by using tensile testing (TIRAtest 2300). The used standard for carrying out the test was TL 52018 and used loading rate or strain rate for performing tensile test was 15 mm/min.

When there was no carbon black present in the absorption part, it was not at all possible to weld the samples because, some kind of additives (glass fibre, carbon black) must be present in an absorption part to convert the laser beam energy into heat. Therefore, it was vital to dope absorption part with carbon black and glass fibre.

Therefore, the evaluation process was started with specimen containing only carbon black (1% and 2%). In Figure 45, there is a detailed information about the breaking force. It is obvious from figure 45 that when the thickness of transmission part is increased from 1 mm to 1.5 mm and 2 mm, there is no significant difference in the amount of breaking force (due to the range of standard deviation). It could be because of the process parameters setting. The adjusted parameters were not the same for all of them. If they were same for each one, there might be a problem of burning the specimens or partial welding. Also when the value of carbon black was increased from 1% to 2% for all the cases, there was very slight change in the force. Again the reason of this phenomena could be different setting of the parameters. But when the absorption part thickness was increased from 1 mm to 1.5 mm, it could be stated that there is some notable deviation in the value of breaking force then the rest. For an example, when the transmission part and absorption part were of thickness 2 mm and 1 mm respectively (for CB 1%), value of breaking force was 946.6 N, whereas it was 1125.7 N for transmission and absorption part 2 mm and 1.5 mm respectively. Table with detailed information about breaking force and standard deviation (with concrete values) for each cases is attached in the attachment.

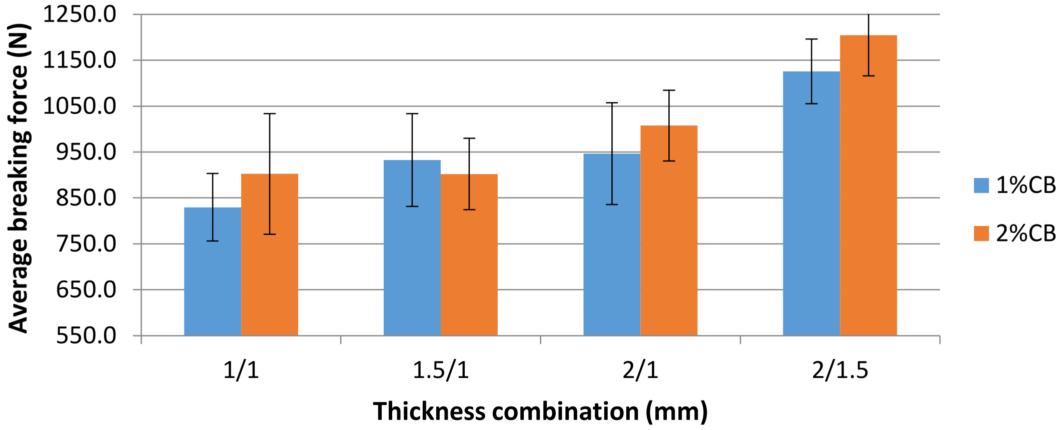

Figure 45 Maximum force for specimens without glass fibre

When the absorption part was mixed with glass fibre alongside with carbon black, mostly it changed the setting of process parameters (either reduce the power or increase the speed) as discussed. According to theory, if any specimen is doped with glass fibres, it aids in enhancing the mechanical strength during tensile test. Moreover, laser beam tends to lose its intensity while passing through the glass fibre doped material and it eventually helps in creating more heat and melt at the weld interface. This could result in better weld joint between specimens. Therefore there was a presumption made that doping of glass fibre in the absorption part alongside with carbon black might help in increasing the mechanical strength. So when the specimens were doped with glass fibres, it could be seen from figure 46 that value of breaking force is slightly raising than the cases without glass fibres. But also it is needless to say from figure 46 that the values of standard deviation were quite high. As like on previous case (without glass fibre), here also the increasing thickness of transmission part did not evoke breaking force, i.e. with an increase in transmission part thickness from 1 mm to 1.5 mm and 2 mm, the value of breaking force was nearly the same for each of them. When the absorption part thickness was increased from 1 mm to 1.5 mm, value of breaking force was not increased significantly. Moreover, from figure 46, it could be seen that when the amount of carbon black is increased from 1% to 2%, value of breaking force is about the same as for carbon black 1%. The root cause of this phenomena was used process parameters. They were not the same for each of them. Though this increase in carbon black changed the process parameters' setting (either increase in the velocity or decrease in power), for getting good quality of weld. These mentioned changes in the process parameters could help the laser welding process economically.

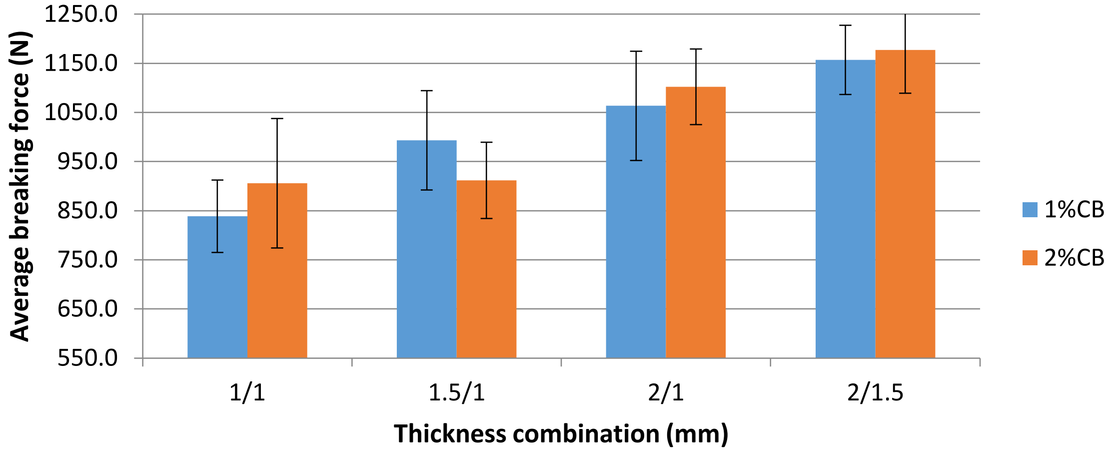

Figure 46 Maximum force for specimens with 10% glass fibre

When the absorption part was mixed with carbon black and 30% glass fibres, results for carbon black 1% were quite impressive. In this particular case (CB 1%), the raise in amount of glass fibre not only altered the setting of process parameters (either reduction in power or increment in velocity) but also increased the mechanical quality of joint. If the values of breaking force for transmission and absorption part 1 mm with CB 1% is compared to the case without and with 10% glass fibre (figure 45, 46, 47), there is some notable difference in them (except the variants of transmission part 2 mm). This raise in breaking force was due to increased amount of glass fibre. From figure 47, it is possible to state that the values of breaking force for all the thickness combinations with 1% of carbon black and 30% of glass fibre are nearly the same. For variants of transmission part thickness 2 mm (with absorption pat 1 mm and 1.5 mm), used process parameters were similar for both. But the value of breaking force was nearly similar here, because of standard deviation. There was a presumption made for variants of carbon black 2% and glass fibre 30% that, the value of breaking force should be the highest amongst each variants (without glass fibre, with 10% glass fibre) or at least on a same level with carbon black 1% but, the outcome for specimens with carbon black 2% was a bit interesting. It was because the value of average breaking force was the least for all the variants.

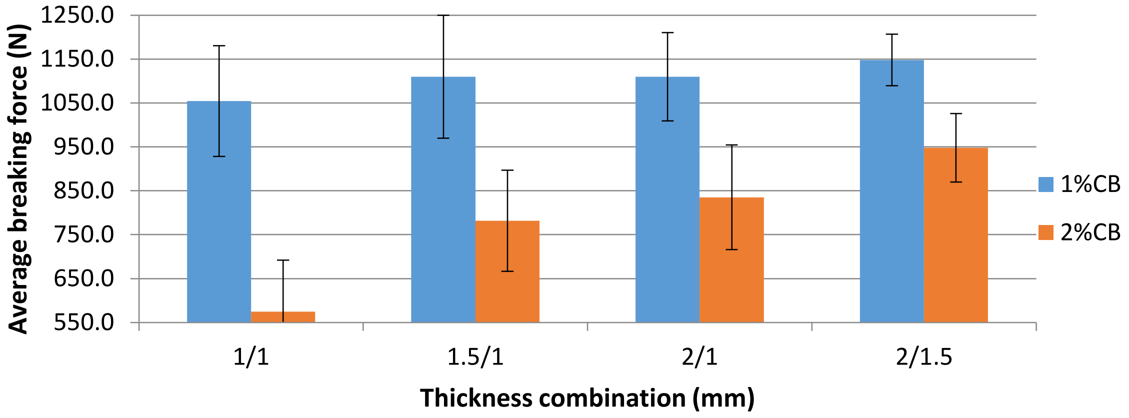

Figure 47 Maximum force for specimens with 30% glass fibre

5. Conclusion

Laser welding is by far one of the most used and precise non-conventional methods for joining two thermoplastic products which have a wide range of applications in all the industries. There are different kinds of lasers (CO_2 laser, Nd:YAG laser, Diode laser, Fibre laser) and all of them can be adopted according to their wavelengths. These different kinds of lasers divide laser welding technology in two: direct laser welding (CO_2 laser) and through-transmission laser welding (Nd:YAG laser, Fibre laser), from which through-transmission laser welding (TTLW) is founded most commonly in practice for joining plastic parts.

The main theme of the thesis was to investigate the weldability of polypropylene homopolymer with respect to sample thickness and chosen kind of additives by laser welding technology. The specimens were produced by injection moulding technology and their thickness was kept lower (1 mm, 1.5 mm and 2 mm), in order to fulfil the increasing demands from companies to achieve as low weight of the part as possible. As an additive of polypropylene, variants with CB (1% and 2%) as well as with GF (0%, 10%, and 30%) were also examined. Glass fibre helps in increasing the mechanical strength and also it has a characteristic of high temperature resistance. Therefore, PP based composites with glass fibre is commonly founded in a lot of the applications. All of these samples were welded on laser welding station LM05/05 X.W, which was designed by VÚTS, a.s. and equipped with a solid state laser with a laser source of Yb:Fibre.

By performing the first experiment, it was detected that despite of keeping the same process parameters, mechanical quality of weld was not similar for each specimen. For example, by keeping the same parameters, sometimes the specimens were burnt or sometimes they were partially welded. This problem could be due to the uneven force distribution on the samples caused by clamping plate and the force distribution problem was increased with higher specimens' thickness. Therefore, to negotiate this problem, optimized clamping (torque wrench) was used to make sure that the force distribution is even and also specimens with lower thickness were injected.

Theoretical presumption says that, if the transmission part thickness is raised, then obviously the laser beam must be able to penetrate deep into the material and by doing so, the beam tends to lose its intensity or energy until it reaches to the absorption part. So to compensate this effect and to have a good quality of the weld, in the laser machine, either the value of power should be increased or the rate of velocity should be lowered so that, the laser beam can properly melt the weld area. A similar thing was witnessed during the experiment. When the transmission part thickness was increased from 1 mm to 1.5 mm and 2 mm, process parameters were also altered as mentioned above. However, this change in the process parameters had a very minute effect on the mechanical weld quality due to the standard deviation factor. On the contrary, when the absorption part thickness was increased (from 1 to 1.5 mm), it was not necessary to change the parameters because increase in absorption part thickness has no dependency on the process parameters. While this increase in absorption part thickness helped in elevating mechanical weld quality (breaking force) by some amount (except for the case GF 30%).

From the performed experiments, it was confirmed that in order to weld plastic parts by laser technology, doping of carbon black into an absorption part becomes necessary. As the theory suggests, when the amount of carbon black increases, then the melting procedure of both the parts at weld area becomes easier due to higher energy generation, which could result in either reduction in the power or increment in the velocity of the beam. Thence, the exact similar thing was observed during an experiment. These changes in process parameters however did not evoke the mechanical quality of weld joint (breaking force), but it could be stated that when the velocity of laser beam increases, it lessens the time of welding and eventually results in higher productivity with similar weld quality.

According to the theoretical presumption, as the laser beam penetrates into the polymer matrix, which is doped with glass fibre, the beam tends to lose its energy and convert it into heat, which results in easier melting of specimens. Before performing an actual experiment, it was assumed that increase in heat generation and easier melting of specimens due to glass fibre would evoke a change in process parameters (either reduce the power or increase the velocity). Even though for specimens with 10% glass fibre, there was not necessary to change the values of process parameters (compared to 0% GF) and moreover, there was no marginal difference in mechanical weld quality. Whereas, when the absorption part was doped with 1% CB and 30% GF, it was necessary to change the process parameters (compared to 0% GF) to maintain good weld quality (no burning or partial welding). Additionally, the mechanical weld quality (breaking force) was also improved by a significant amount. However, for specimens with 2% CB and 30% GF, there was observed very interesting results than the presumption. The mechanical weld quality was decreased in this particular case.

To put all these things in a nutshell, it could be concluded that for successful laser welding between two parts, the absorption part must be doped with some sort of additives (carbon black, glass fibre). Also, it is better to increase the thickness of an absorption part rather than increasing transmission part thickness in light of a fact that, if the absorption part thickness increases, it does not require any adjustment in the process parameters’ setting and in addition, it also helps in building some good mechanical quality of joint.

Finally, it is noteworthy to mention that these experimental measurements were made only for one kind of polypropylene. Therefore, the introduced results could not be general. For general conclusion, it would be necessary to do more experiments on a different kind of polypropylene (copolymers, polymer blends). Very interesting information could be for example to know the influence of different kind of additives (colorants, minerals, natural fibres) on weldability. Next recommendation is to find a better solution for optimization of clamping units. Although there was made an optimization of specimens' fixation, value of standard deviation for evaluated results (breaking force) was still high. Therefore next optimization of this process should be made.

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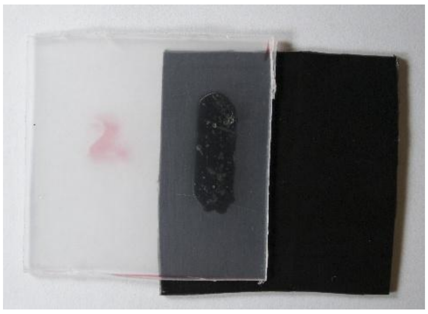
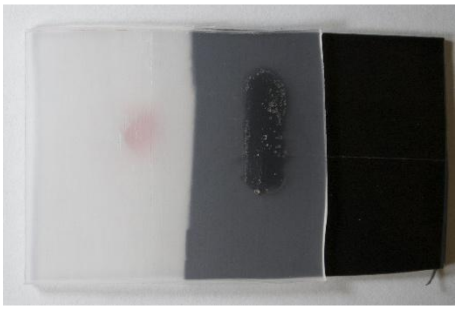
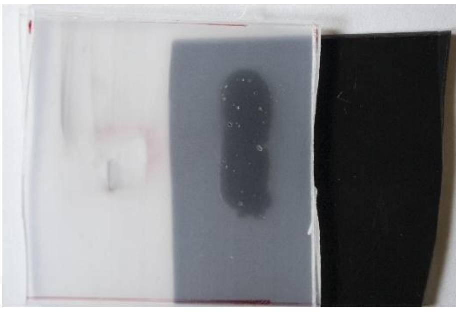
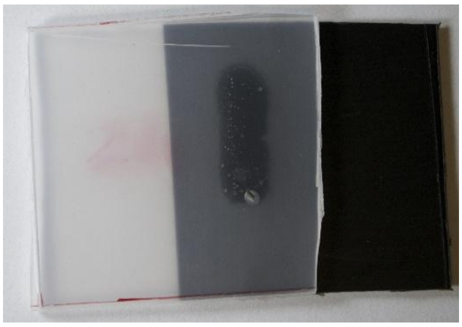
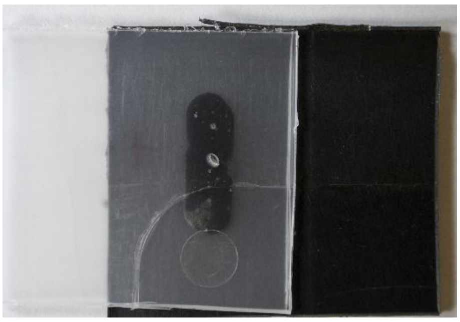
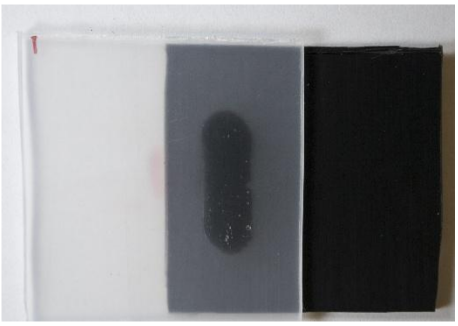
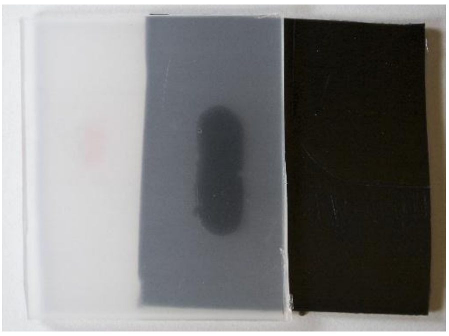
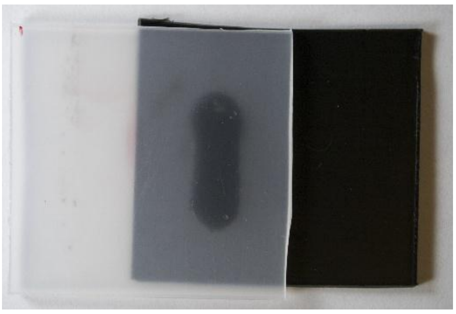
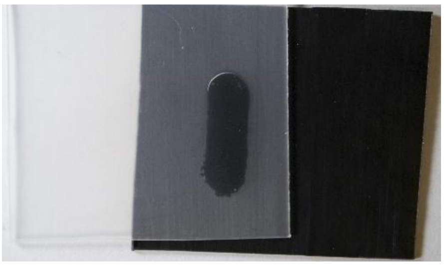
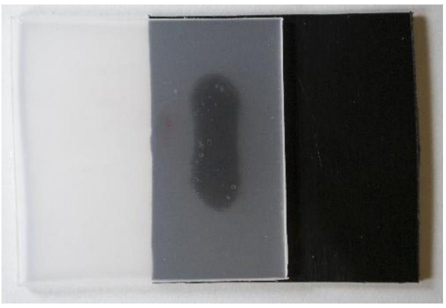
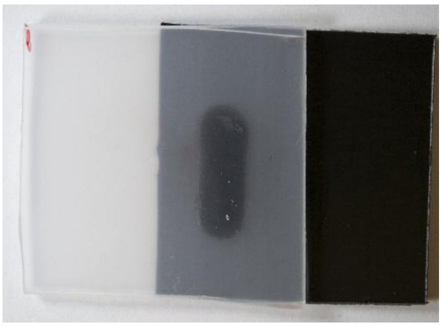
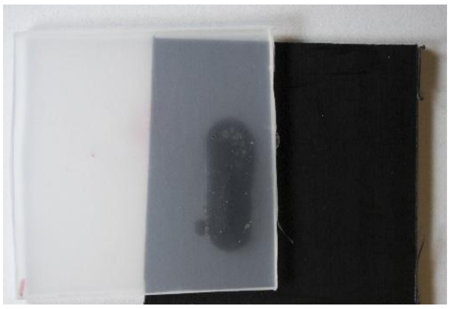
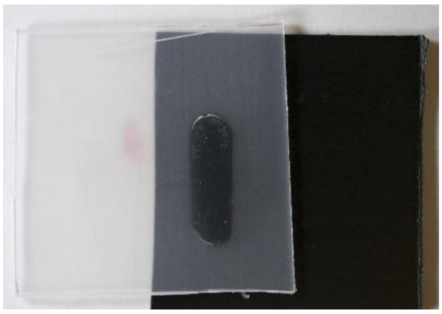
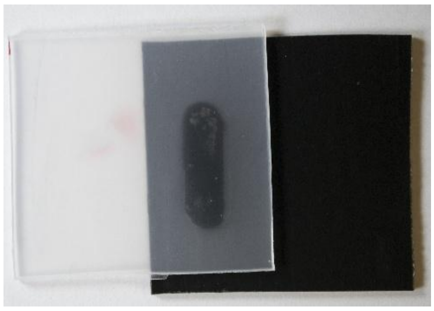
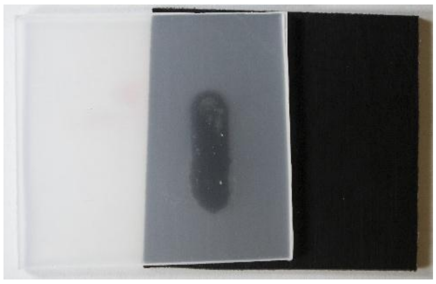
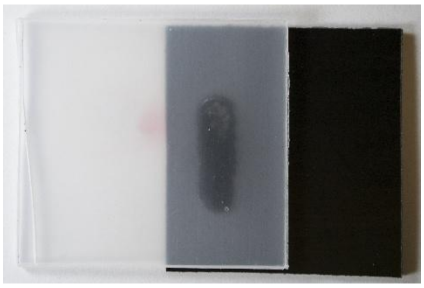
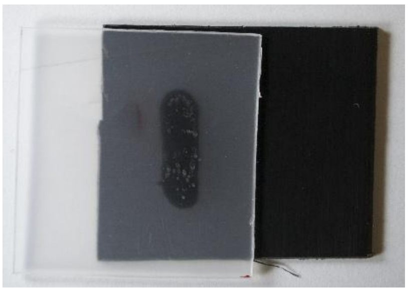
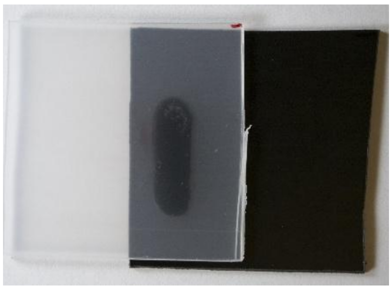
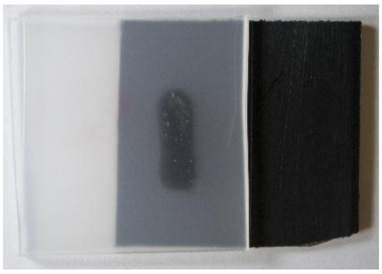
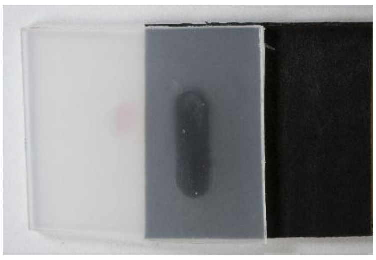
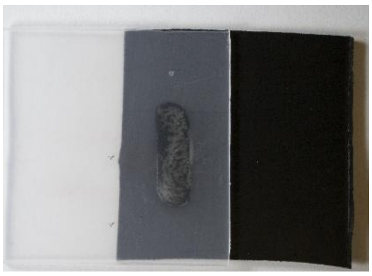
List of figures

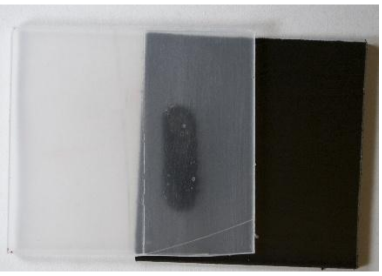
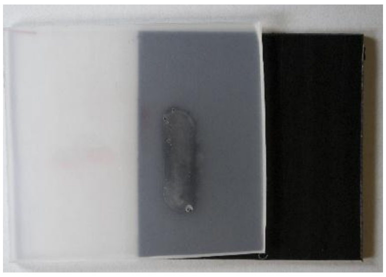
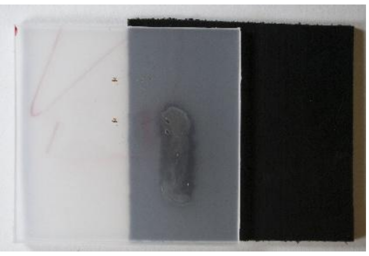
- **Attachment 1**

No.	Specimens combination	Visual quality of weld
1	Transmission 1 mm and absorption part 1 mm with 1% CB and without GF	
2	Transmission 1.5 mm and absorption part 1 mm with 1% CB and without GF	
3	Transmission 2 mm and absorption part 1 mm with 1% CB and without GF	
4	Transmission 2 mm and absorption part 1.5 mm with 1% CB and without GF	
5	Transmission 1 mm and absorption part 1 mm with 2% CB and without GF	

6	Transmission 1.5 mm and absorption part 1 mm with 2% CB and without GF	
7	Transmission 2 mm and absorption part 1 mm with 2% CB and without GF	
8	Transmission 2 mm and absorption part 1.5 mm with 2% CB and without GF	
9	Transmission 1 mm and absorption part 1 mm with 1% CB and 10% GF	
10	Transmission 1.5 mm and absorption part 1 mm with 1% CB and 10% GF	

11	Transmission 2 mm and absorption part 1 mm with 1% CB and 10% GF	
12	Transmission 2 mm and absorption part 1.5 mm with 1% CB and 10% GF	
13	Transmission 1 mm and absorption part 1 mm with 2% CB and 10% GF	
14	Transmission 1.5 mm and absorption part 1 mm with 2% CB and 10% GF	
15	Transmission 2 mm and absorption part 1 mm with 2% CB and 10% GF	

16	Transmission 2 mm and absorption part 1.5 mm with 2% CB and 10% GF	
17	Transmission 1 mm and absorption part 1 mm with 1% CB and 30% GF	
18	Transmission 1.5 mm and absorption part 1 mm with 1% CB and 30% GF	
19	Transmission 2 mm and absorption part 1 mm with 1% CB and 30% GF	
20	Transmission 2 mm and absorption part 1.5 mm with 1% CB and 30% GF	
21	Transmission 1 mm and absorption part 1 mm with 2% CB and 30% GF	

22	Transmission 1.5 mm and absorption part 1 mm with 2% CB and 30% GF	
23	Transmission 2 mm and absorption part 1 mm with 2% CB and 30% GF	
24	Transmission 2 mm and absorption part 1.5 mm with 2% CB and 30% GF	

- **Attachment 2**

Table 1 Breaking force and standard deviation for all the cases

Glass fibre 0%								
Carbon black	Transmission part / Absorption part thickness (mm)							
	1 / 1		1.5 / 1		2 / 1		2 / 1.5	
	Breaking force (N)	Standard deviation (N)	Breaking force (N)	Standard deviation (N)	Breaking force (N)	Standard deviation (N)	Breaking force (N)	Standard deviation (N)
1%	829.5	73.6	932.5	101.2	946.6	111.0	1125.7	70.4
2%	902.2	131.7	902.0	77.6	1007.6	77.0	1204.2	88.1
Glass fibre 10%								
Carbon black	Transmission part / Absorption part thickness (mm)							
	1 / 1		1.5 / 1		2 / 1		2 / 1.5	
	Breaking force (N)	Standard deviation (N)	Breaking force (N)	Standard deviation (N)	Breaking force (N)	Standard deviation (N)	Breaking force (N)	Standard deviation (N)
1%	838.6	59.7	993.4	55.8	1063.4	97.6	1157.2	53.5
2%	906.1	51.8	911.8	75.9	1102.3	79.9	1177.3	56.7
Glass fibre 30%								
Carbon black	Transmission part / Absorption part thickness (mm)							
	1 / 1		1.5 / 1		2 / 1		2 / 1.5	
	Breaking force (N)	Standard deviation (N)	Breaking force (N)	Standard deviation (N)	Breaking force (N)	Standard deviation (N)	Breaking force (N)	Standard deviation (N)
1%	1054.2	126.2	1109.6	139.9	1109.4	100.5	1147.9	58.9
2%	574.4	117.3	781.7	115.0	835.0	119.3	947.9	77.9