Doctoral Dissertation
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Study and design of hollow core wave guide for LASER beam propagation

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Carmelo Nicosia
Turin, January 28, 2021

Summary

In most of the components, plastics are replacing the use of other materials. Since plastic allows for a lighter product, it is also possible to obtain more complex shapes with the use of less energy for forming the plastic components. This determines a substantial increase in the use of polymeric materials in many industrial applications. The increase in production volume leads to a greater investment by industries in technologies for processing plastics.

The components that make up a product have different functions and properties. In other cases, the unique option to produce a part is to divide it down into sub-parts. For these reasons, it is often necessary to fasten several components together. Among the various joining methods, there are gluing, mechanical fixing, welding. Each type of fixing has its advantages and disadvantages.

Welding is one of the most widely used technologies in the industrial field. For plastic, different welding technologies have been studied and developed, through transmission laser, in particular, is the most widely used. There are different technologies for transmission. Some are still new and therefore need to be optimized for industrial applications.

The subject of this thesis work is concentrated on this context. Simultaneous laser welding has been studied and developed.

Laser welding was introduced several years ago and is widely used in the industrial sector. However, different technologies or applications have developed in recent years and although simultaneous welding was known theoretically, its industrial application is not widespread or is used for easy applications. In this thesis work, methodologies to make this technology suitable for many industrial sectors are researched.

The system for simultaneous laser welding through transmission consists of optical fibers coupled with a hollow core waveguide, which transmits and uniforms the energy on the pieces to be welded.

The beam coming from a diode laser source enters a bundle of optical fibers which divides the power proportionally over several branches. Therefore, each branch of the bundle has a fraction of fibers that are enclosed in a metal shell called ferrule. Each ferrule behaves as a single point of light with a Gaussian outgoing energy profile. The ferrules of many bundles are mounted next to each other and facing the waveguide, that is the element that completely uniform the laser energy.

The main part of the research is the study of hollow core waveguides. These components allow to homogenise the laser beams coming from the different sources, therefore they are the fundamental elements to obtain a good simultaneous laser welding. On the parts to be welded, a homogeneous energy contour is obtained through the waveguide, that profiles the Gaussian power distribution at the output of the optical fibers. Many tests have been carried out to evaluate the characteristic parameters that influence the energy distribution. Geometric parameters (e.g., shape, height, etc.), materials and treatments on the materials have been studied to obtain the present result. A model of the system in an optical simulator and ray-tracing software, OpticStudio Zemax, was developed. In this way, it was possible to design the waveguide and evaluate the parameters to obtain the homogeneous energy distribution for the welding of the plastic components.

The waveguide is specific for each application. Depending on the component to be welded and the welding path, a dedicated waveguide must be designed. Often the components were very complex so the simulation and design times were lengthened, so there was the need to implement a tool that would help designers in evaluating the best waveguide parameters. In this regard, a code has been written in the SolidWorks API which allows analysing and simulating numerous solutions. When the macro was completed, it was implemented with some dialog boxes in such a way that it resembled a SolidWorks add-in. From the dialog box can be set the simulation parameters of the waveguide. Through a repetition process, the program simulates various geometric parameters and different positioning of the waveguide and ferrules on the ray-tracing software. After the simulation phase, the results established the position and the parameters with the greatest efficiency. The operator can choose the best positioning and develop the complete waveguide that matches the needs of the parts to be welded.

Acknowledgment

My deepest gratitude goes to my Supervisor Prof. Luciano Scaltrito, who has followed me in these years of research, who has always supported me and which allowed me to join the work group in which I shared many experiences and I increased my university and working background. A big thank you to my co-Supervisor Prof. Sergio Ferrero which help me in my university career.

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Finally, I want to thank my family, who have been by my side in all these years of study and work, supporting my choices and supporting me in every way to realize my life path.

Alla mia famiglia che mi
ha sempre supportato

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Chapter 1

1- Introduction

1.1 Expansion of Polymers in the market

The use of polymers in industries is exponentially increasing. Much of the plastics market is dominated by packaging, medical, construction, electronics and automotive.

The transport sector is one of the most important segments in the society. The automobile market is growing fast, as evidenced by the data that led to an increase of 143% per hundred inhabitants in the USA from 1950 to 1996 [1]. The growth of the population, the increased mobility, the technological development and the following reduced purchase costs are the main reasons for the rise of this market. Forecasts say that by 2030, mobility with personal automotive in terms of mileage could increase by 23% in Europe, by 24% in the US and by 183% in China [2].

In the automotive sector, the use of polymers is growing considerably to the detriment of metal components. Plastics are used to obtain lighter vehicles. This characteristic increases efficiency and reduces the consumption of fuel, it follows lower emissions of pollutants. In fact, a strong incentive for the replacement of metals with polymers came from the need and obligations of the nations to reduce emissions. In addition, the lower weight increases the life of the essential components of the vehicle such as the brake system, suspension and propulsion system [3].

Nowadays average car, more than half of the components are made of metal, with 55% of cast iron/steel and 9% of aluminium alloys, the second place is occupied by polymeric materials with 11% [4].

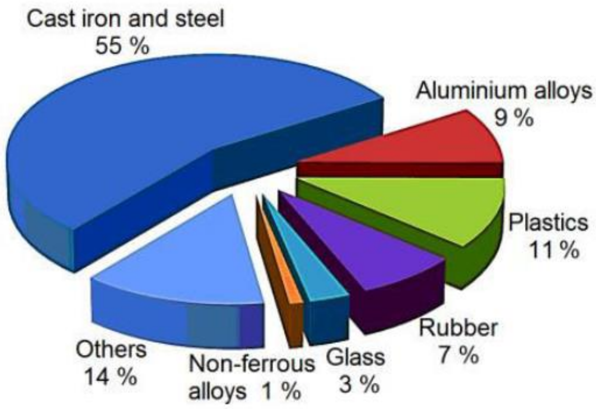


Figure 1-1 – Composition of materials of the car's components [4]

In a vehicle, approximately 1160 kg is of metal and 150 kg is of plastic materials [5]. A trend in the plastic increasing could be seen in Figure 1-2.

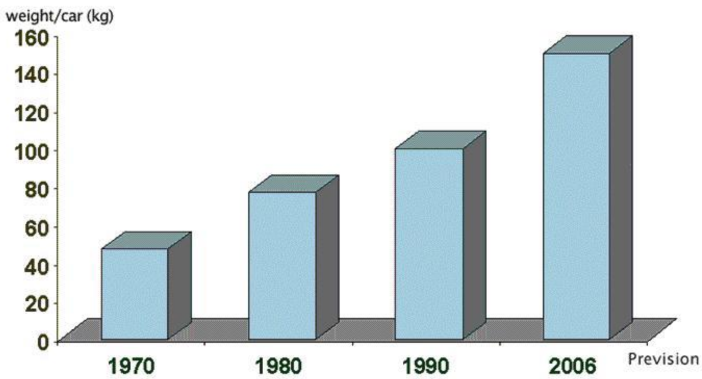


Figure 1-2 - Increasing use of the polymers in automotive sector [6]

From 1977 to 2014, 10-15% of steel / iron was reduced in the distribution of materials in an average car [7]. The share of use of steel has been replaced by polymeric materials and aluminium alloys.

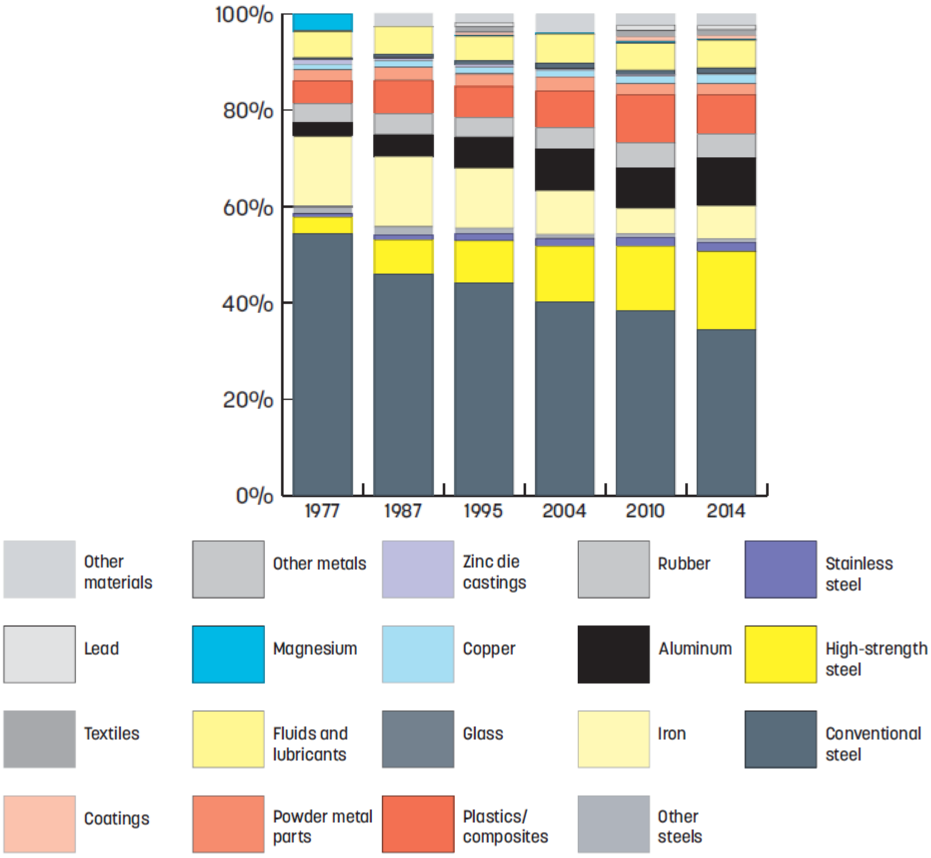


Figure 1-3 – Trend in the past years of percentage of materials used in a car [7]

The growth of plastic occurred when there was substantial development of thermoplastic materials, such as ABS, polyamide, polycarbonate, polymethylmethacrylate. The need to move on to the development and expansion of alternative materials, such as polymers, occurred after the end of the Second World War, as there was a shortage of metals. Before that, plastic was used exclusively for military use, this led to the so-called polymer revolution [8].

The first substantial advantage of plastic components is the ability to be produced and molded much more easily than metal materials. This feature allows obtaining complex geometries and reducing time needed for production and assembly. Therefore, plastic has replaced other materials, or it is used in the composite for the interior and exterior aesthetic components, bumpers, rear window and windshield, front and rear lamps, components under the hood. Thanks to the replacement of plastic, for example, it is possible to realize the fuel system of the tank with a more complex design.

In Figure 1-4 the materials used in a modern car and a forecast on changing in the composition. [9].

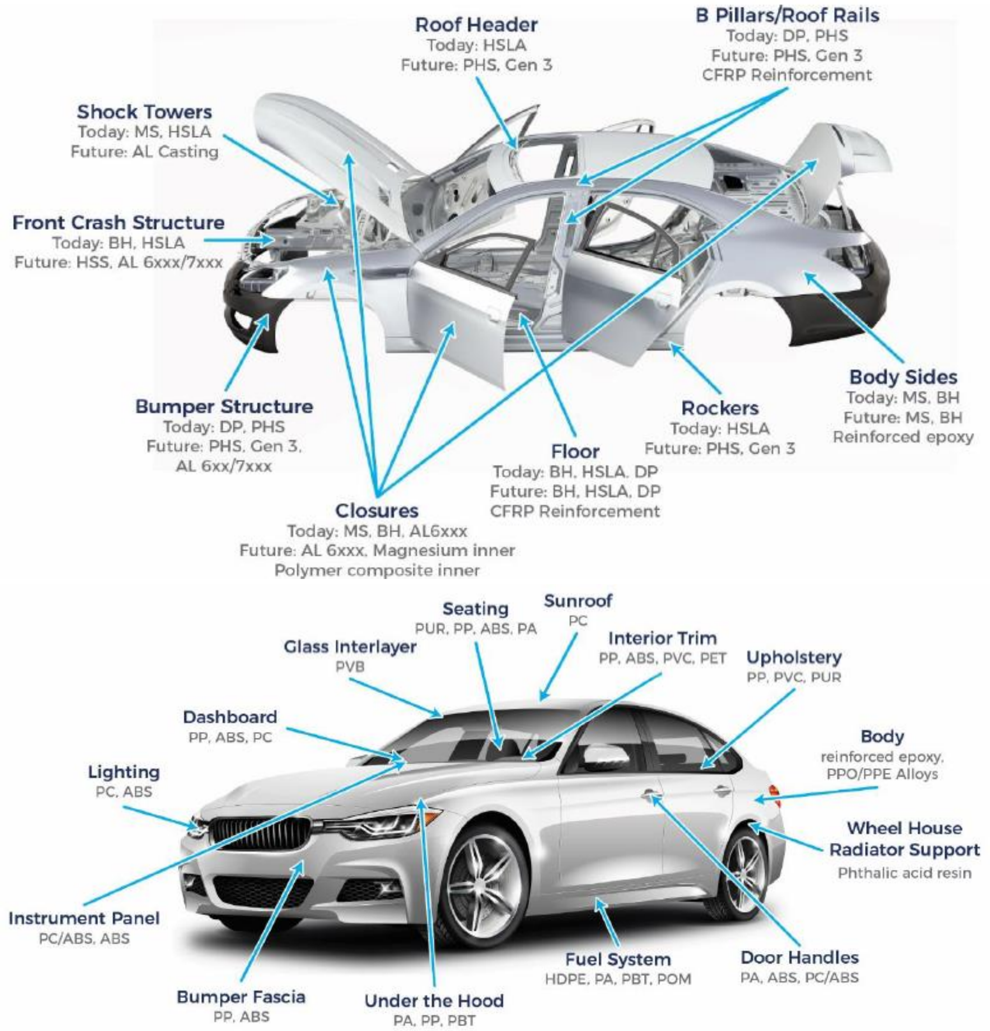


Figure 1-4 – Main materials in the structure of a car [9]

Metals				
HSLA	High-strength low-alloy steel		PHS	Press Hardenable Steel
BH	Bake-Hardenable Steel		Gen 3	Generation three steel
DP	Dual-phase steel		MS	Mild Steel
Plastics and Polymers Composites				
ABS	Acrylonitrile Butadiene Styrene		PET	Polyethylene terephthalate
HDPE	High-density polyethylene		POM	Polyoxymethylene
PA	Polyamide		PP	Polypropylene
PBT	Polybutylene terephthalate		PPE	Polyphenylene Ether
PC	Polycarbonate		PPO	Polyphenylene Oxide
PUR	Polyurethane		PVC	Polyvinyl Chloride
PVB	Polyvinyl butyral		CFRP	Carbon Fiber Reinforced Composite

Table 1-1 – Materials Legend refers to Figure 1-4 [9]

Another advantage of plastics is the high ratio between strength and density. This property makes them excellent substitutes for metals in some applications. Figure 1-5 shows that some classes of polymers with a confrontable strength have a density minor of about 4-10 times [10].

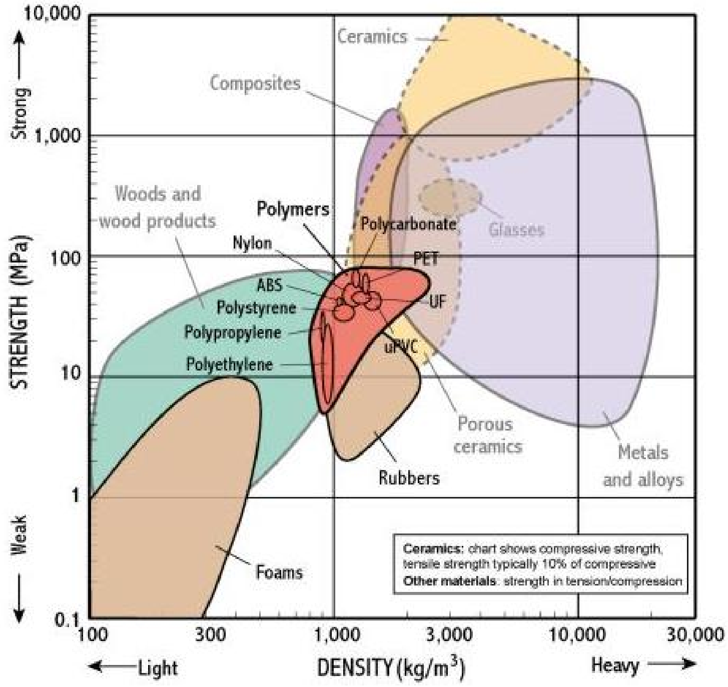


Figure 1-5 - Strength vs Density for industrial materials [10]

Polymers have good values of breaking strength (energy that can be absorbed until the breaking of the material), but the most important key feature is yield strength, which measures the load that the material can withstand without plastic deformation. These characteristics give good workability, both in the production and in post-production phase. They are easy to handle for the assembly or for the subsequent processes, e.g., compression of components during welding or adhesion phases.

Other properties of polymers are good fatigue resistance, good thermal stability and good thermal insulation [11].

Below a summary of the principal advantages of polymers:

- High specific resistance ratio between strength and density,
- Flexibility for the design and production,
- Low production costs,
- Good corrosion and environment resistance,
- Thermal and electrical isolation,
- Durability

The polymeric materials can be classified in three types: thermoplastic, thermosetting and elastomers. The most common materials are thermoplastics because even after the polymerization process they can be heated and reshaped. In addition, they can be easily recycled. The properties of most thermoplastics are not modified even after reaching the glass transition temperature, the phase where the material liquefies and can be reformed. This property makes them particularly suitable for injection molding.

Thermoplastics have characteristics that make them very suitable for a wide range of applications and needs [5]. For instance:

- PA (or nylon) offers high abrasion resistance and good chemical resistance, used in cams, bearings.
- PC resists and maintains its properties even when subjected to atmospheric agents and UV rays; the excellent transparency allows using it in safety screens, aircraft panels, lenses.
- PMMA is more transparent than glass, it has good shatterproof properties and resistance to UV rays, which is why it is used in displays, screens, taillights, lenses.
- ABS is durable and resistant to atmospheric and chemical agents. It is a rigid plastic with rubber that has characteristics that give it a good impact resistance.

Thermosets become hard after the polymerization process and high temperatures cause degradation of the material.

1.2 Joining of thermoplastics

Nowadays it is increasingly necessary to combine different materials and this factor is one of the most significant challenges for the use of materials. In industry, there is a need to have a final product with the modularity of components [12]. Components are often made of different material, or produced with diverse process, so it is necessary to assemble these subparts to obtain the final product. The joint of different plastic parts plays an important role in all major industrial sectors such as automotive, medical, household appliances, transportation. Furthermore, sometimes it is necessary to hermetically join the parts, e.g., in the packaging industry. There are three reasons to join the plastic:

- The production of the entire component is uneconomical from the point of view of production;
- By separating a component, it is possible to prevent complex prototyping and expensive tools;

- Allows the use of different materials.

The continuous development of products entails increasingly higher demands in mechanical terms. Multicomponent systems and the use of distinct materials for different components allow that the optimal material is used for each individual function [13].

Companies are constantly researching new technologies to improve the process and the quality of the final product.

Three main techniques are used to join thermoplastic materials:

- mechanical fastening,
- adhesive bonding,
- direct bonding.

Mechanical fastening includes clips, screwing elements or riveting. In adhesive bonding, a third material (adhesives) is used to create the joint. Direct bonding or weld includes all the processes with a permanent joint without the use of adhesive or chemical products, normally it occurs by applying heat and pressure located in the joint area [14].

The mechanical fixing has the disadvantage of the connection complexity in case a hermetic environment is necessary. In the case of hermetic applications, the direct bonding is usually preferred. This is the most used and developed methodology in the automotive sector [15].

The weld creates a joint that generally has the same characteristics as the original material. It is possible to classify the direct bonding methods into three main categories: thermal, friction and electromagnetic. Figure 1-6 shows some of the technologies belonging to the direct bonding.

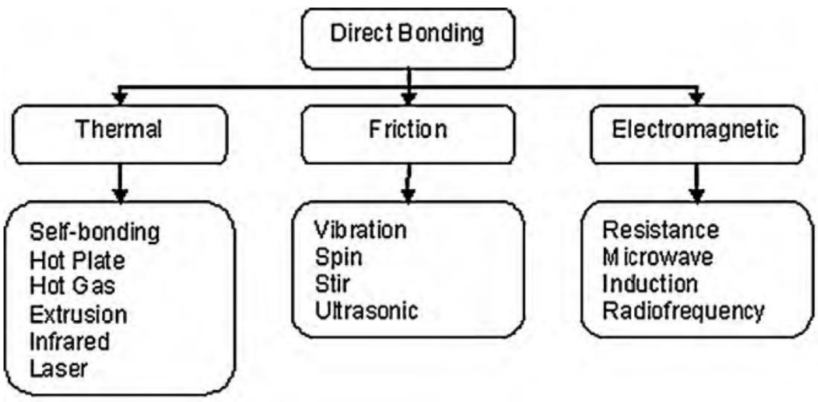


Figure 1-6 - -Welding technics for thermoplastic materials [14]

1.2.1 Laser Welding

Laser application is greatly demanded for its versatility. In fact, this technology offers significantly higher precision, good visual appearance, flexibility and productivity in the material processing application than any other traditional approach. The process of laser welding is very fast; therefore, it creates a very resistant weld joint and a heat affected zone reduced in comparison with the other methods. This permits that internal components, sensible to the heat, aren't damaged. It is a clean process i.e. it does not create dust or residues. These features are leading to growing interest in the laser technology-based material processing.

The serial production of solid-state lasers has enabled a reduction in costs. The increasing use of high-power laser diodes is accelerating the growth of this market. The coupling of a diode laser source with optical fibers has led to the expansion of a variety of industrial applications such as: welding, heating, cutting. This was one of the main factors that allowed laser welding for polymeric materials to enter the market. Among the first applications of laser technology with polymers was a car key in 1997 for the Mercedes Benz type 190 [16].

The main differences between laser welding for plastics depend on how the radiation reaches the weld joint and how it is absorbed. It is possible to identify different kinds of junctions, where both materials absorb the radiation electromagnetic, either or both are transparent and a bond is realized at the interfaces, or one material is transparent and the other one is absorbent.

The first classification, according to the irradiation method and the type of junction, it can be made:

- **Butt joint welding**, shown in Figure 1-7, both materials must be absorbent, or if they are transparent the interfaces must absorb the radiation. Usually, butt-welding needs additives with high absorption coefficient to add in both parts or specific coatings in the surfaces must be used.
- **Through Transmission welding**, shown in Figure 1-8, one material is absorbent to the laser radiation and the other one is transparent or both with the same light absorption properties (e.g., used to join films or layers). This method of laser welding is called Through-transmission Laser Welding (TTLW).

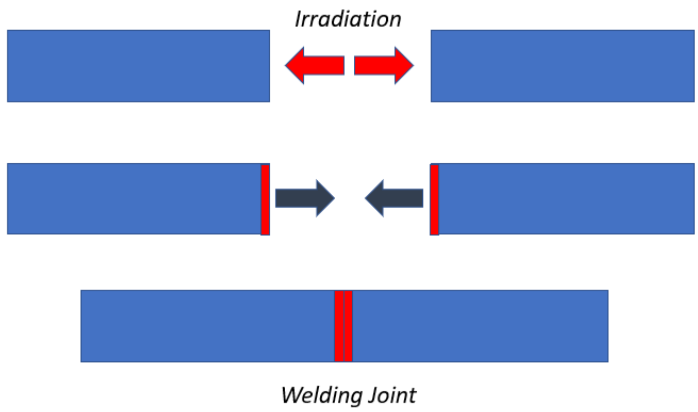


Figure 1-7 – Butt welding phases: 1) Irradiation of the two components, 2) Heating and pressing, 3) Cooling of the heated part.

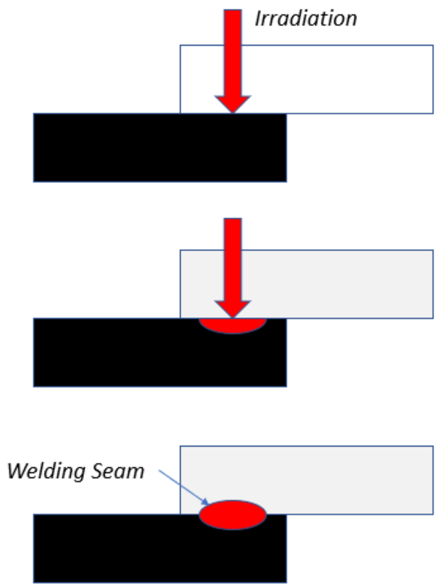


Figure 1-8 – Through transmission welding phases: 1) Irradiation, 2) Heating of the absorbent material, 3) Transferring of heating in the transparent material.

Both processes have advantages and disadvantages to take into account in the choice of the method of joint.

Nowadays the TTLW is the most used in industrial processes that utilizes lasers [16]. Usually, this process allows joining a plastic absorbent component with a laser-transparent one. The infrared radiation could be driven, passing through the transparent part and heating the absorbent component until the melting point. The absorbent component, according to the principle of conduction, heats the transparent one, allowing the welding. The heated material causes a flow of heat to the cold layers, resulting in inter-diffusion of the material. To have a good weld both the transparent and the absorbent material must reach the melting point. To ensure a perfect welding and sealing quality, the two components are pressed together in order to have the surfaces in contact during the emission. The surfaces have a roughness that hinders the flow of heat, for this reason, a good thrust allows the molten material to move in the spaces and the heat flow increases. Too much roughness increases the activation times of the melting process [17].

An example (Figure 1-9) is the taillights of automobiles where a plastic lens, transparent even at the visible spectrum, is joint with a housing that has a structural function. Due to the characteristics of the product, application in the lights is the most common. In fact, all the lenses are produced in PMMA or PC, materials with high laser transparency, while the bodies of the lights are usually in black ABS. The colour is due to the carbon black additives, which makes the material absorbent to electromagnetic radiation.

Figure 1-9 –Taillight: 1) lens in PMMA, laser transparent, 2) housing in ABS, laser absorbent

Excellent strength qualities and improved visual aspects are some of the advantages of these applications in the automotive field. The visual aspect is important for aesthetical components like taillights (Figure 1-9), instrument cluster (Figure 1-10).

A good degree of cleaning is also required in the elements of the engine, researching a reduction of the dust, usually produced to the joining process. Laser technology achieves these results.

There are large cost reductions when laser welding is used in high volumes or mass production, thanks to its low cycle time. [17].

Figure 1-10 – Other examples of laser welded components in the automotive field: Instrument Cluster, Key, micro-fluidic device and tank

Usually, different types of material can be joined together, however, there must be chemical compatibility and similar melting temperatures. Tests to prove the compatibility and the grade of cohesion need to be made. In Figure 1-11 the state of the art of compatibility knowledge.

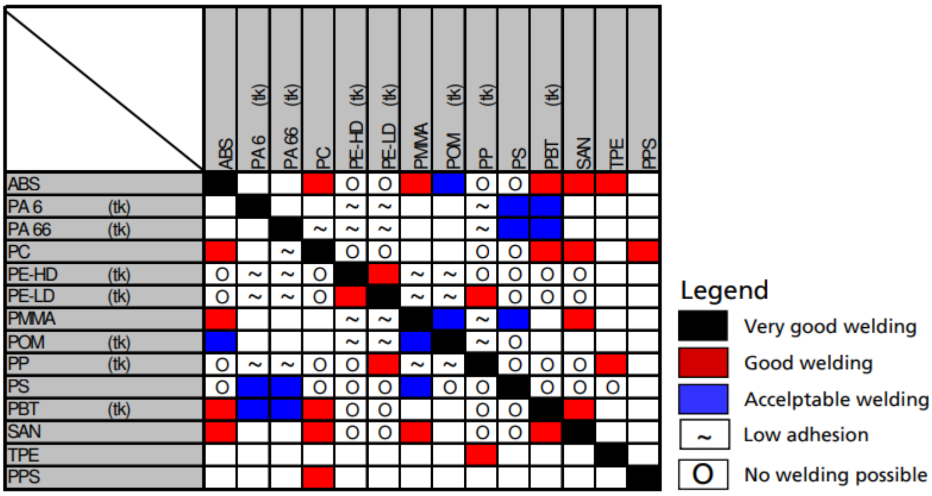


Figure 1-11 – Compatible materials combination [18]

Depending on the irradiation strategy in the TTLW, these main technologies can be identified:

- Contour welding;
- Simultaneous welding;
- Quasi-simultaneous welding;
- Radial welding;
- Mask welding;
- Diffractive optical elements welding.

These and many other factors must be considered for the development of the technology and to obtain a product suitable for the needs with wanted quality. The diagram in Figure 1-12 considers the main essential points to be developed and analysed in the study of the technology.

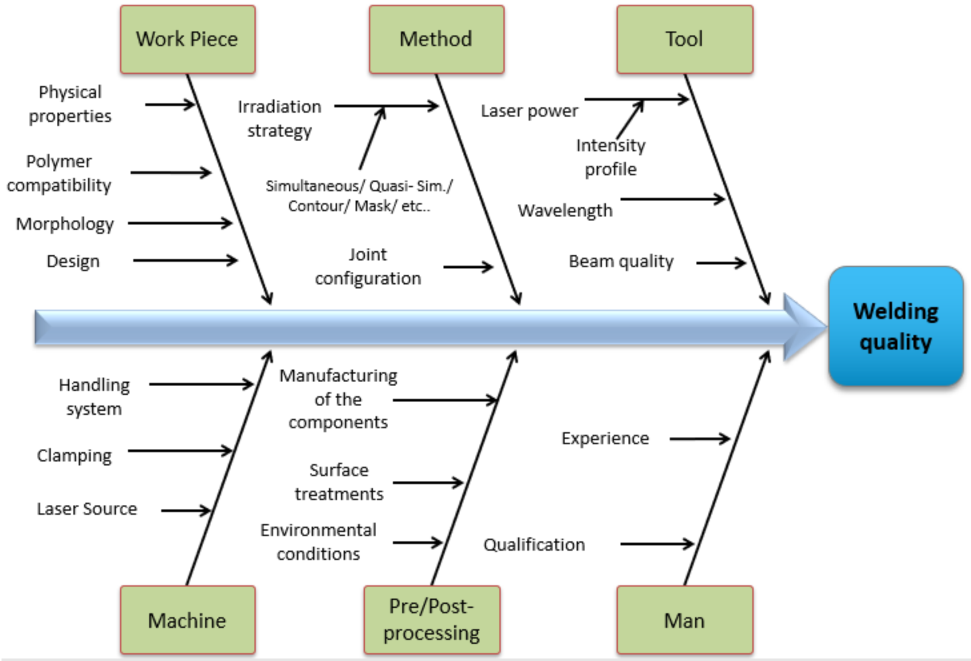


Figure 1-12 – Ishikawa diagram (process influencing factor) for polymerics laser welding

1.3 Scope of the work

Industries are always looking for new technologies to improve products, reduce production costs or save energy. The market and needs primarily drive the development of a sector or branch of technology. However, in some cases some discoveries, inventions or availability of resources pushes the product in an obligated direction. The growing use of plastics has prompted numerous companies to expand in this sector to invest in products and technology development.

As previously mentioned, laser welding has a fundamental and expanding market. Furthermore, laser welding for polymeric materials is one of the most recent and innovative in which it is possible to take large steps or explore new methodologies, applications or limits.

In this context, thanks to the opportunity offered by the Dipartimento di Scienza Applicata e Tecnologia (DISAT) of the Polytechnic of Turin, my Ph.D. is carried out in the industrial field, collaborating with companies in the surroundings of Turin. The main part of this Ph.D. The thesis work is the study of the effects of laser density and energy distribution. In the investigation of simultaneous welding with TTLW, a lot of attention had to be paid to obtain the minimum optical power density to weld polymers and guarantees the needed strength of the joint. Although the technology is known and listed in the bibliography, it is new in industrial applications in production lines. But the various advantages that could be had on the products justify the study and industrial development.

Most of my work took place in the company. The industrial research team designed and fabricated a proprietary laser source. The main goal of my Thesis was the complete design of "**metal hollow core laser waveguide design**" for complex structure. This guide acquires in input a huge number of fibers coupled in the different ferrule as well discussed in Chapter 2.

Thanks to experimental activities that were carried out in the laboratories of the company Cemas Elettra Srl, with the contribution and support of Microla Optoelectronics Srl a prototype machine was realized, and tests were matched with a computer model in order to have a comprehensive behaviour of the phenomena. The prototype permitted modifying density energy, changing the distance of the sample from the laser sources. By matching experimental and calculate data the optimal distribution of energy was found, in order to have good resistance to strength tests and no damage to the components, due to excessive overheat.

Simultaneous laser welding through laser transmission guided by metallic waveguides on different types of polymeric materials was studied, looking for the optimal values of power density and thrust. Components with increasingly complex geometries have been taken into consideration. In these cases, even the solutions and the study of the waveguide became more complex. This is a second research activity that the thesis focused the attention. A tool able to guide the designer in the positioning of each ferrule along the path of the hollow guide has been created. This macro is capable of finding solutions even for complex and non-linear geometries and simultaneously simplify the optical simulation phase.

The SolidWorks macro, used for the mechanical design of the waveguide, behaves like an add-in integrated within the software. This program demonstrated great potential in supporting the study and design, in the different applications, for simultaneous laser welding. In fact, through this application, it was possible to simulate multiple waveguide solutions and choose the best one based on the mechanical project needs.

Chapter 2

2- Laser and Optical Fibers

2.1 Laser Principles

This paragraph will deal with the fundamentals of laser technology, and then focus on the typologies used in this thesis work, laser diodes.

2.1.1 Introduction

LASER is an acronym for “light amplification by stimulated emission of radiation”, which indicates a device that obtains intense and extremely concentrated beams of coherent electromagnetic radiation in the infrared, visible and ultraviolet fields.

Light is defined as that portion of the electromagnetic field visible to the human eye. Laser radiation is also defined by the name of light. However, it can include slightly longer or shorter wavelengths than visible light. The electromagnetic field has the characteristics of a wave that allows the transport of radiant energy without needing any means of propagation [19]. Electromagnetic waves are made up of electric and magnetic fields that oscillate alternately in a synchronized way (Figure 2-1).

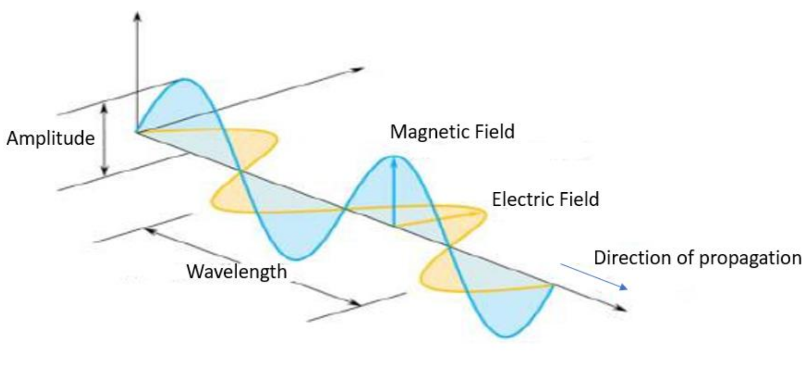


Figure 2-1 - Schematic representation of an Electromagnetic wave

An electromagnetic wave is described by the oscillation frequency (*f*), which represents the oscillation speed in the unit of time, and the wavelength (λ) that measures the distance between the crest of the oscillation. These characteristics are linked by Equation 2-1

$$v = \lambda \cdot f$$

Equation 2-1

v is the speed of the wave in the medium where the wave passes through, in case of vacuum v = c (speed of light in the vacuum). It is clear that the frequency is inversely proportional to the wavelength.

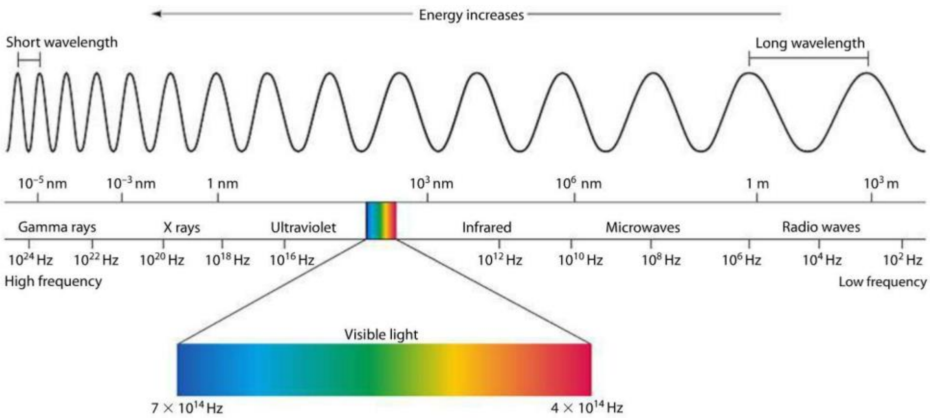


Figure 2-2 - Electromagnetic spectrum [20]

Figure 2-2 shows the wavelengths and frequencies of a generic electromagnetic radiation. It is common to identify bands according to the wavelength. In these bands the radiation is called by different names: radio waves, microwave, infrared, visible light, ultraviolet rays, X-rays and γ-rays. These bands are not defined uniquely and strictly [21].

This description of electromagnetic waves follows a classical wave model. However, radiation can also be studied under a quantum approach. In fact, radiation has a dual nature. According to this second approach, light is composed of photons, particles that transport energy and interact with matter. Photon energy (*E*) is quantized as follows:

$$E = h \cdot f = \frac{h \cdot v}{\lambda}$$

Equation 2-2

Where *f* is the photon frequency and *h* is the Planck constant.

2.1.2 Characteristics of lasers

Laser is electromagnetic radiation generated by an active medium [22]. Using the process of stimulated emission of the active medium, it is possible to amplify light irradiation.

The laser has as main characteristics:

- Directionality: emits radiation in a unique direction.
- Monochromaticity: very narrow emission band, which remains constant on a single wavelength.
- Values of radiance very high: the radiance is defined as the amount of energy emitted per unit of solid angle and in the lasers, the number of photons per unit of frequency is particularly high.
- Coherence: each photon has the same phase as the photon that induced the emission. The phase is maintained in time and space.

This device can emit coherent light radiation, where all the rays are in phase. This spatial property, where the phase difference of photons is constant, allows to have a unidirectional and collimated beam over great distances or to focus the light in a small spot. The unidirectional and coherent emission entails the possibility of reaching a very high irradiance or power density, capable of carrier high focused energy [23]. This property of light, of forming a well-directed laser beam that propagates in one main direction, is called brightness, i.e. the power emitted by the surface unit under a solid angle.

The property of the waves of a laser to have the same phase, allows the light to be confined in a narrow spectrum, in this way the radiation is emitted with a single colour or a single frequency. While the light possesses a wide spectrum of wavelength, laser on the other hand can emit with a very narrow band spectrum, such as to be able to define it monochromatic, as shown in Figure 2-3. It is considered like a monochromatic wave even if some laser devices can simultaneously emit a discrete number of beams at different wavelengths.

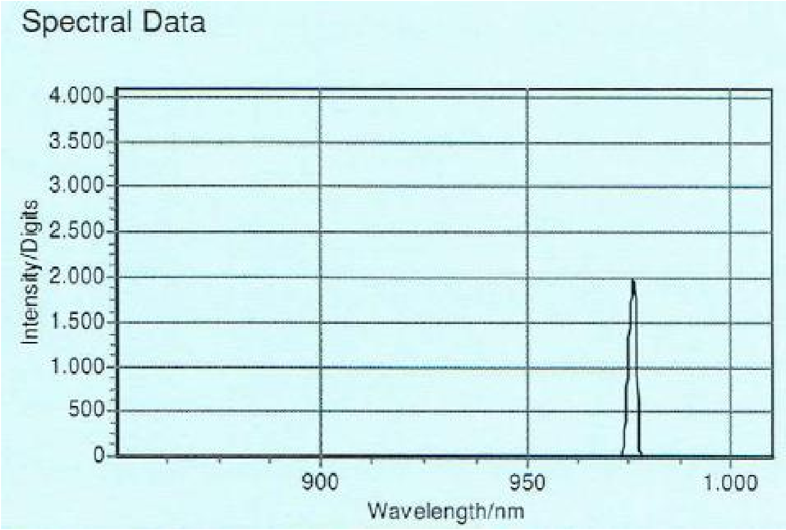


Figure 2-3 – Bandwidth of a laser diode

2.1.3 Laser Theory

The theory of laser light emission is complex. The interaction between electromagnetic radiation and materials must be studied. To simplify the discussion, the three phenomena that occur simultaneously are described [24]:

- **Absorption**: an atom in equilibrium condition has at level 1 a population density of electrons n_1 with characteristic energy E_1 (Figure 2-4) and a population density n_2 with energy E_2 on the second level. The atom is not in the excited state $n_1 > n_2$. If enough energy is supplied to the system, the electrons move to level 2. Energy levels have quantized values that depend on the atom and orbital levels. The electron can do a level jump if the atom absorbs an energy equal to the potential difference:

$$hf = \Delta E = E_2 - E_1$$

Equation 2-3

$n_1 < n_2$, and in this case it is said that the atom is in an excited state.

- **Spontaneous emission**: the excited atom tends to restore the original energy conditions, returning to the minimum potential. When this transition occurs, the atom emanates an energy equal to the level jump, there is an emission of photons with a frequency described by Equation 2-3. The random transition is called spontaneous emission.
- **Stimulated emission**: if the atom is in an excited state such that $n_2 > n_1$, and it is hit by a photon with energy equal to the level jump (Equation 2-3), the atom returns to a fundamental state and emits a photon in resonance with the photon with which it interacted. The two photons have the same frequency and direction. This chain emission is called stimulated emission (Figure 2-4). If this phenomenon is repeated with the other atoms in the system, the radiation is amplified. The process

of stimulated emission of excited atoms amplifies the wave and it creates a coherent and intense beam radiation.

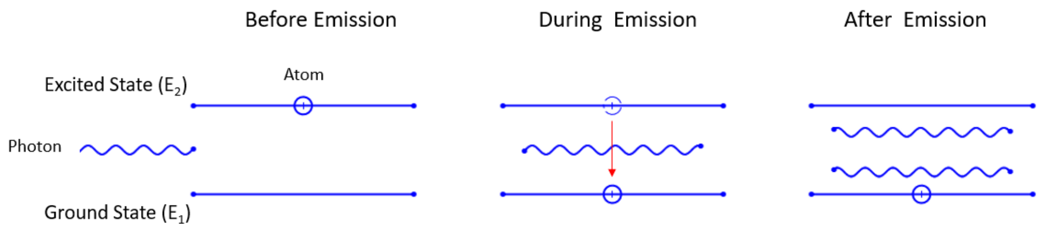


Figure 2-4 – Stimulated emission scheme

In a laser system, it is necessary to have a stimulated emission. In order to obtain this result, a population inversion must be obtained, in which $n_2 > n_1$. This population inversion process is called pumping. To control the stimulated emission, a system with at least three energy levels must be used, this to avoid that a dynamic equilibrium is reached and all three phenomena (absorption, spontaneous emission and stimulated emission) are equivalently probable. The pumping level must have a rapid decay, while the level that receptions the electrons, that have decayed previously, must have a slow decay. This material is called active medium.

A four-level active medium is more easily excitable, as a population inversion from level 1 is obtainable because much more power is needed than among the other levels. The space where pumping process happens, is called resonant cavity.

Laser systems are principally consisting of three parts (
Figure 2-5):

- A medium;
- A pumping system or another source (e.g. another laser);
- An optical or resonant cavity.

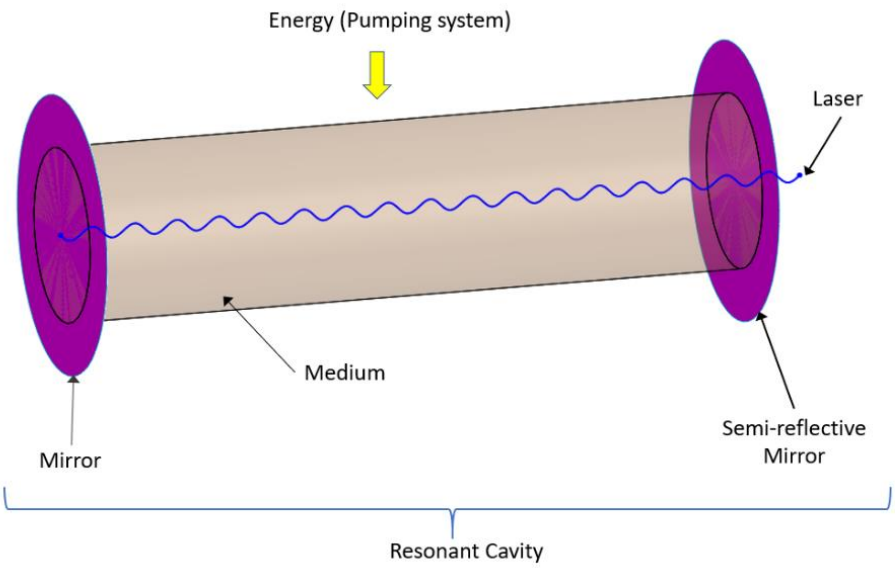


Figure 2-5 – Schematic components of lasers

The medium may be gas, liquid, solid, semiconductor [25]:

- Crystals, doped with rare earth ions (e.g., Neodymium, ytterbium or erbium) or metal ions (titanium or chromium); aluminum yttrium garnet (Y3Al5O12), orthovanadate yttrium (YVO4) or sapphire (Al2O3), cadmium cesium bromide (CsCdBr3);
- Glasses, e.g., silicate or phosphate glasses, doped with active ions;
- Gas, e.g., mixtures of helium and neon (HeNe), nitrogen, argon or metal vapors;
- Semiconductors, e.g. gallium arsenide (GaAs), indium gallium arsenide (InGaAs) or gallium nitride (GaN);
- Dyes based on organic molecules.

Stimulation or pumping of a laser can happen optically or electrically. Optical stimulation can be carried out by a lamp that wraps the active material all inside a mirror. In this method the population inversion is obtained with a light beam. Electrical stimulation, on the other hand, happens by applying a potential difference and is only applicable to conductive materials such as metal vapours.

The cavity is made up of two mirrors that border the active medium, one of which is semi-reflective and allows the beam to exit.

The function of the two mirrors is to cause, through reflections, numerous passages of the emitted photons through the active medium and increasing the intensity of the light beam. Furthermore, the length of the cavity also allows selecting the wavelength of the emitted photons.

In addition, the two mirrors allow that only the photons that move horizontally with respect to the cavity can undergo reflections, and therefore amplification. All the other photons with random direction, coming from spontaneous emission, could be absorbed by the media and they excite the electrons.

A semi-reflective surface allows the exit of the beam, which ensures that the resulting beam has the desired direction, concentration and amplitude. All the process is represented in Figure 2-6.

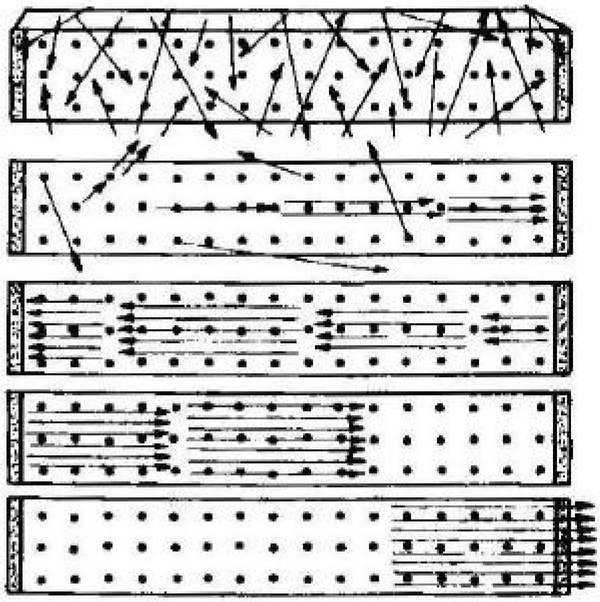


Figure 2-6 – Operating scheme of resonant cavity

2.1.4 Laser Diode

The laser diodes are described below, as they are the devices that will be used for the realization of the laser sources in simultaneous welding.

Lasers with a gain medium solid are highly used in a wide field of applications. A particular type of laser is the diode laser which uses semiconductors as active media [26]. Laser diodes can convert electrical energy into electromagnetic radiation. The active media are usually ion-doped crystals, glasses, semiconductors. The dopants are usually rare-earth elements. Initially, it was difficult to use in the mass industry and only thanks to the development of the diode bar, that it was possible to mount numerous emitters on a heat sink. A diode can be consisting of one or several laser diodes. The overlapping diode bars allowed reaching powers of few kW, while nowadays even 100kW can be reached. Their wide use is due, in addition to the high output power, also to their high energy efficiency. With some types of diodes, it is possible to obtain excellent beam quality and therefore very good values of focusing.

This type of laser is described in more detail below, as it will be the one used to construct the source of the welding system.

2.1.4.1 Operating Principle

Some semiconductor materials such as gallium arsenide, indium phosphide, gallium antimonide and gallium nitride can be used to create laser diodes. Spontaneous and stimulated emissions are better in direct broadband semiconductors, for this reason silicon is not widely used in this type of laser.

A semiconductor with a **p-n** or a **p-i-n** junction permits an electrical pump in the laser diodes.

In the bipolar inter-bands, the current flowing can combine electrons and gaps in order to create wave radiation. The surplus of electrons (layer n) and gaps (layer p) are obtained by doping of the materials with various techniques. If electrons and holes are present in the same region, they can recombine, i.e. the electron can occupy the energy state of the hole. This falling of the electron between two different energy levels allows generating radiation with the emission of photons. This recombination between electron and gap produces a spontaneous emission. Spontaneous emission is essential to start the oscillation of the laser, but it is a form of inefficiency when it oscillates. The energy released as photons can be spontaneous or stimulated by external energy, in the way to obtain an optical amplification in the resonator cavity of the laser.

A p-i-n diode (p-type, intrinsic, n-type diode) is a diode with a large region of non-doped semiconductor material, contained between a p-type semiconductor and an n-type semiconductor.

The active region is the middle layer (intrinsic region), the gaps and electrons are pumped by the n- and p-regions. The difference with a p-n is in using the i-region to recombine electrons and gaps in and generate light.

Semiconductor wafer with coated or uncoated ends represents the laser cavity resonator. The heterostructure inter-band creates a restricted region for the resonance of the beams and it has the task of leading the beam from an optical point of view in these narrow areas, which allows low threshold and high efficiency in the pumping system.

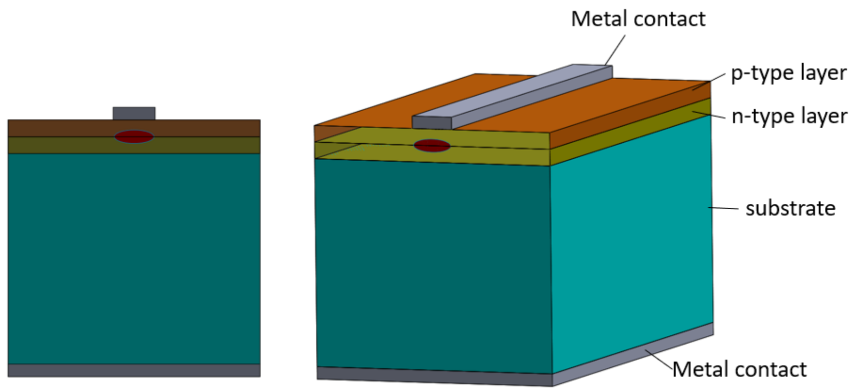


Figure 2-7 – Main structure of a laser diode

The laser diode usually uses thin layers of semi-doped material on the surface of a crystalline wafer, in this way an overlapping of semiconductor regions of the n- and p-type is obtained (Figure 2-7). If the device is polarized directly, the electron gap in the p- region is transferred to the n- region, in which there are electrons. Thus, the electrons in the zone are transferred to the p- region. Spontaneous emission occurs if the gap and the electron are combined in the same region. In this way, emission of photons is obtained, the energy depends on the difference of the layers of the gap and of the electron. The spontaneous emission created with the combination of gaps and electrons represents the injection current of the diode, the laser starts oscillating.

Under controlled conditions, the gap and the electron can coexist without combining for a short period, about a few microseconds. A photon with energy equal to the combination energy can cause a stimulated emission, the photon that is generated has the same frequency, direction and polarization as the first photon. The stimulated emission allows having a continuous process that generates coherent light, with equal wavelength and the same phase. In this way the gain increases with the number of electron-gaps that combine through the injection into the junction, thus obtaining the gain of an optical wave. Charge injection is widely used to power diodes, which is why they are sometimes called "injection lasers".

The optical cavity limits the gain region. In a simple form of diode, the surfaces of the crystal (made flat and parallel) are used as an optical guide that encloses the wave in a narrow region. By working the faces of the crystal properly, the Fabry-Perot resonator can be obtained. The waveguide allows reflecting the photons between the faces many times, and each time the wave passes through the cavity there is an amplification due to the stimulated emission of the photons. A small part of radiation is lost for optical reason such as incomplete reflection. Absorption loss must be added to this loosed part. If the system has been well-structured, the amplification is greater than the losses and the laser emission can finally be obtained.

The main characteristics of laser diodes depend on the geometry of the optical cavity. In the vertical direction, the light propagates perpendicularly along very thin layers. In this direction, this is the only mode of optical propagation. While in the lateral direction, there may be several optical modes. This can only happen if the waveguide is longer than the wavelength of light. If there are many laterals optical modes, the laser can be defined multi-mode. This type of laser is used if high power is required, but its divergence is not so narrow. For applications where a thinly focused beam is required, the waveguide must have a length comparable to the wavelength for the lateral direction. This allows obtaining only one mode of wave propagation.

The laser wavelength depends on the characteristics of the materials and the mode of propagation in the optical cavity. It is also a function of the energy gap between the semiconductor layers. The maximum gain is obtained if the energy of the photons is slightly higher than the gap energy and the propagation modes emit closer to the gain peak. Usually, the diodes need to work at a single and predeterminate wavelength. This characteristic even depends on the temperature and current, therefore these values in the diode cannot change over time.

Mainly the laser wavelength is influenced by the semiconductor band gap. Photons have energy close to the band gap. Thanks to a large variety of materials used, laser diodes can cover a wide range of wavelengths and spectral regions. In some composite semiconductors (ternary or quaternary) it is sufficient to change the material of one of the components to have different band energy and therefore different laser emission length.

Due to the diffraction when the light exits from the resonator, the beam coming out of the cavity diverges at a greater angle in the vertical direction (about 30°) than in the lateral direction (about 10°). Subsequently, it is necessary to design an optical system in order to obtain collimated or focused beams.

To obtain a high-power laser it is possible to stack diode bars with wide area emission. In this way, powers of hundreds or thousands of watts are obtained, at the expense of the quality of the beam.

Below the threshold value, laser diodes do not have a linear response between power and current. The power is minimal in the level below the threshold value, instead the intensity increases considerably beyond this value (Figure 2-8).

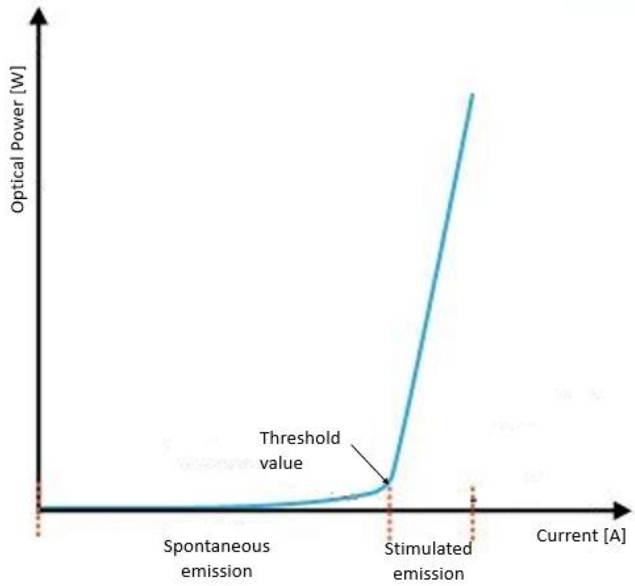


Figure 2-8 - Laser diode characteristics of emission

Spatial coherence determines a good property to create collimated beams with low divergence and a good capacity of focusing. Generally, the laser beams can be approximated to Gaussian waveforms.

The Gaussian waveform can be considered with relatively simple equations. In the case that the beam cannot be matched on an ideal Gaussian form, the equations consider a quality factor of the ray M^2. These equations cannot describe the evolution of the profile but manage to predict the beam radius of the second moment of intensity profile.

Normally the laser beam is linearly polarized, i.e. the electric field oscillates perpendicular to the direction of propagation. However, some lasers have an indefinite polarization.

2.1.4.2 Laser Diode typologies

Laser diodes have had considerable variations due to the development of new technologies and knowledge of new materials and production processes. A variety of types of diodes can therefore be identified:

- **Double hetero-structure laser diode**. This type of diode is made through layers of low bandwidth materials enclosed between two high bandwidth materials. The joints are composed of different materials and not only between the same materials with different doping. This gives the name of hetero-structure. Hetero-junction helps to keep the light within the active region by reflecting the wave. The advantage of this typology is that the active region is very limited, so that many gaps and electrons contribute to the optical amplification of the laser.
- **Quantum well laser diode**. When the intermediate layer is very thin, this creates a quantum well. The vertical component of the wave function is quantized. In the quantum well exists an abrupt edge which promotes the efficiency of the system, in fact the electrons are concentrated on the energy layer that contributes to the action of the laser. Having multiple quantum wells improves the overlap between the gain regions and the optical waveguide mode.
- **Quantum cascade laser diode**. This type of diode is a hybrid form between a quantum well and hetero-structure. This typology of diode allows generating a beam with medium-long wavelengths. The difference between the energy levels of the quantum well is used for the laser transition, instead of using the band gap of the hetero-junction.
- **Separate confinement heterostructure laser diode**. The problem with some laser diodes is that a very thin layer is necessary to limit the light. In this case, two other layers are added externally to the existing ones. In this way, it is possible to confine the light in the diode.
- **Distributed feedback laser diode**. For this type of diode, it is important that they are stable at a single wavelength. However, the temperature and the current modify this property. Therefore, a diffraction grid is imprinted in the p-n junction to stabilize the wave. This grid has the function of an optical filter, which causes a single wavelength to return to the gain area. The structure of the grid is established by temperature. These diodes are mainly used in data transmissions and telecommunications, where it is essential to have a stable wavelength.
- **Vertical cavity surface emitting laser**. They are diodes with emission from the surface of the cavity, and not from the edge. The beam is perpendicular to the wafer, i.e. the axis of the optical cavity is along the direction of the current flow (unlike other kinds of lasers). It has a good characteristic of quality. Dielectrics mirror have a high selective reflection, this gives lower output powers than other types of diodes. However, there are many more construction advantages compared to the diodes with emission from the edges, as it is possible to test them before the final assembly. In addition, multiple emitters can be assembled on a single wafer and checking and predicting the results.

They usually emit few milliwatts, but they have a high quality of the beam.

- **Vertical external cavity surface emitting laser**. Similar to the previous ones, but one of the two mirrors is external to the diode structure. The cavity is external and the diode is optically pumped. Mirrors are grown epitaxially, therefore they are part of the diode, or connected to the active region of the semiconductor. They maintain a good beam quality, but it is possible to obtain higher powers than the previous type.

- **External cavity laser diode**. They are lasers that have a diode laser as medium of gaining a longer resonator diode. It is also composed of other elements such as laser mirrors or diffraction grating [27].

Another classification can be made independently of the structure of the diode and the physical process used to obtain and amplify the light. This second classification of the diodes considers the mode of emission. A distinction is made between edge-emitting or surface-emitting.

Edge-emitting diodes give a horizontal beam. The layers are overlapping vertically, and the wave is guided by the upper and lower layers.

In surface-emitting lasers, the emission direction is perpendicular to the surface of the wafer. Unlike the edge-emitting, the overlapping layers act as mirrors. The gain of the optical cavity is provided by a succession of quantum wells. The cavity is electrically pumped. The mirrors are designed as distributed Bragg reflectors. Light is reflected between the lower and upper mirror in the active region which then amplifies it. In comparison to other diode lasers, they have more practical and effective test methods. Thanks to the manufacture as epitaxy, a better roughness of the state is obtained. The beam can be emitted in the free space or coupled with a single-mode fiber.

2.1.5 Beam quality

A beam focalized is characterized by:

- Radius at beam waist, w_0;
- Far-field half-angle beam divergence, θ_0;

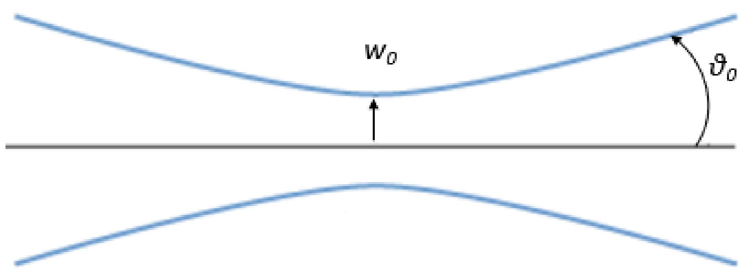


Figure 2-9 -Focalized Laser Beam

Their product $(w_0 \cdot \theta_0)$ is called Beam Parameter Product and it depends exclusively on the density distribution of the beam power, i.e. on its spatial profile.

The quality of the beam is defined in multiple ways; however, it indicates the quality of the distribution and how small the focus can be. One of the main quality factors used is the beam quality factor M^2, it does not provide information on the spatial characteristics of the laser beam, but it permits evaluating the smallest beam of the focused beam and the divergence of the beam can be determined [28]. A beam has a good quality when M^2 is close to the unit. It is possible to link the quality factor with the beam parameter product:

$$M^2 = \frac{\pi}{\lambda} \cdot w_0 \cdot \theta_0$$

Equation 2-4

To find the M^2 value, some acquisitions must be made with a beam profiler, treating the beam with a focusing lens and measuring waist and divergence [29]. Instead of the quality factor, in some cases it is preferred to use another parameter, the propagation factor of the beam K. It is linked to M^2 from the relation:

$$K = \frac{1}{M^2}$$

Equation 2-5

These parameters are used to describe the laser beams that tend to the ideal. The range for which it is possible to define good quality lasers are:

- $0.1<K<1$
- $1<M^2<10$.

If K approaches to 0.1 and M^2 to 10, the beam is far from the ideal distribution and another parameter is used, called beam parameter product. The characteristic parameters presented can be used to characterize axial-symmetric lasers.

In choosing the diode and lenses suitable for laser beam treatment, these design characteristics will be taken into consideration.

2.2 Optical fibers

Optical fibers will be briefly presented, they are fundamental elements to transport the light and necessary to effectively exploit laser technology.

The paragraph describes the characteristics of the optical fibers, the operating principle and finally the application as a bundle of optical fibers

2.2.1 Description

An optical fiber is made of glass or plastic materials with a very small diameter. Used as a carrier for the light, it can transmit radiation even at long distances. Light has a high propagation speed, therefore in optical fiber the data transfer speed (bandwidth) is higher than in electrical cables. For this reason, optical fibers are often used in place of metal cables. In fact, they have better properties, in addition to a high bandwidth, plus glass is not an electricity conductor therefore it does not have electromagnetic interference [30]. As well as in the telecommunications, optical fibers are widely used in fiber laser applications. They are very flexible, even though they are made of glass. They are usually coated with a polymeric coat, called jacket (Figure 2-11), which gives better mechanical resistance.

Often the element used is pure silica or even doping components. Its purity gives good mechanical resistance.

2.2.2 Total internal reflection

The fundamental physical principle used in optical fibers for the transmission of light is total internal reflection.

Total internal reflection is the optical phenomenon in which light is reflected like in a mirror, without loss of intensity. It can occur when the waves reach the border between two vehicles with an angle that meets particular conditions. The second medium must be transparent to the waves.

A ray that travels in a medium if it hits a surface of interface with another medium with a different density could divide its energy in a portion reflected with the same angle of incidence θ_i [31], and a portion refracted with an angle θ_r in the other material (Figure 2-10). Reflection is generally accompanied by partial refraction. When the beam is refracted from a material n_1 denser to a medium n_2, the refractive angle θ_r is greater than the angle of incidence θ_i. In this case, if the angle of incidence approaches a certain limit, called the critical angle, beyond which the refractive conditions can no longer be satisfied, there is no refracted ray and the partial reflection becomes total.

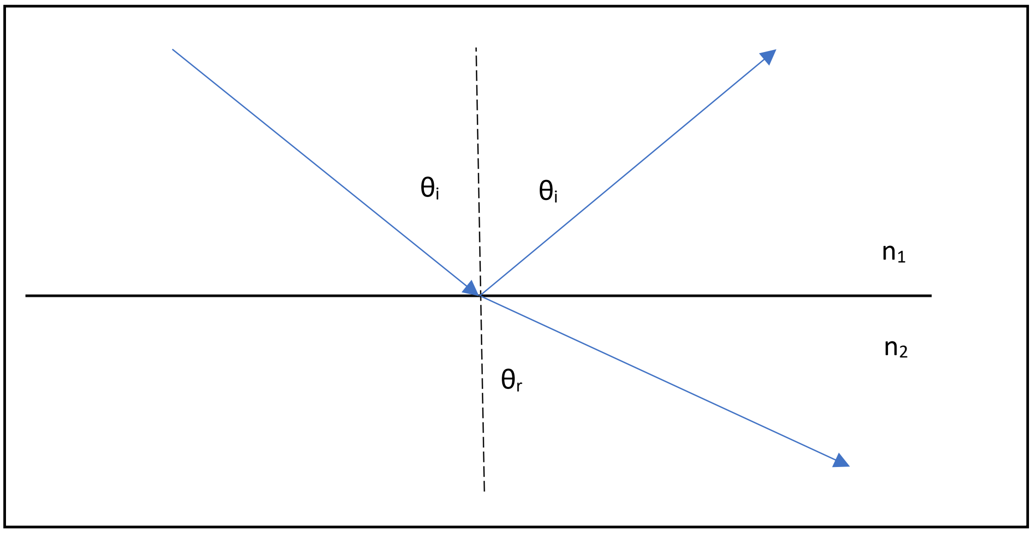


Figure 2-10 – Reflection and refraction phenomena for an incident beam

Thanks to Snell's law:

$$\frac{\sin\theta_r}{\sin\theta_i} = \frac{n_1}{n_2}$$

Equation 2-6

it is possible to identify a critical angle θ_{cr} for which it is possible to have total internal reflection:

$$\theta_{cr} = \arcsin\frac{n_2}{n_1}$$

Equation 2-7

If $\theta_i > \theta_{cr}$ the total internal reflection is verified.

2.2.3 Structure and principle of operation of optical fibers

Optical fibers use the total internal reflection phenomenon, in order to have the light beam propagation. The optical fibers are formed by a core surrounded by a cladding (Figure 2-11) with a lower refractive index, the total internal reflection is thus performed. Nowadays most of the fibers have a small difference among the core and the cladding [32].

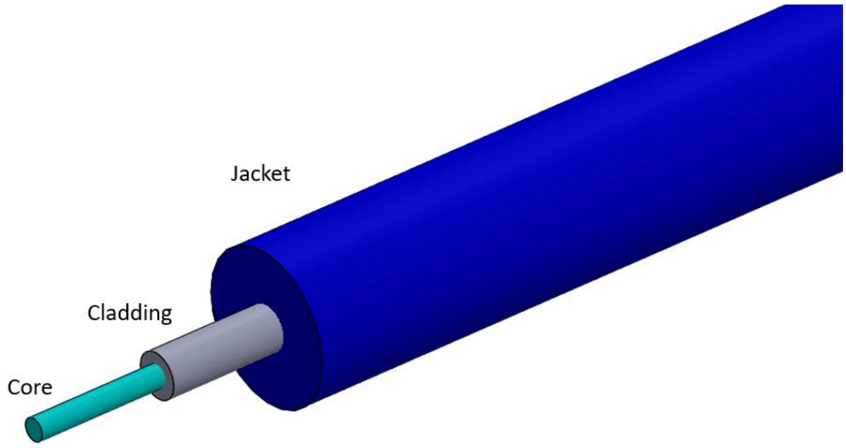


Figure 2-11 – Structure of an optical fiber

So, the light hitting a separation surface between two materials has no refracted component (Figure 2-12), but it is mainly reflected following Snell's law. The line red and black in Figure 2-12 represent a possible path of rays that are reflected in the interface between the core and the cladding.

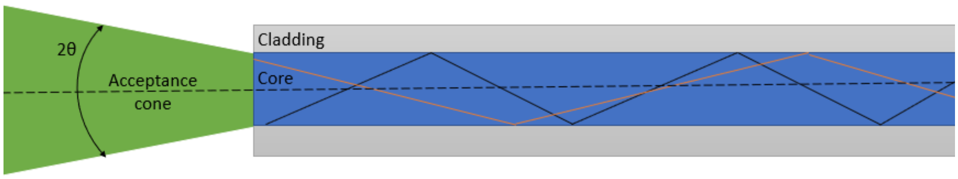


Figure 2-12 – Light propagation in optical fiber

The difference in the refractive index between the core and the coating gives the numerical aperture of the fiber. The beam is then guided into the fiber core.

Fibers with different indexes between the core and coating are called step-index fibers (which differ from the graded-index where the refraction gradually changes passing from the core to the cladding). In this typology, the fundamental parameters are the radius of the core and the differences between the refractive index.

By reference to the:

$$\theta_{cr} = arcsin\frac{n_2}{n_1}$$

Equation 2-7

it is possible to find the value of the critical angle for what light is not transmitted. In this case n_1 is the refractive index of the core and n_2 is the refractive index of the cladding.

The numerical aperture (*NA*) indicates the number of modes in which light can propagate through the fiber. It is related to the width of the acceptance cone with respect to the fiber axis, in order to have a total internal reflection. *NA* can be defined by the equation:

$$NA = \sqrt{n_1^2 - n_2^2} = sin\theta$$

Equation 2-8

With increasing *NA*, the sensitivity of the fiber to contain losses decreases in the case of bending.

2.2.4 Fiber typologies

A distinction can be made between the fibers that can support many propagation modes, called multi-mode fibers, and those that support only one mode of propagation, single-mode fibers. Generally, multi-mode fibers have a larger diameter than single-mode, but they can transport beams for a few meters with high power [33]. Single-mode fibers are mainly used in remote telecommunications. The spatial distribution is constant and does not depend on the fiber input. Usually, the diameters for single-mode fibers are few microns.

In order to have a good beam transport in the optical fiber it is necessary to have a laser with good beam quality and a properly organized and aligned optics. Therefore, the most delicate task is to launch the beam into the fiber core. Fiber launching is more difficult in single-mode fibers, as there must be a focus in the fiber inlet with flat wave fronts and a transverse profile intensity like that of the fiber. It is easier to couple in multi-mode fibers than single mode, also it may not be necessary to have the beam focus at the fiber inlet. Instead, the larger diameter of the multi-mode fibers simplifies the design of the coupling, but they have major losses and intensity reduction over long lengths. Cores of multi-mode fibers are about ten / hundred microns. The difference of refractive index between the core and the coating is higher in multi-mode fibers.

The characteristic of the output beam depends on the launch conditions.

Compared to other beam transport methods, such as a mirror system, the fiber laser is widely used because it is very stable and safe, as it is less sensitive e.g. to impacts. Even high powers of some kW can be transported. They are also very efficient, and the minimum losses do not allow the heating of the fiber.

2.2.5 Bundle of optical fibers

It can often be convenient to group a large number of optical fibers together (Figure 2-13-A). This creates a bundle of optical fibers, where there is a single input with a variable number of output legs, as shown in Figure 2-13-B. A broader discussion will be addressed in the Chapter 4.

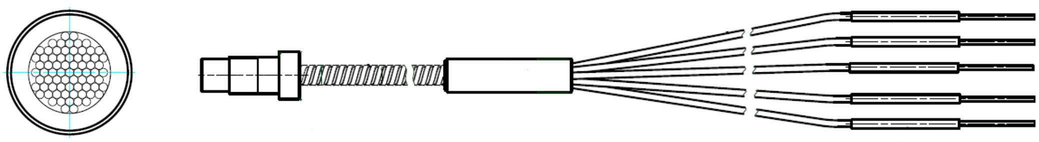


Figure 2-13 - Example of a bundle of optical fibers: A) Group of optical fibers that composed the bundle; B) Bundle subdivides in multiple legs

The fibers have a large core diameter. The fiber optic bundle can be used for transmission of high-power laser, or imaging applications.

The fibers of the bundle can be arranged randomly or following a pattern, usually circular or hexagonal. Some bundles at the termination of the fibers have a thin polymeric coating which reduces mechanical stress. At the end and especially at the entrance extremities, the interstices can be left empty or filled. In some cases, the fibers can be melted together (fused-end bundle), however this makes these fiber portions less flexible than normal. In this way, it is possible to minimize the coupling losses. The number of fibers used in a bundle varies from few tens to many thousands.

With this methodology, in the launching of the laser the beam is focalized the active entrance area as uniformly as possible. So, part of the light will be lost at the entrance, in the cavities between fibers, or in the cladding. Usually, fibers with a large core diameter are used to minimize these coupling losses. It is also possible to have interface losses due to Fresnel refraction; they could be reduced with antireflection coating. There are also internal losses to the fibers although they are negligible compared to the other phenomena just described.

Chapter 3

3. Polymers Welding State of Art

In the following chapter, a brief presentation of the polymeric materials and their structure will be given. Subsequently, some welding technologies of polymeric materials will be described, focusing the aim on laser welding.

3.1 Introduction to Polymers

Polymers are materials composed of a sequence of one or more fundamental units formed by repeating atoms, molecules or macromolecules [34]. Usually, the molecules are formed by atoms linked with a covalent bond. These agglomerations of matter are called monomers, which can form chains of different length, during the polymerization process. If the polymer contains only one repeated unit it is called homopolymer, if it contains multiple basic units it is called copolymer [35]. They are organic or inorganic compounds, respectively with or without carbon in the polymer chains.

Polymers have good mechanical characteristics, for example, high toughness and elasticity, which is why they are increasingly used.

3.1.1 Polymeric structures

Due to their large molecular mass, they tend to form amorphous or semi-crystalline solid. The structure of the polymers is described by the ordering of the monomer chains.

The first classification on the spatial distribution of polymers is based on whether the chains form an ordered or random structure. If the structure is disordered and with extensive branched randomly arranged chains, this is an amorphous polymer (Figure 3-1-a). While if the structure is linear with little degree of branching, they are called semi-crystalline. In turn, the crystal is composed of chains arranged three-dimensional ordering with intramolecular folds or stacking (Figure 3-1-b). The dimensions of the crystal grains have extensions in the order of tens of nanometres. They are defined as semi-crystalline because they have crystal grains in an amorphous material matrix. This morphological composition gives the material better physical characteristics, such as great stiffness, density and hardness, high melting temperatures.

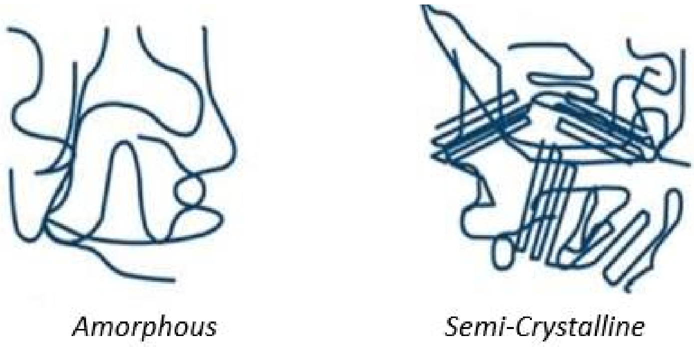


Figure 3-1 – Morphologies of polymers.

Some polymers can have both compositions, others, such as polyethylene (PE), polypropylene (PP), nylon (PA) are only semi-crystalline, while polycarbonate (PC), polymethylmethacrylate (PMMA) are amorphous. Amorphous thermoplastic polymers, free of additives, are transparent in the visible spectrum. In contrast, semi-crystalline thermoplastic polymers appear opaque or milky at sight.

Another kind of structure of the polymers can be defined on the basis of the arrangement of the chains. Linear, branched or cross-linked mesh structures are possible [36] as shown in Figure 3-2.

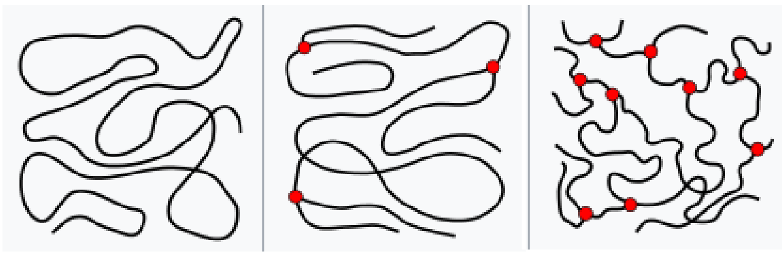


Figure 3-2 –Arrangement of Polymers Chain- a) linear; b) branched; c) cross-linked

Depending on these structures, further classification can be made. The linear and branched chains generally define thermoplastic materials, while a cross-linked structure with a wide mesh identifies the elastomers, finally the cross-linked with strict mesh identifies the thermosetting compounds [37].

Thermoplastics have mainly linear macromolecules. The bonds between macromolecules can be broken and recombined with heat. Even after solidification, the solid-fluid transition is reversible, the polymers soften with high temperatures, so they can be easily remodelled and recycled.

Thermosets are characterized to have numerous bridges between chains in addition to bond between monomers. This structure confers resistance to high temperatures. However, once polymerized, the process is irreversible. So, it is impossible to recycle them to get the same polymer again. However, they could be reused as fillers for other compounds. They are favoured in some applications for their properties: thermal stability, high rigidity and stability, resistance to sliding and deformation under not excessive forces.

The elastomers have a low degree of cross-linking, and the bonds between the chains do not allow sliding, this gives good elasticity even for high deformations. It is possible to have thermoplastic and thermoset elastomers [38].

3.2 Joining of Polymeric Materials

In production, the design of a single and complete component is advantageous and economical. However, technology has limitations, so sub-part design is often needed and must be an assemble phase later. The junction points or areas must have strength and properties similar to the rest of the component, usually there can't be discontinuities [38]. Plus, the components are often made of different polymeric materials; it is necessary to assemble these sub parts to obtain the final product.

Therefore, it is necessary to join the individual parts of a component. The main methods are mechanical fastening, adhesives bonding and welding methods.

Mechanical fastening uses screws, bolts and rivets. This type of fixing is particularly useful to join a plastic component with a metal, ceramic part, it is also easily removable and allows accessibility to the parts for a possible maintenance intervention. It has some limitations due to weight of the fasteners, in addition there are great stresses in the fixing points.

In the connection with adhesives, the adhesive or a solvent is distributed over the entire joint perimeter. This method has a low cost, joining different compounds of plastic materials and allow distributing the stresses on the whole joint. However, the materials must be suitable for the adhesive or solvent, and the surfaces must be properly treated.

In the welding technology, the components are heated to melt the materials on the contact surfaces [39].

The possibility of reducing the number of processes or the preparation of the surfaces to be joined makes welding preferable to other joining methods [40].

3.3 Welding Technologies for Polymeric Materials

Thermoplastic materials are widely used because they have a good weight-resistance ratio. For this reason, they replaced other materials previously used in industries, such as metals [41]. Other key features are low manufacturing costs, long lifetimes, easy manufacturing of complex parts, good degree of recycling and re-modelling [42].

Thermoplastic materials can be softened with heat. All the materials in this category are weldable by melting the two parts that are intended to join.

Welding of thermoplastic polymers consists in the bonding of components under heat and pressure [43].

The heat required for welding can be generated in different ways and methodologies. In Figure 3-3 the main technologies for polymeric welding classified in function of fusion methodologies [44].

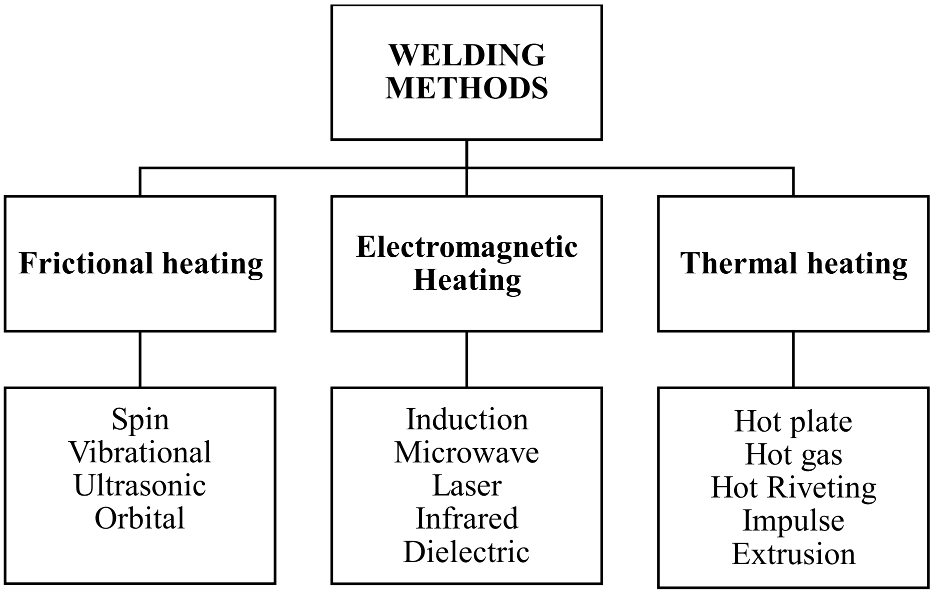


Figure 3-3 - Classification of bonding methodologies in function of fusion techniques

It will be presented some technologies used in plastic welding in the largest part of industries [39] [45] [46] [47] [48] [49]:

- **Hot plate**. A hot blade (which has the negative shape of the pieces to be welded) reaches a higher temperature than the melting of the material and it is brought in contact with the two welded elements. After the heating and melting of the surfaces, the blade is quickly removed, and the two elements are pressed against each other and left them to cool [50]. Hot blade welding presents the problem of the adhesion of the molten material to the walls of the blade. This problem was solved many years ago by applying a non-stick paint called Teflon. Or steel or bronze slats are introduced, and the heating temperature is increased, so that the material remains on the slats, always leaving the blade clean.
- **Infrared plate**. Technology similar to the previous one. However, the materials are heated without contact, exposing them to infrared radiation [43] [51]. In this type of welding there are no contacts and the problems of Teflon and smoke are avoided. This is obviously the best way to weld, compatible with all materials. Heating can be carried out with special infrared lamps or with resistances. In the first case, it becomes very important to shield the parts that should not be irradiated with a reflective metal and this is not always possible. In the second case a resistance that reaches 800-1.000° C is installed on a ceramic support, resistant to high temperatures. With this system, it is much easier not to heat the parts that must remain cold but at the same time it is a much more ‘demanding’ system. In fact, remembering that the irradiation is proportional to the square of the distance, it is very easy to switch from insufficient heating to burning of the component.
- **Ultrasound**. This technology is called ultrasound because waves are used at frequencies higher than those that the human ear can hear. The pressure waves are produced by a generator that sends an alternating current of the order of kHz to piezoelectric ceramics. Piezoelectric ceramics are able to produce alternating

stretches if subjected to a voltage difference. In this way, ceramic is shortened or lengthened. Once the vibration has been produced, it is then necessary to amplify it and transmit it to the parts to be welded. The component responsible for the amplification is called sonotrode. It is a piece of metal that stretches and shortens at a frequency of 20-40 kHz with an amplitude of a few micrometres. These components are placed on the part to be welded [43].

- **Vibration**. The two parts to be welded are brought in contact with each other with a certain pressure. Subsequently, a part moves with an oscillation. The friction generated by rubbing heats the materials locally and melts them [52].
- **Laser**. This technology uses one or more laser beams to heat the components. There are two main methods of laser welding: direct laser welding (DLW) and through transmission laser welding (TTLW). In DLW the surface of the two components are irradiated and heated, then the components can be joined together. Both materials have to be laser absorbent. In TTLW one of the two components is transparent to the radiation, while the second one absorbs it, allowing the interface to heat and the two materials are melted [44].

Each methodology has its advantages and disadvantages and can have specific areas of application according to the characteristics of the product to be welded (geometries, materials, number of components, etc.). In the Table 3-1 is presented the advantages and disadvantages of the welding technologies descripted above [44] [53].

Welding methods	**Advantages**	**Disadvantages**
Hot Plate	Simple and economical	- Two-step process, - Contact of heating element, - Long process - Time, - Overheating and degradation
Infrared	- Non-contact heating, - Short process time	- Two-step process, - Highly dependent on polymer's absorption
Ultrasound	- Economical, - Mass production, - Short process time	- Requires energy directors to be incorporated at seams. - Limitations associated with semi-crystalline polymers.
Vibration	- Short process time	- Limited to larger components, - Restricted to not high inclination surfaces, - Not for thin wall parts, - High internal bending forces
Laser	- One-step process, - Highly localised heating, - Instantaneous bonding, - No vibration, contact or particulates, - Little or no flash, - Low residual stresses, - Complex shape, - Broad range of laser absorbers available and corresponding wavelengths.	- May requires top part to be laser transmissive, - Part thickness limitations in TTLW, - Surfaces must be of good quality - High capital costs.

Table 3-1 - Advantages and Disadvantages of main technologies of plastic welding

3.4 Laser Welding

Laser welding is widely used for its versatility, cleanliness and effectiveness. In fact, the amount of energy in the welding area can be easily controlled. The laser provides precise heating and localized fusion, the mechanical strength resistance is also greater than in other technologies. In addition, lasers can be used with wavelengths that have good interaction with polymeric materials.

Another characteristic of laser welding is a non-contact distribution of energy. This aspect reduces thermal and mechanical stress [54].

3.4.1 Laser interaction with materials

When a laser beam hits the surface of any material, the radiation interacts with matter. Usually three contributions are identified: reflection, transmission and absorption (Figure 3-4). The radiation is partially reflected, partially passes through the component.

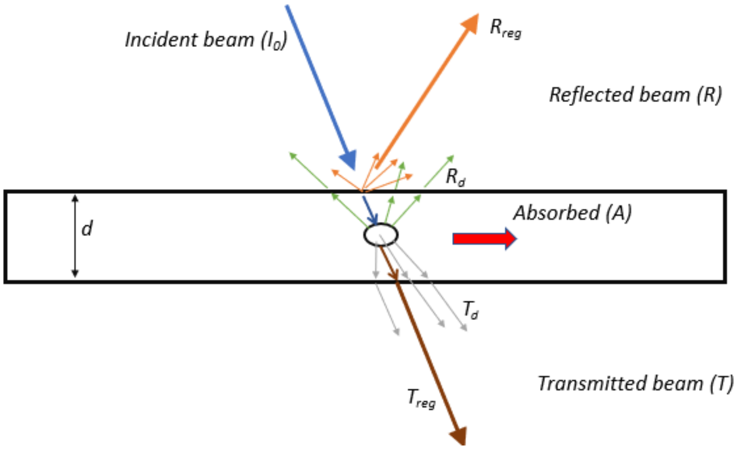


Figure 3-4 - Interaction between Plastic and Laser radiation

A beam with intensity I_0 enters the material and is attenuated according to Lambert-Beer's law [55].

$$I(z) = I_0 \cdot e^{(-C_{ex} \cdot z)} \qquad C_{ex} = C_{ab} + C_{sc} \; ; \qquad 0 < z < d$$

Equation 3-1

Where z is the space coordinate, and C_{ex} is the extinction coefficient [56]. The extinction coefficient consists of two parts. The first component is the absorption coefficient (C_{ab}) that represents the radiation absorbed and transformed into heat, due to the property of the polymer. In laser transparent material, the absorption coefficient is usually close to zero, whereas in the absorbent plastics it assumes a high value.

The structure of polymers (for instance, the presence of crystals, fillers or additives) can deflect the radiation out of the beam normal path of propagation. This phenomenon is represented by the scattering coefficient (C_{sc}). The scattered part is not absorbed. It is divided into diffuse reflectance (R_d) and diffuse transmittance (T_d) [57].

The total transmittance (T) is given by two contribution regular (T_{reg}) and diffuse transmittance (T_d):

$$T = T_{reg} + T_d$$

Equation 3-2

Instead, the portions of reflectance regular and diffuse can be summarized as total reflectance (R).

$$R = R_{reg} + R_d$$

Equation 3-3

Radiation absorbed (A) can be calculated from the measurement of the transmittance and reflectance [58].

$$A = 1 - T - R$$

Equation 3-4

3.4.2 Laser welding techniques

Based on these principles, two main types of polymeric laser welding can be identified: direct welding and through transmission welding.

In direct laser welding both materials are heated by irradiation of the beam, so it is possible to have butt or corner joints. The wavelengths used are between 2 and 10.6 micrometres, in fact many plastic materials are absorbent at some values in these wavelengths (Figure 3-5) [59].

In through transmission laser welding, the parts are pre-assembled, and the beam passes through a component that is transparent to the laser and reaches the second radiation-absorbing component. At the interface, there is heating and fusion of the two materials. Wavelengths of 0.8-1.1 micrometres are used, as many natural polymers are transparent in this range Figure 3-5. This type of welding has numerous advantages over the previous one, such as the possibility of welding components with small thicknesses or non-rigid components, good aesthetic and quality properties. As a disadvantage, a component must be transparent. A semi-crystalline polymer could need a lot of power, as there is a high degree of diffusivity of the beam [60].

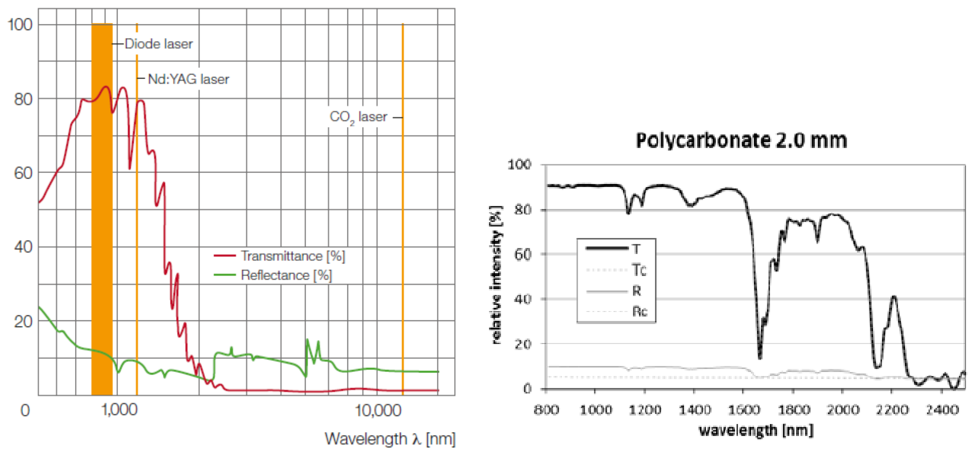


Figure 3-5 - Example of Transmittance Spectra of PA66 [61]and PC [62]with a thickness of 2mm

3.4.3 Trough Transmission Laser Welding

One of the most common types of polymeric materials welding is through transmission laser welding (TTLW) [59]. Where one of the joining materials must be partially optical transparent to laser radiation in near-infrared, and the other part must be laser absorbent. TTLW allows joining a plastic laser-absorbent component with a laser-transparent one. The laser passes through a transparent material and hits the second component which absorbs the radiation and melts it (Figure 3-6 -a). Through heat conduction, the other component is melted, and a joint between the interfaces is formed (Figure 3-6 -b).

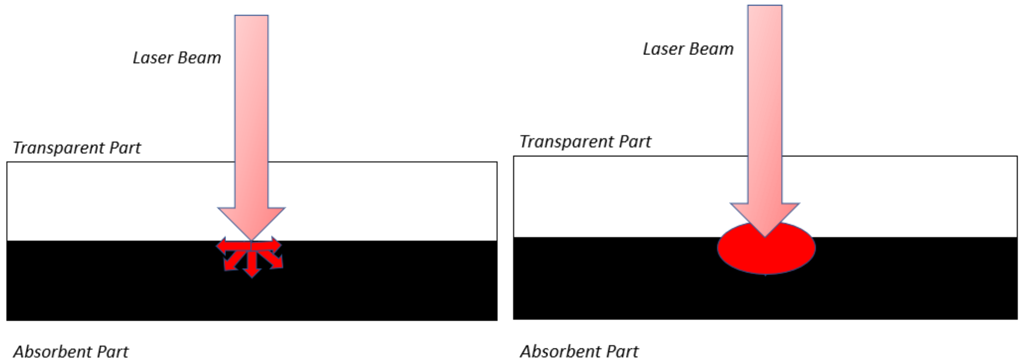


Figure 3-6 - Through Transmission Laser Welding Process. a) Material absorbs the radiation; b) Welding seam

Remaining in the infrared field, each material has a different coefficient of absorption, depending on the wavelength. The electromagnetic wave interacts with molecular structures, and it causes vibrational motions that is converted into heat. For this reason, it needs to use wavelengths that have minor self-absorption. Commonly, the lasers used in this technology have wavelengths between 800-1100 nanometres [44].

It is necessary to consider optical properties that have a decisive impact on the outcome of a laser irradiation process. However, a distinction should be made between amorphous and semi-crystalline thermoplastic polymers. In amorphous thermoplastic polymers, radiation is also transmitted in the case of high thicknesses, almost without loss (Figure 3-7-a). Instead, in semi-crystalline thermoplastic polymers, the radiation scatters on the crystals and it is refracted (Figure 3-7-b). Grains diffuse the light giving a typical milky appearance and limit the laser transmission. This is a limit for the thicknesses that can be welded with the laser. Therefore, a dispersion occurs, which mainly depends on the degree of crystallinity and the thickness to be radiated. The depth of optical penetration is a criterion for measuring the properties of the joint part. This value indicates at what depth the radiation should penetrate the surface before heat develops. Ideally, the depth of optical penetration is in the range of micrometres.

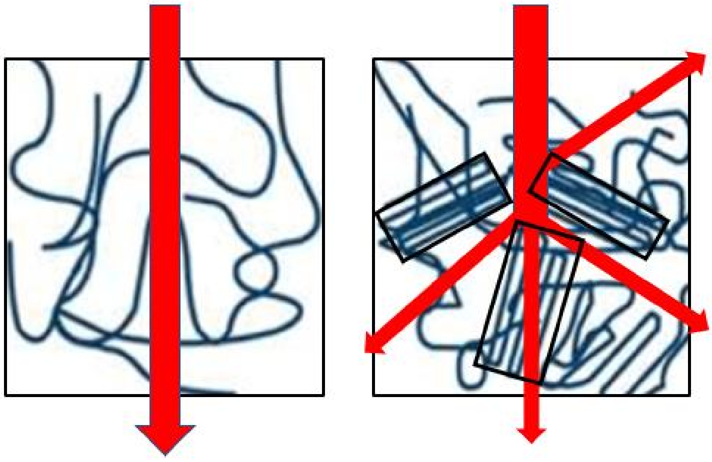


Figure 3-7 - Amorphous and Semi-crystalline structures and interaction with laser beam

The same effect is noticed with the use of reinforcement, such as glass fiber. The transmittance decreases substantially with the increase of the percentage of fillers [54].

While the first component must be transparent to the laser, the second component must be absorbent. If they do not completely absorb radiation additives, pigments or fillers are often added. So, often the materials that need to be absorbent, are filled with carbon black which easily absorbs laser radiation. The quantity of dispersion influences the coefficient of absorption, thus also the parameters and results of welding process [63]. The increase in carbon black fillers changes the absorption, passing from a volume absorption to surface absorption of the radiation. The widths of the welding areas increase. The radiation is absorbed by the carbon fibers, it is also a good heat conductor with respect to the polymer matrix. The heat is diffused mainly along with the carbon black fiber, this process depends on the orientation of the fibers. In lasts years, additives have been developed for selective absorbing range of wavelengths, in this way parts can maintain the colour wanted by customers. In fact, carbon black tends to darken the objects, so it is not suitable for aesthetic objects. Additives are near infrared absorber and can transform the radiation in heat that permits the softening of the matrix, even if it is a laser transparent. However, even pigments that colour the materials black with high transparency for the laser, exist [64].

The surface that heats up is that of the absorbent material, however for the heat conduction also the material coupled has a layer of molten material. Ultimately the depth of the molten material is the same in the two components.

Welding efficiency depends on many characteristics of the materials. It is influenced not only by the optical properties, but also by the composition and use of fillers, dyes, thickness. Colour dyes and stabilizers reduce the transmittance of the polymer.

In order to join the two components, usually they are made of the same material, or they are composed of the same plastic family. The last condition to be joined successfully, they could be having similar melting/softening temperatures. This condition has to be verified with tests of compatibility.

Due to the heat developed during the welding process, a thermal impact zone is generated which can be seen using a microscope. The profile of the weld bead must be managed in such a way that there must be uniform physical contact in the welding area. If this does not happen, the heat is not transmitted from the absorbent material to the transparent material causing a burn.

3.4.3.1 Typologies of through transmission laser welding

In TTLW it is possible to define a classification of the type of laser welding depending on how the welding joint is heated:

- **Contour welding**. A concentrated laser emission passes once on the weld path, melting it locally. The relative motion occurs through the movement of the components, the laser or a combination of both (Figure 3-6 - a). The components during the emission process are pressed together. The characteristic of the welding joint is influenced by the geometry of the focal point and time frame of the liquid phase of the welding joint.
- **Simultaneous welding**. In this process, the entire weld path is heated instantly, i.e., simultaneously by one or more laser sources (Figure 3-6 - b). Weld seams can be designed easier than the other methods. Any molding tolerances can be recuperated by forming a bead due to the mutual compression of the parts to be welded during the welding process.
- **Quasi-simultaneous welding**. The laser beam is guided by an automatic high-speed scanner. Two scanning mirrors deflect the laser emission and reflect it with a high speed along the welding edge (Figure 3-6 - c). The beam passes on the joint area several times per second, to allow the laser emission to heat and plasticize the welding bead practically instantly. In this type of technology, the molding tolerances can be partially recuperated.
- **Radial welding**. The laser emission is deflected by a radial mirror to the roto-symmetrical surface of the component to be welded (Figure 3-6 - d). The light interreferences between the components to be joined provides sufficient compression for the welding process. This type of continuous and hermetic welding seam requires keeping tight the components.
- **Mask welding**. A mask is inserted between the laser source and the parts to be welded (Figure 3-6 - e). Above the joint parts, a linear and well-collimated laser emission is transversely scrolled. Laser radiation occurs only at the junction points not obscured by the mask. The mask allows creating very thin structures in the order of the micrometres. It follows that welding with a mask reaches a very high resolution. Welding with a mask allows creating weld seams of various structures, for example straight and curved welding profiles of various widths and with flat surfaces in a single process. The welding joint is illuminated at the same time.
- **Diffractive optical elements welding**. For the purpose of the laser welding process, diffractive optical elements (DOE) can be applied (Figure 3-6 - f). These optics are used in processes such as edge welding, quasi-simultaneous welding or simultaneous welding. Starting from a point laser emission, they generate a

distribution of the power density according to the application. The DOE is an optical component that allows adjusting a contour with a point laser emission. Along this contour, through the DOE, it is possible to adapt the power density distribution to the requirements. This type of optical elements is used for complex welding profiles in the context of simultaneous welding but also in edge welding and in almost simultaneous welding for the optimization of the distribution of power density. DOEs adapt to the type of activity to be carried out and must therefore be calculated and simulated in advance, since they are designed for a single wavelength. Even if the production of a DOE is expensive, integration into one of our optics can be easily accomplished.

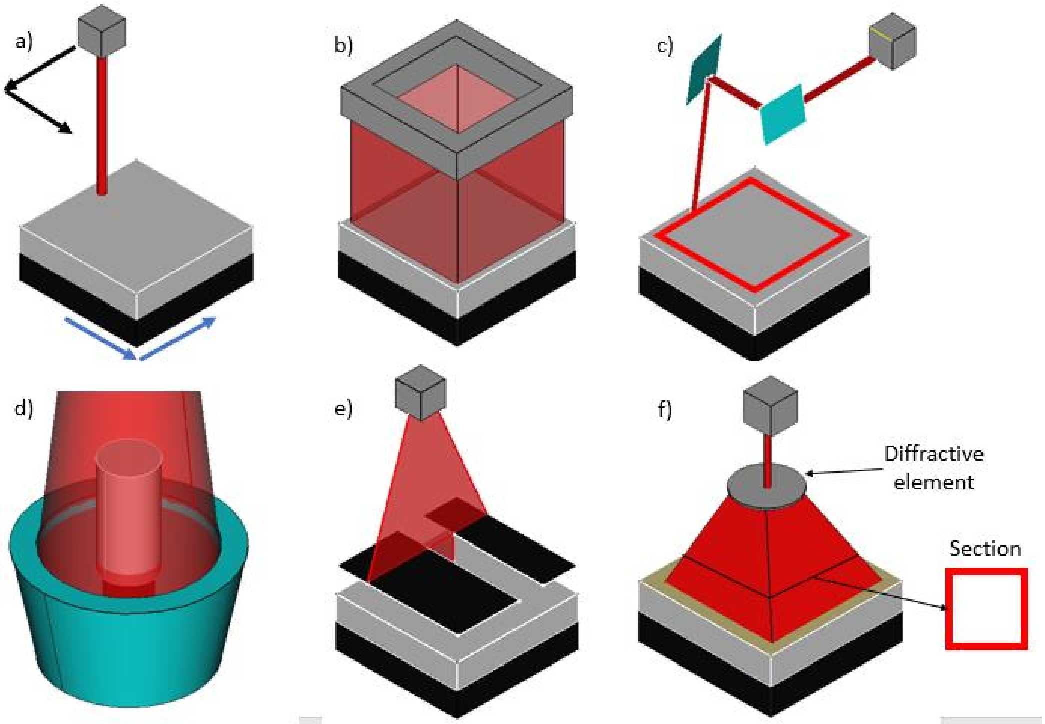


Figure 3-8 – Through Transmission Laser Welding typologies: a) Contour, movement of the source (black arrows) or the components (blue arrows); b) Simultaneous; c) Quasi-simultaneous; d) Radial; e) Mask; f) Diffractive Optical Element

In Table 3-2 the main advantages and disadvantages of the described methods of laser welding are presented [65] [66].

Welding methods	Advantages	Disadvantages
Contour	- Flexible - Excellent monitoring - Wide work area	- Slow - Medium cost
Quasi-simultaneous	- Fast cycle times - Flexible - Excellent monitoring	- Components mainly in a plane - Limited work area - Medium/high cost
Simultaneous	- Fast cycle times - Complex shapes - Wide work area - Good monitoring	- Medium/high cost
Radial	- Excellent monitoring - Flexible	- Only for Radial shapes - Limited dimensions
Mask	- Complex shapes	- Medium cost - Slow
DOE	- Complex shapes - Fast cycle time	- Limited dimensions - Complex design of beam and lens for each application - High cost

Table 3-2 - Advantages and Disadvantages of main technologies of Through Transmission Laser Welding

3.4.4 Simultaneous laser welding

The simultaneous laser welding is the most interesting method for the industries since it permits minimizing the deformation of the ultimate product, decreasing polymeric remains and it could reduce movement of mechanical components in the machines. This is a new technology not widely used for now, despite the numerous advantages (Table 3-2). It has the major advantages of quasi-simultaneous but fewer drawbacks. For this reason, it was decided to develop a system suitable and competitive for this technology.

With the methodology of TTLW, usually more laser sources heat the entire weld path simultaneously. The whole welding path is irradiated with one single emission, the parts are pressed and welded together. It is simple to achieve linear welding seams, but even complex paths can be treated. The complexity of the process is to obtain a homogeneous distribution of energy along the entire seam, it is difficult particularly if the parts have a non-linear profile with a lot of change of section. To reach this result, a metal waveguide with hollow core has been designed and located between sources and the components to be welded. This element helps to guide and mix the light of the different sources. In this way the blended beams reach the welding seam. The entire dissertation about the waveguide will be debate in Chapter 5.

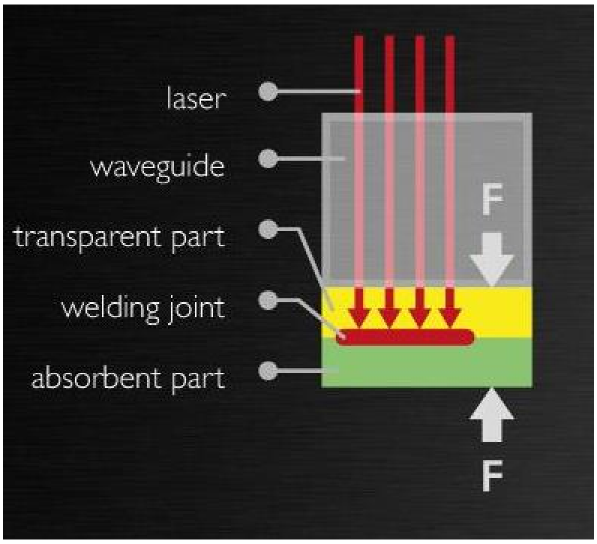


Figure 3-9 – Scheme of a Simultaneous Laser Welding System with a Metallic Waveguide

Simultaneous laser welding also allows welding joints with a T cross section (Figure 3-10). This joint is convenient because in addition to obtaining an interdiffusion in the interface like in Figure 3-6, it extends the fusion zone outside the seam (Figure 3-10-c).

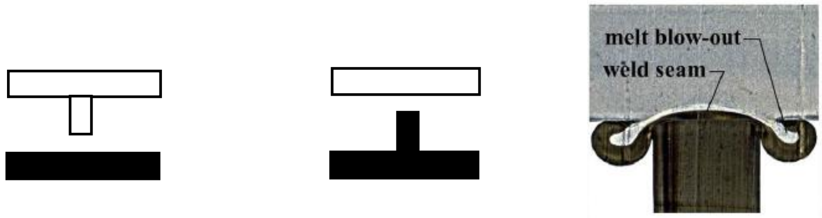


Figure 3-10 - T-Joint samples. a) sample with the rib in the upper part; b) sample with the rib in the bottom part; c) welding junction of b [67]

Mainly used in the automotive industry and where components have irregular 3D shapes. With the sinking of one component on the other, there is a compensation of the tolerances and deformations of the injection molded parts. Furthermore, after welding, the residual stress on the joint is reduced [67]. Thanks to emission simultaneously along whole the welding perimeter, it is possible to compress the components together and having an interpenetration that uniforms the irregularities. If the rib is on the transparent component, it can behave like a solid-core waveguide. Thanks to the geometry, total internal reflection is possible, and the light is led on the welding seam.

Chapter 4

4. Laser source for plastic welding

The studied and developed technology in my thesis work, as already presented in the Chapter 3, is the simultaneous welding of polymers through transmission of laser beam. To achieve this aim, the laser source and propagation system on the workpieces to be welded must be engineered. To obtain the simultaneous welding of an extended perimeter it is necessary to have multiple sources with the same characteristics. The sources will emit simultaneously in order to have homogeneously distributed lighting on the welding perimeter.

First of all, the typology of laser emitter must be chosen, afterward the transmission system has to be designed. Finally, it is necessary to define a system for homogenizing the beams in terms of power density. The latter part of the system is essential to obtain good welding. Furthermore, by improving the efficiency of the system, savings in laser sources and electrical power can be achieved. The first component that permits to reach the homogenization is the bundle of fiber optics described in Chapter 2. The other part to have a complete uniformity of the energy is the waveguide.

The activities carried out in this Chapter concern the study, the development and the fabrication of a prototypal system for the first welding machine, that uses a technology based on a multi-emitter source and a bundle of optical fibers.

In the initial phase, the work focuses on prototype engineering and on the search for multiple suppliers for each component. The evaluation of the suppliers is necessary to define the characteristics of the product, the quality-price ratio, the supply times and the production technology. Emitters and lenses have been on the market for a long time and therefore production technology and reliability are well-established features. While fibres optical bundles have not been used for a long time, the results can be uncertain or inconsistent with needs. The various construction parameters must first be verified, and laboratory tests have to be carried out.

The characteristics of the system must be established and after that the new system can be designed. After defining the characteristics, the components can be evaluated to obtain the desired result.
The system to be obtained has the following starting point. The laser beam is conveyed within a custom bundle of optical fibers. Summarizing the main components of the system to be chosen/designed:

1. Laser source;
2. Focalization optics;
3. Bundles of optical fibers;
4. Homogenization system, hollow core waveguide.

4.1 Laser Source

The main laser sources used for laser welding are solid state emitters. Here comparison of the properties [44] [68] [69].

Parameter	Type of Laser System	
	Nd:YAG	Diode
Laser active medium	Crystal	Semi-conductor
Intensity in focus [W/cm^2]	10^5-10^8	10^3-10^5
Efficiency [%]	40	30-60
Wavelength [nm]	1064	800-900
Size [cm^3/W]	20-50	1
Maintenance [hours]	500	None
Price [$/W]	180	70
Beam Quality	High	Medium-Low

Table 4-1 – Comparison between laser source used in laser welding

Because laser diodes are flexible and have a high efficiency cost/power, they are widely used, furthermore in plastic welding of polymers there is no need for high-power concentration [70]. For these reasons, laser diodes are the most used in this technology.

From an optical cost-power standpoint a continuous high-power diode laser bars is chosen. Diode bars contain an array of semiconductor laser emitters. They can contain from 20 to 50 emitters and can therefore reach high levels of optical power. The power is linked proportionally with the numbers of emitters. It is important that the emitters are well-positioned and cooled, to obtain good beam efficiency and performance [71].

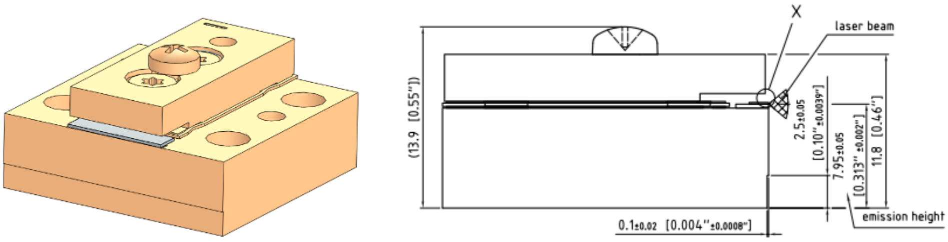


Figure 4-1 - Laser Diode Multiple Emitters

The characteristics of the laser source chosen are:

- Center wavelength = 976 nm
- Center wavelength variation = 5 nm
- max optical power = 100 W
- operation = continuous
- energy pumping = electrical energy
- Maximum operating Voltage = 1.8V
- Maximum operating Current = 126A
- Typical threshold Current = 14A
- Typical slope = 1W/A
- cooling = passively cooled
- Typical Slow Axis Divergence 86 % = 7°
- Typical Fast Axis Divergence 86 % = 36°
- Operation Temperature = 25°C
- Power conversion efficiency = 60%

The great difference in divergence of the beam emitted in the two directions is notable. The beam along the fast axis requires a collimator that reduces the excessive divergence. For this reason, appropriate optic components must be used to allow the beam to be focused.

A Peltier cell is used to allow keeping the temperature constant in the diode and to not alter the characteristics of the laser beam during its use. The Peltier cell is a thermoelectric device consisting of many Peltier effect junctions in series [72]. It is basically a solid-state heat pump: one of the two surfaces absorbs heat while the other emits it. The direction in which the heat is transferred depends on the direction of the current applied. The cell is mostly used to subtract heat of the cold side so that the body, in this case of the diode, can be cooled (Figure 4-2). The subtracted heat is transferred to the hot side; therefore, a heat sink must be combined with the Peltier cell to transfer it to the external environment.

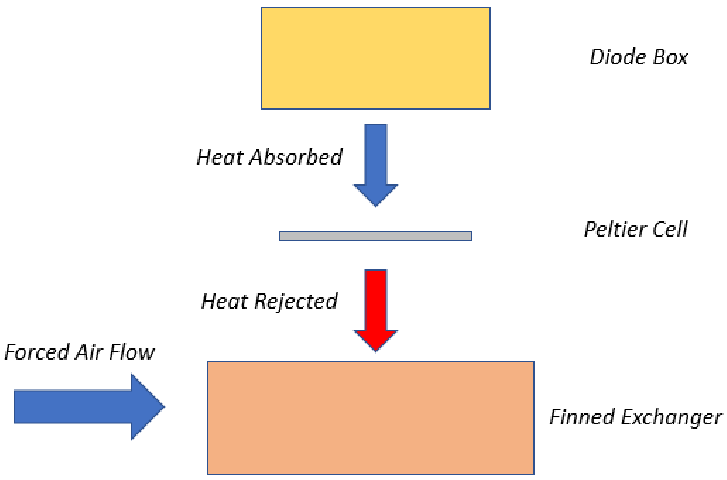


Figure 4-2 – Heat subtraction scheme of laser diode

Initially, an air-cooled system with finned surface and forced ventilation is used (Figure 4-3).

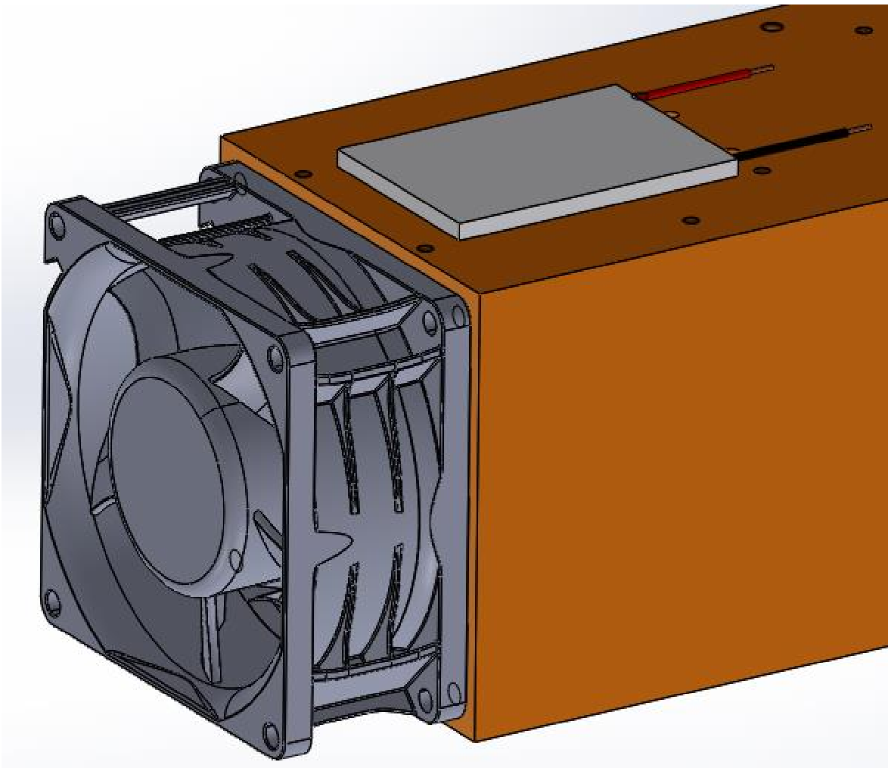


Figure 4-3 - Peltier Cooling Module and finned exchanger

4.2 Fiber Coupling System

The beam must be transmitted from the laser source to the workpiece in the most efficient, precise and safe way possible. To do this, optical systems such as lenses, mirrors, optical fibers are used.

Since in most industrial applications there is relative motion of the pieces, in addition to bringing the beam into the area of processing, a transport system must ensure the presence of adequate degrees of freedom of movement. Generally, six degrees of freedom are needed to be able to move a laser beam as desired with respect to a piece. Furthermore, to have low losses, the optical systems used must maintain good beam quality with reduced beam deformation, in order to focus or distribute it optimally.

The beam coming out of the diode is divergent, as reported in 4. Two main directions are defined, according to which the diode has two different diverging angles. The fast axis has greater divergence than the slow axis. Along the fast axis, before focusing, the beam must be collimated, that is, it is necessary to have all the rays almost parallel.

Only after having collimated the laser can the beam be focused.

4.2.1 Lenses Optical Principles

A laser beam can be focused in two different ways: by transmission through lenses or by reflection through a concave mirror [73].

The lenses are generally flat convex or have a meniscus shape, while the mirrors are parabolic or spherical. The first solution is typical of lasers or sources of relatively low power (indicatively up to a few kW) because for higher powers the lens has an excessive temperature increase which leads to damage to the lens itself. The mirror solution, on the other hand, is typical of higher power sources.

Optical lenses are defined by certain parameters such as the focal length and the diameter.

In theory, the beam could be focused in a dimensionless point, but the physical reality of the phenomenon prevents this. Therefore, a spot with a defined radius will be obtained.

The simplest case to focus a beam is to start from a collimated beam and use a thin focusing lens. In this case the beam is focused at a distance equal to the focal length of the lens (Figure 4-4-a). For a defocusing lens the focal distance is the distance between the lens and the virtual focus, indicated with a negative sign (Figure 4-4-b).

The curvature of the lens is positive for convex surfaces (Figure 4-4-a) and negative for concave surfaces (Figure 4-4-b).

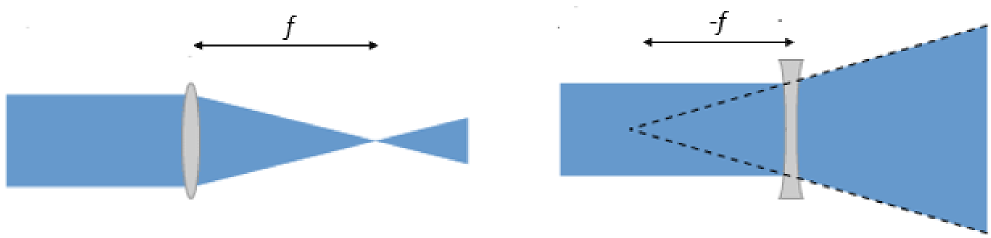


Figure 4-4 - a) Focusing lens with bi-convex surfaces; b) Defocusing lens with bi-concave surfaces

In this simple case, a lens that focuses a beam with a radius r, the focal length can be determined using the thin lens approximation:

$$f = \frac{r}{\tan \Theta}$$

Equation 4-1

Where Θ it is the divergence of the beam.

A thick lens has two main planes, and the focal length is the distance between the plane and the corresponding focus point.

In this case, the focal length of the lens can be calculated by the lensmaker's equation [74]:

$$\frac{1}{f} = (n-1) \cdot \left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n-1)d}{n\, R_1\, R_2}\right]$$

Equation 4-2

Where:

f is the focal length of the lens,

n is the refractive index of the lens material,

R_1 is the radius of curvature of the lens surface (positive for convex surfaces, negatives for concave surfaces) where the beam enters,

R_2 is the radius of curvature of the lens surface where the beam exits,

d is the thickness.

In thin lens approximation the Equation 4-2 becomes:

$$\frac{1}{f} = (n-1) \cdot \left[\frac{1}{R_1} - \frac{1}{R_2}\right]$$

Equation 4-3

However, an optical system consists of multiple lenses and other optical elements, so the previous method cannot be used to define the focal length. Thus, the focal length and the focal distance can be distinguished. The latter can be defined as the distance between the focal point and the exit or entrance of the optics.

In another case a divergent beam is passing through a lens. Under this circumstance the focusing distance increases according to the equation:

$$\frac{1}{a} + \frac{1}{b} = \frac{1}{f}$$

Equation 4-4

Where a is the focus distance of the incident beam, b is the focal distance, f the focal length of the lens.

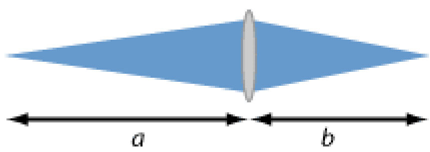


Figure 4-5 - Focus for a divergent beam

$b \approx f$ if a is much larger than f, but $b > f$ in all other cases. If $a \leq f$, the equation has no real solutions, then the lens cannot focus the beam.

In the focus point the extension is not dimensionless, so the radius of the small spot must be defined.

4.2.2 Optical system design

In reference to the laser diode chosen in 4, the divergence is wide along an axis, so the curvature for the collimation lens is only according to the fast axis.

At the exit of the bars of emitters, the laser beam passes first through a collimation lens that straightens the rays along the fast axis.

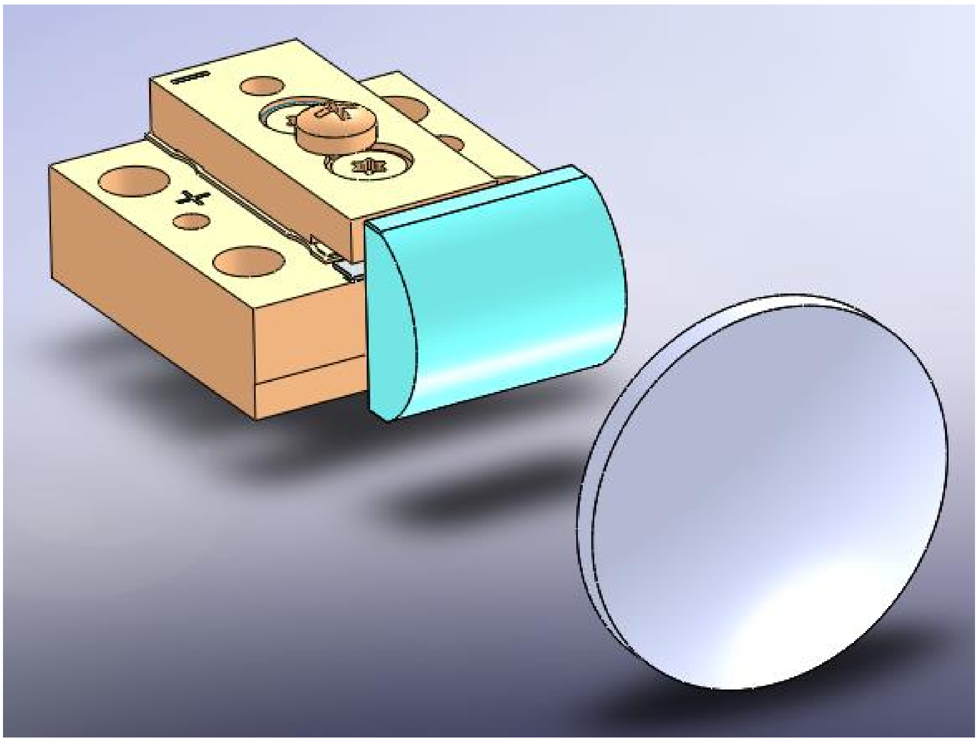


Figure 4-6 - Diode and Lenses. First on the left the collimation lens for the fast axis of the laser diode. The second one for the focusing the entire beam

Finally, the laser beam passes through the focusing lens that allows focusing the beam, with a focal spot of about 9 mm^2, on the active area of a bundle of fibers.

It is necessary to check whether this optical system allows to obtain a compliant distribution in the final application, such that, at high power no damage to the bundle occurs.

To obtain a spot with a homogeneous power distribution at the entrance of the bundle, the distances of the lenses L1 and L2 have been modified (Figure 4-7).

The L2 lens was also replaced with a lens with a shorter focal distance, to obtain a greater divergence of the laser beam at the output from the individual ferrules.

In fact, the output characteristic of the bundle ferrules depends on the launch condition [75]. The numerical aperture of the input beam influences the output divergence. Having a greater divergence helps for a better homogenization of the laser on the component that is to be welded.

It should be noted that:

- The distance L1 refers to the source-flat surface distance of the lens
- The reported distance of the L2 lens refers to the distance: source-center lens

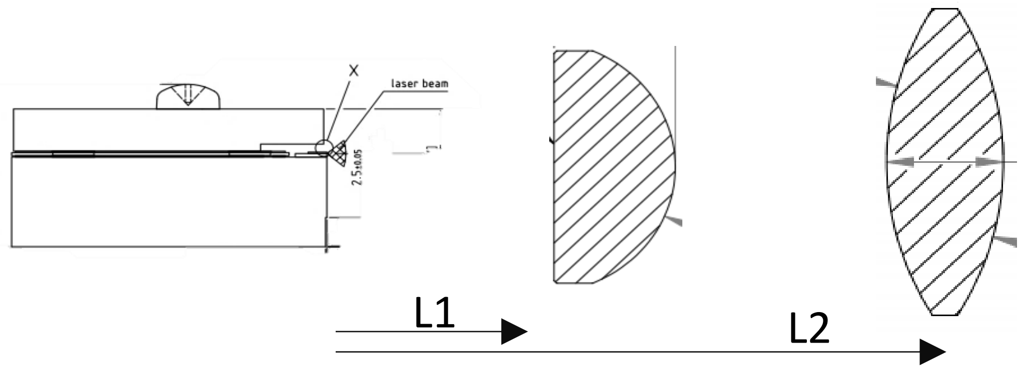


Figure 4-7 – Schematic Optical System: Diode, Lens of collimation and Lens of focusing

Various solutions have been tried for lens curvatures and focal distance to optimize the focusing spot. Values of power density that are too high could damage the bundle. Optics chosen in the first test phase were not optimal, for this reason the best configuration changing lenses, focal length and profile of the focal spot were researched. The lenses and the measurements were repeated, until the correct distances were found in the optical test bench.

At the beginning of the work an elliptical laser spot (showed in the Figure 4-8) was used.

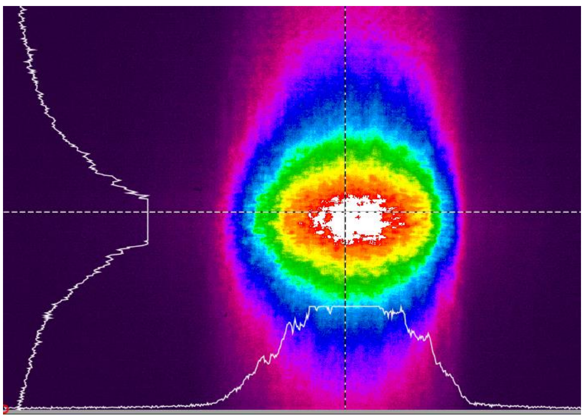


Figure 4-8 – Distribution of energy in focal point in the first tests

A better homogeneity of the spot has been searched, therefore the distribution in the input of the bundle was changed. Working with a simil-squared spot (3.5 mm x 3.5 mm), there is not a high central peak value in the Gaussian beam, but the value of power is homogenized. This leads to two different profiles in the two main directions: in one direction it still takes on a typical Gaussian trend, while in the perpendicular direction it takes a top flat trend.

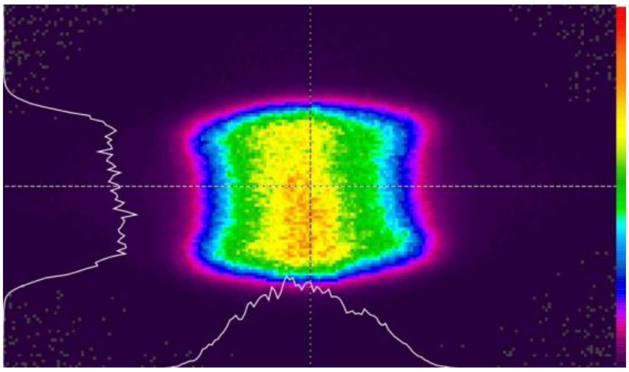


Figure 4-9 – Final distribution of energy in focal point

As for the focal lens - bundle distance, the optimal value has been researched in terms of homogeneity and efficiency. Thanks to a test bench, the set-up was tested, and laboratory tests were carried out to find the suitable distance. It was therefore necessary to arrange a prototype to verify and establish the distances listed above.

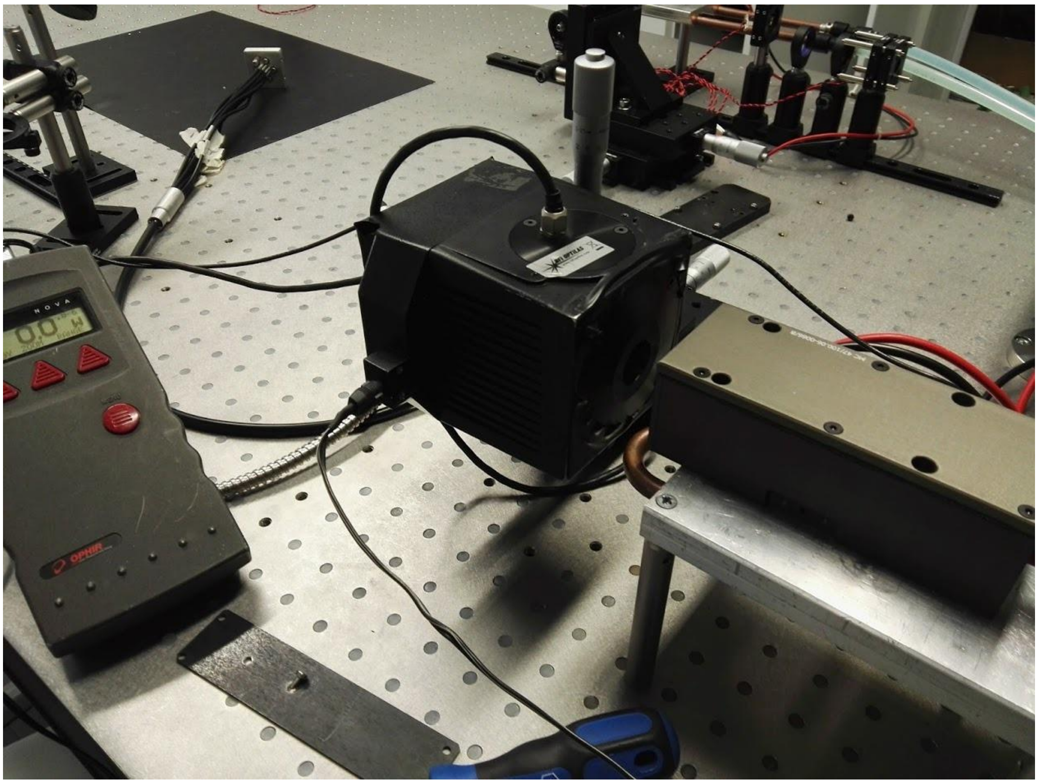


Figure 4-10 – Sources system, diode and optics in the test bench.

The diode-optical lens system shown in Figure 4-7 is enclosed in the box on the right in the Figure 4-10. This allows to manage components safely and to fix them in a stable position.

On the left in Figure 4-10 at the exit of the diode focusing system there is a power meter. The device is in the position that the bundle would be in.

The power meter is a sensor that allows to measure optical power even with high power laser devices. It uses a thermal method, so that the absorbed energy is converted into heat, which is measured through thermocouple matrices. Energy is determined by measuring the temperature gradient by the device. The temperature difference is proportional to the incident and absorbed radiant power.

With the power meter it was possible to obtain the following graph (Figure 4-11) of the power, exit from the source box.

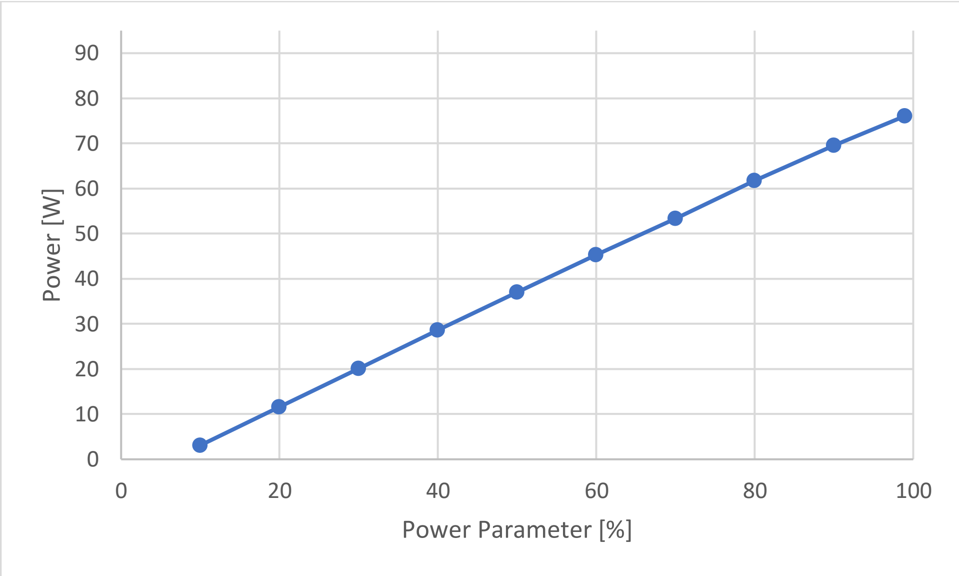


Figure 4-11 - Power characteristics of the source

It should be noted that the current value corresponding to 100% of the set parameter is 90A. With this current, the diode emits an optical power beam of 78 watts. The laser device driver interface is calibrated with a percentage parameter of the maximum power. In this way it is possible to have a better understanding of the level of use of the diode and of the power still available. The power adjustment will be a crucial point for welding management and good quality of the cohesion joint.

Below in the Figure 4-12 the CAD project of the source system, consisting of box laser source, cooling system and control drivers.

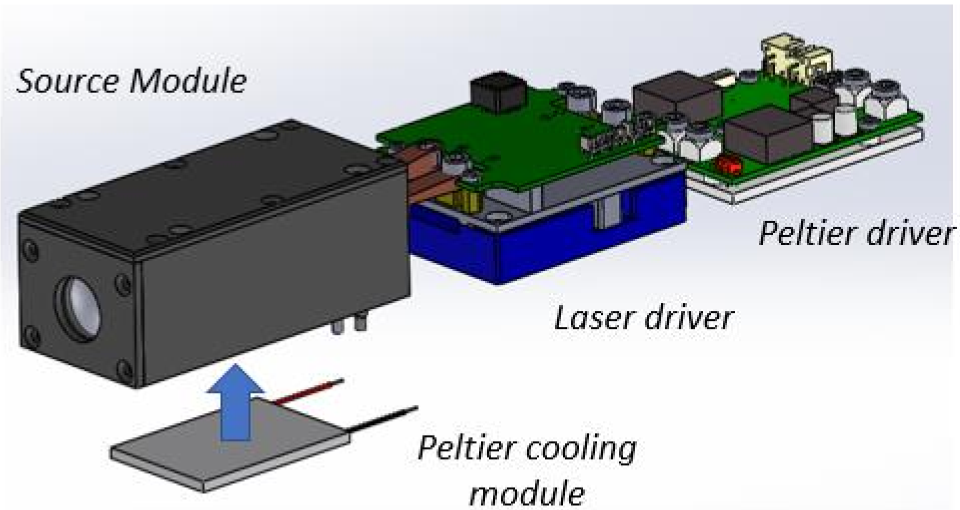


Figure 4-12 – Laser and cooling module with a driver of communication and control

4.2.2.1 Safety system using laser in the laboratory

The housing box has the function of fixing the components with well-defined position tolerances. This aspect had a fundamental role in the development of a subsequent serial production of the module. In addition to this task, a level of safety appropriate to the characteristics of the laser must be ensured. In fact, all laser equipment produces intense monochromatic light rays which can present risks. These risks depend on numerous factors including the wavelength, the energy power of the beam and the duration of the emission. The eye is the most vulnerable organ, especially if the light reaches the retina, which due to the focusing action the density of energy dramatically increases. If the laser power is high enough, exposure to the beam can also cause damage to the skin. For these reasons a system and device to eliminate the risks of accidents needs to be used.

There is a regulation that classifies the laser source according to its effects on humans and limits applications according to the characteristics. From the analysis of this regulation, only Class I, Class II and Class III sources are safe. However, only Class I sources are intrinsically safe for the purposes.

Laser safety is covered by legislation that requires laser classification according to the characteristics of the beam. This regulation is essential for all laser users and for manufacturers of objects using laser sources. When classified as O.E.M. equipment, wavelength and output power conditions comply with Class I, Class II, Class III of laser products.

Class I laser products emit visible light and in no way present a potential danger to the human body.

Class II laser products emit visible light and although they are not completely safe, eye protection normally takes place as an aversion response, including blinking. Random observation is not dangerous, especially if optical aids are used. The user should avoid staring into the beam. No skin damage will result from exposure to the beam.

Class III laser products can emit visible or invisible radiation, they are potentially dangerous if a direct beam or specular reflection is seen from an eye. Some precautions should be taken to avoid direct view of the beam and to control specular reflections.

- The laser should only be used in a controlled area.
- Care should be taken to prevent unintended mirror reflections.
- The laser beam should be terminated, where possible, at the end of its useful path by a material that diffuses it and reflection such that the danger of the beam is minimized.
- Eye protection is required if there is any possibility of direct observation, or specular reflection, of the beam or diffuse reflection.
- Laser warning signs should be posted at entrances to controlled areas. Any company or organization wanting to use a Class III laser, or a laser of comparable wavelength and power.

- Hermetic closures of the environment where the laser beams spread or can be diffracted, reflected.

Other safety systems will also be adopted at the exit from the diode / lens box and subsequently the entire welding system will be placed in certified cabins for the safety of operators.

4.3 Fibers Optical Bundle

The next part of the system to be defined is the fibers optical bundle.

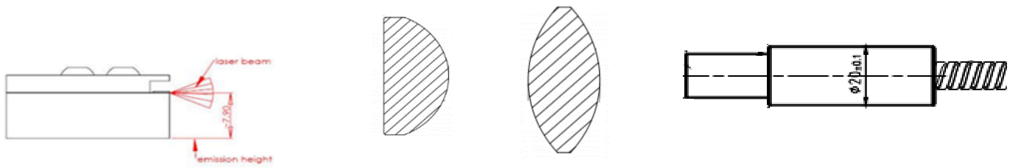


Figure 4-13 – Source system. Bundle placed in the focus point.

The study and research of a bundle, suitable for the required characteristics, was the most demanding part of the engineering of source laser system.

The bundle of optical fibers was considered essential for the homogenization of the laser beams and for the splitting of energy, useful for reducing the number of sources. In addition to an economic gain, the minor number of sources has facilitated and shortened the set-up times in the welding (especially of extended components), as it was necessary to manage a smaller number of parameters and sources.

Often a bundle of optical fibers is used for imaging and laser beam transport applications. A bundle of optical fibers, as already described in Chapter 2, is a set of fibers bonded together. This group of fibers can have a single entry and then divide along the path into multiple legs, each of which with a fraction of the number of initial fibers.

This solution allows to divide the input power from a diode into a defined number of legs, according to the power fraction needs. The power is divided and homogenized between the various terminal legs; this permits not only a reduction of sources to be used in welding but also a more efficient energy distribution in the welding joint. Furthermore, the laser beam in the inlet of bundle does not have a regular and symmetrical characteristic, instead the light after the passage in optical fibers assumes an axial symmetric behaviour, which is easy to manage and lead to the welding seam. From the studies carried out and from the collected data it has been noted that to obtain improvements in terms of efficiency and homogeneity of the bundle output beam, an input with fused fibers and randomized fibers is necessary. For these reasons afterwards first tests were requested versions with these features.

All bundles have subdivisions in 10 legs. The initial and ends parts are covered with steel protection called ferrules.

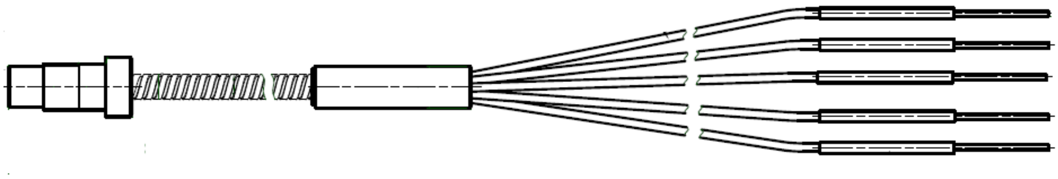


Figure 4-14 - Bundle Structure with an input and 5 output ferrules

Figure 4-15 shows a comparison of the input ferrules of fused silica bundle and soft glass bundle.

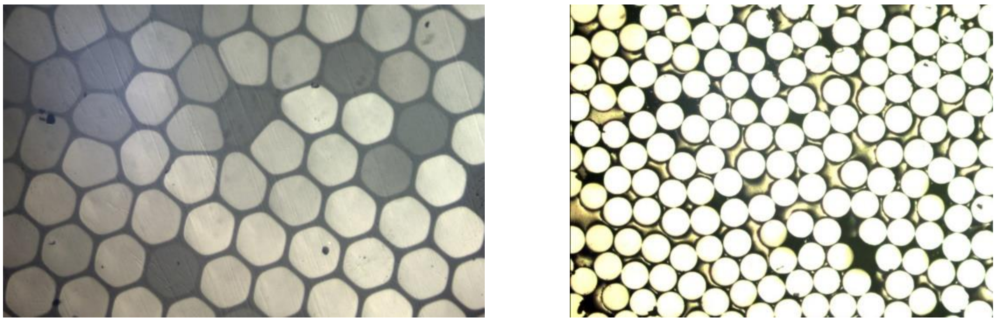


Figure 4-15 – Bundles inlet. a) Fibers fused; b) Not Fused

Here are presented some features and results of the bundles that have been used for the first characterization and welding test, designed with the support of the relative suppliers. The parameters indagated and compared were the efficiency and the deviation from the mean. The efficiency is the power fraction in the output respect of the input, and it measures the losses and the effectiveness of the coupling among the source and the bundle. The deviation from the mean has been calculated by measuring the power of the single ferrules, finding the mean and evaluating the deviation of the ferrule with the largest value from the mean. This value gives an indication of the homogeneous distribution of power in the ferrules.

After the first designs were tested, an advanced version was reached with an input with fused fibers and randomized fibers.

- Bundle 150-fibers, fused end, non-randomized fibers: efficiency of this bundle was approximately 85%. As Figure 4-16 clearly shows, the fibers have not been randomized. For this reason, the percentage deviation measured from the mean value was almost 23%. The percentage deviation of the target beam was approximately 3%.

Figure 4-16 - Bundle 150 fibers output ferrule– Not randomized method

- Bundle 150-fibers, fused end, randomized fibers. The measured efficiency was around 85%. The percentage deviation measured from the mean value was about 10%. The improvement in this value was due to the randomization of the fibers (Figure 4-17). To get better values, more fibers need to use.

Figure 4-17- Bundle 150 fibers output ferrule–Randomized method

- Bundle 670 fibers, fused end, non-randomized fibers. The measured efficiency was approximately 77%. The fibers were arranged in strips. The percentage deviation measured from the mean value was about 6%. The fibers have not been randomized; this is the reason why the target of the percentage deviation has not yet been achieved.
- Bundle 2300 fibers, fused end, non-randomized fiber. The measured efficiency was about 65%. The fibers have been correctly randomized. The percentage deviation measured from the mean value was about 1.5%.
- Bundle 1450 fibers. The measured efficiency was around 56%. No problem occurs with the laser on. The low efficiency value was due to the fact that the input was not melted.
- Bundle 670 fibers, fused end, randomized fiber. The measured efficiency was about 78%. The fibers have been correctly randomized. The percentage

deviation measured from the mean value was about 2%. This package was chosen for production.

Material	Soft glass	Soft glass	Soft glass	Soft glass	Soft glass	Boro-silicate (not fused end)
N. of fibers	150	150	670	670	2300	1450
Efficiency (%)	85	85	77	78	65	56
Deviation from mean (%)	23	10	6	2	1.5	12
Randomized	No	Yes	No	Yes	Yes	Yes

Table 4-2 - Comparison between bundles

It was evaluated that the randomized bundle of 670 fibers is the best compromise between price and performance. The soft glass bundle has resisted to the power density of the laser source. Figure 4-18 shows the arrangement of the fibers in the entry and exit ferrules of the bundle chosen for the system.

This bundle, coupled to the source system, allows a maximum power of about 6 watts to be obtained from each ferrule, with a percentage difference with an average value of less than 3%. A low value of difference between ferrules is fundamental to obtain a homogeneous welding profile. For instance, among the bundles produced and tested, there is one (150 fibers) that allows to obtain 6,6Watts output from each ferrule. However, its efficiency is disadvantageous to the homogeneity between the various ferrules, which is slightly less than 10%.

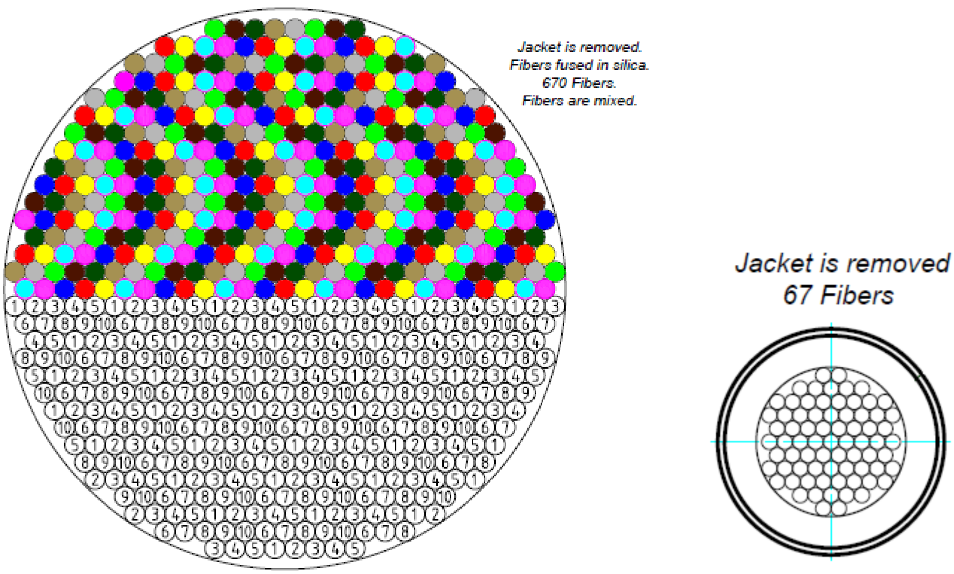


Figure 4-18 - Optical Fibers Bundle, Inlet Ferrule and output ferrule fiber disposition and randomization

The bundle can also be produced with different output configurations, with 1-2-5-15 ferules, in dependence of the quantity of energy the components request.

Below the characterization of the power of the 670 fiber bundle is shown.

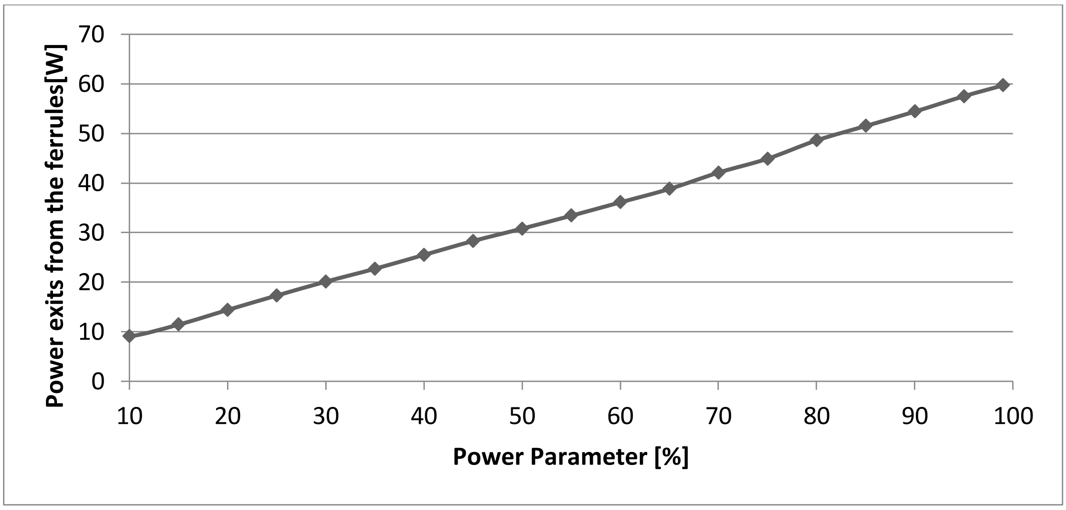


Figure 4-19 - Power characterization

4.4 Beam Profiling

Considering planes perpendicular to the direction of emission, it is possible to evaluate and define the power profile, the beam amplitude and the study of the propagation of the beam in space.

A wave sensor (Shack-Hartmann) can be used to study the characteristic of monochromatic beams. This allows identifying the place of the points from the propagation in phase of the position; that is a set of points that is to "vibrate" in phase. The measuring system can consist of a matrix of suitably spaced holes or lenses, a CCD sensor for image detection and an acquisition system. However, in this way the wave front is measured only on some point grids.

With some methodologies only the distribution of energy is measured, but not the optical phase, which on the other hand can be measured using only a camera. However, the quality of the beam can be estimated.

When measurements in parallel planes at increasing distances are made, it is possible to study and evaluate the spatial propagation of laser beam.

One problem that must be addressed is that the intensity profile can change or that the beam diverges rapidly. So, in some planes it is not possible to measure entirely the intensity. For this reason, some devices do not measure the whole beam, but only a portion. Often the beams are characterized differently by some reference parameters such as full width half maximum (FWHM) or the radius in which the intensity is $1 / e^2$ value of the peak intensity. This feature can be used if the beam can be approximated with a Gaussian.

Measurements in the different planes along the propagation axis allows to define the M^2 factor and the beam parameter product. This parameter is the product of the divergence angle of a laser beam and the beam radius at its narrowest point (waist beam), it gives an indication of how well the beam can be focused on a small point.

The beam profiler is used to aid laser alignment, positioning of the optical system and launch in the fiber. In some cases, it is very important to monitor the spatial trend of the beam.

For the infrared and near infrared regions, CCD cameras are among the ones most used. The sensors are able to record beams from several millimetres up to the order of tens of microns, since the pixel resolution is few microns.

To evaluate wavelength beams in the visible or near infrared, silicon-based sensors are used. With this technology the pixel size is less than ten microns.

Another fundamental parameter for sensors is the number of pixels, which allows to acquire and measure beams of larger diameters. Being sensitive sensors, the laser power could be critical, for this reason sometimes the beam must be attenuated before entering the camera. Using a beam expander or reducer it is possible to change the measuring range. It is possible to evaluate the beam in an imaginary position.

With the acquisition system the results can be analysed by software. It was evaluated the beam radius, position, ellipticity or Gaussian approximation.

A CCD camera (Ophir-Spiricon LLC: SP620U, beam splitter LBS-300) has been used to beam profiling. The camera's CCD chip is made up of 1600 × 1600 pixels.

The CCD camera was used to investigate the distribution in entrance of the bundle, the dimensions of the focus point and how much the focus covers the active area in the inlet ferrule. Placing a CCD sensor in the focal point of the source makes it is possible to define these properties for the beam, just as shown in Figure 4-8 and Figure 4-9.

The main part of the beam profiling is the characterization of the exit beam from the ferrules because this is the real input for the welding system. For this reason, the CCD sensor was placed in the exit of the output ferrule (Figure 4-20).

Depending on the number of subdivisions of the extremity the beam outgoing from the ferrule changes. When 10 exit ferrules for a reference bundle is established, it is possible to definite the profile of the irradiation.

The trend of the power was studied and showed in 4.2.2 and 4.3. To have the entire description of the beam it is necessary to have the spatial propagation.

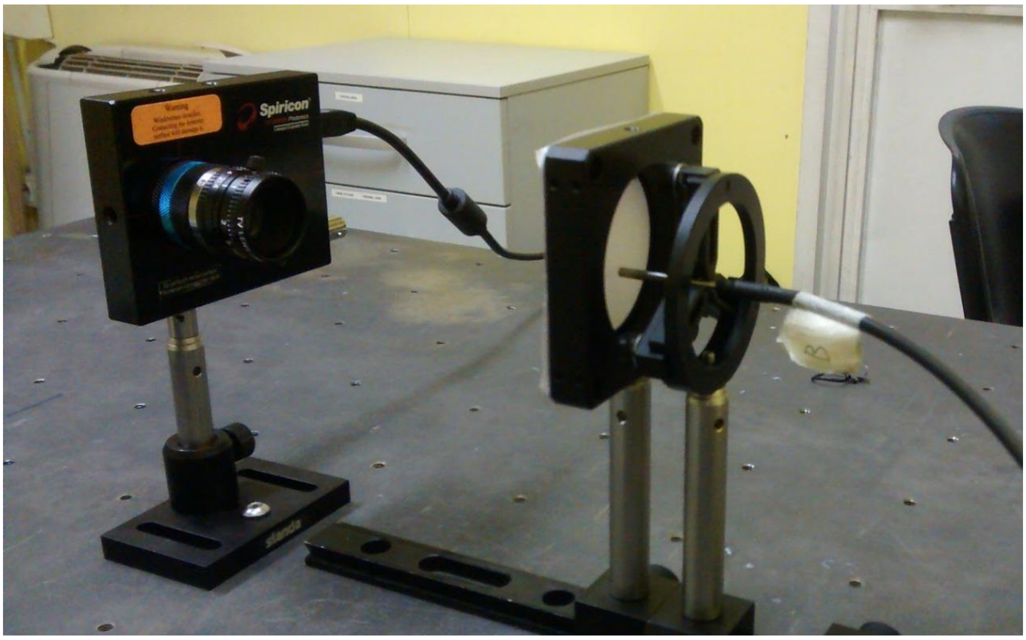


Figure 4-20 – Beam Profiler sensor at the exit of the ferrule

The measurements of the shape are carried out in two ways, both with Beam Profiler:

1. Direct measurement of the size of the beam leaving the ferrules at established distances.
2. Indirect measurement of the size of the beam coming out of the ferrules through an Ophir consolidated system, using a diffusive component and a high optical performance lens mounted on the Beam Profiler capable of framing the area of interest with micrometric resolutions.

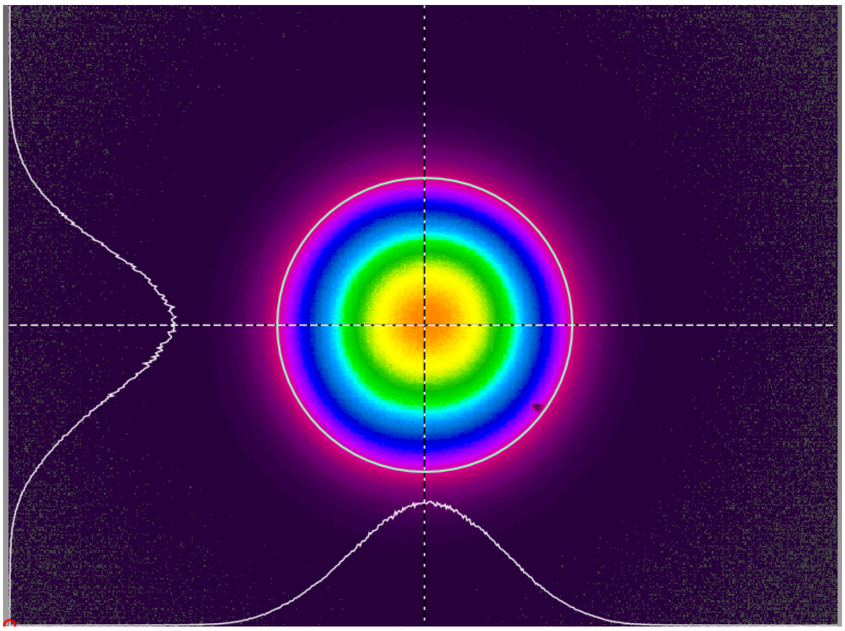


Figure 4-21 - Profile in the output of the ferrules in 2D analysis

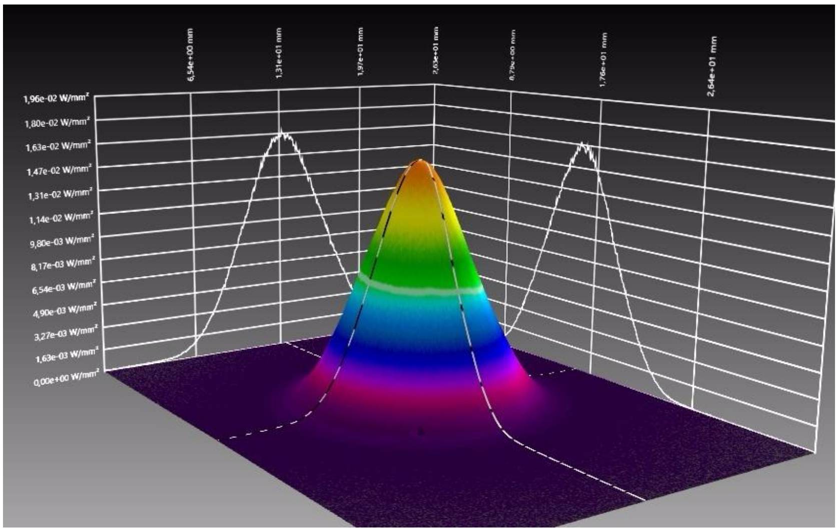


Figure 4-22 – Profile in the output of the ferrules in 3D analysis

As shown in the Figure 4-21 and Figure 4-22, the bundle has a Gaussian output beam. This shape of the beam permits simplification and an easy modelation in the raytracing software.

Measurements in parallel planes at the ferrules output were conducted to establish the divergence of the beam. In Figure 4-23 it can be noticed how the gaussian beam expands in the space. In the image it is possible to see the intensity values of the pixels, the Gaussian values are to be normalized with the power used in the measurement.

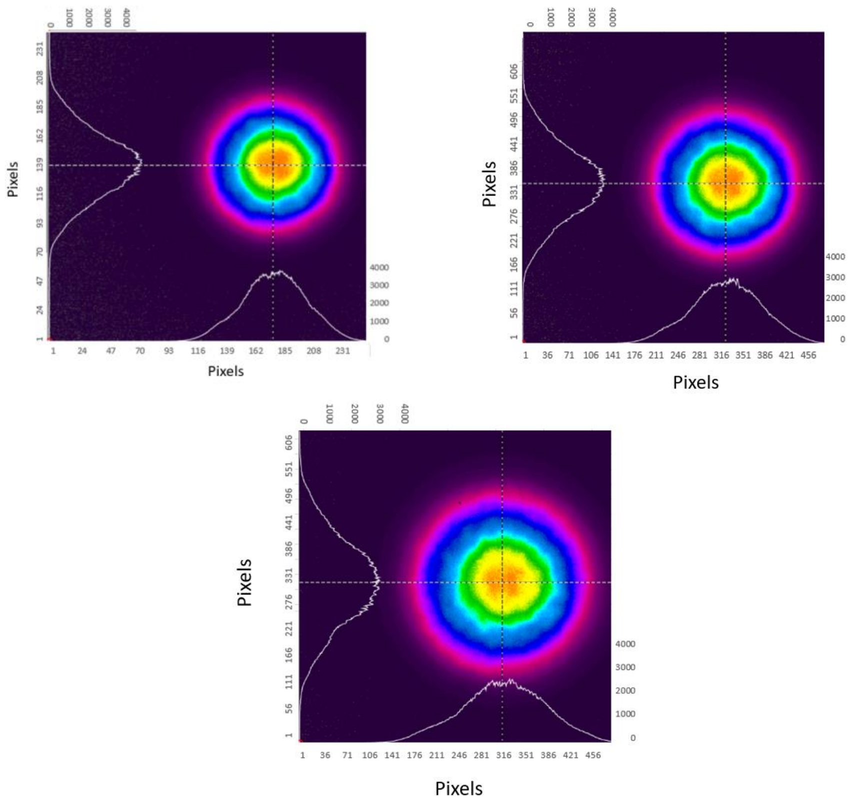


Figure 4-23 – Beam Profiling measurements in parallel plane at 20mm, 25mm, 30mm from of a ferrule of output

From measurements it was obtained that bundles with 5-10-15 ferrules have similar characteristics of the output beam. The power of a single ferrule is proportional to the subdivision of the ferrules of the optical fiber bundle. Based on these experimental measurements, the bundles are totally interchangeable and replaceable with each other. This behaviour allows having more power available if it is needed.

The 1-2 ferrule output bundles have a Gaussian with different characteristics in comparison with the previous bundles. Interchangeability can only be achieved between 1 and 2 ferrule bundles.

The Table 4-3 summarizes the powers that are available for ferrules in bundles mainly used in welding applications. Further configurations can be made but have not yet been tested or used.

Number of Ferrule	Max Available Power per ferrule [W]
1	60
2	30
5	12
10	6
15	4

Table 4-3 - Power per ferrule in the main fibers optical bundles used in the welding applications

4.5 Ray-tracing model

Ray-tracing is a procedure for tracing the path of wave beams that interact with bodies with different optical properties, that is, with characteristics of absorption, reflection, refraction. To simplify the tracing, the beams are approximated with straight rays. This approximation is valid as long as the dimensions of the bodies are greater than the wavelength, in fact with this kind of analysis, phenomena such as interference and diffraction are not considered.

The wave is shaped like many linear rays. A ray advances straight in the system until it encounters a medium or surface with different optical properties. From this point, a new beam is sent in a direction depending on the new medium. This process is repeated until the beam completes the path and occurs in all rays of the system.

4.5.1 Ray-Tracing Software: OpticStudio Zemax

OpticStudio Zemax is a ray-tracing and optical design software. A ray-tracing software simulates numerous and complex propagations of the rays in the components with which they interfere, purely optical elements such as lenses, mirrors, diffractive elements, bodies with assigned optical properties. It is used for imaging and lighting analysis.

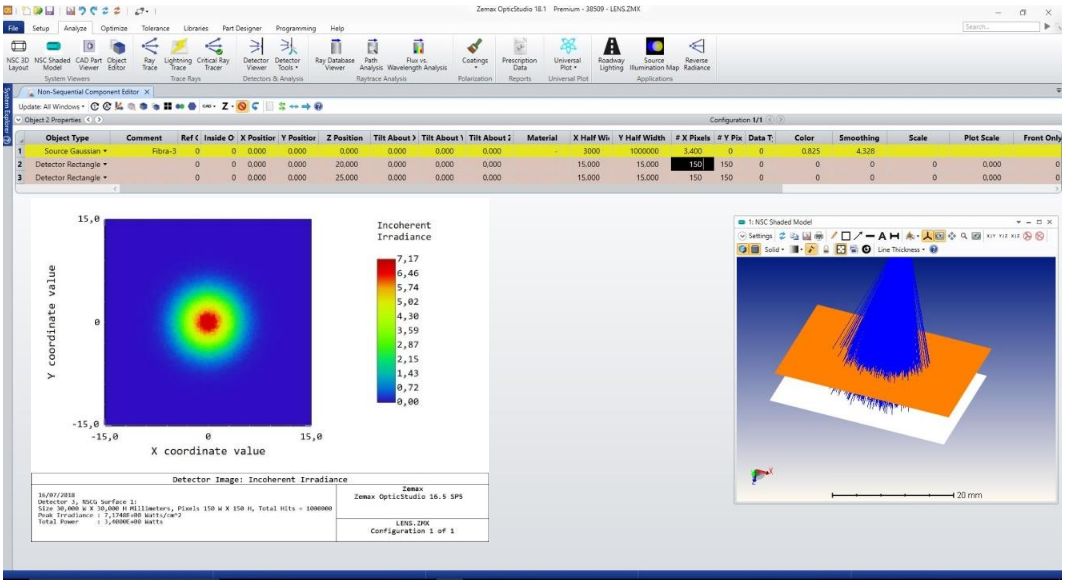


Figure 4-24 - OpticStudio Zemax environment

Thanks to the ray-tracing software it is possible to analyse the system to simulate the energy distribution and make the opto-mechanical design.

In order to have design support for the focusing system, a diode-lenses model was created (Figure 4-25-a), and the characteristics of the bundle's incoming spot (shape, power distribution, etc.) have been checked (Figure 4-25-b).

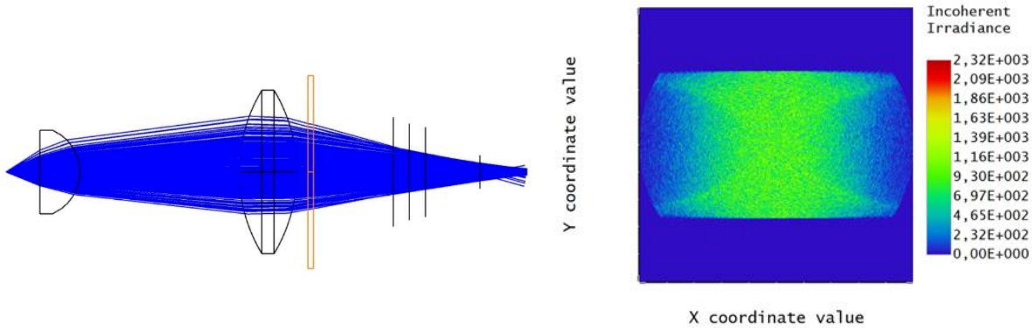


Figure 4-25 - Focusing Beam in the input of the fiber optics bundle simulated with the OpticStudio Zemax: a) System diode-lenses; b) Spot point distribution

It can perform sequential and non-sequential ray tracing:

- In the sequential environment, the rays are traced to approximate the characteristics of the source, intersecting the optical elements one at a time and in a predefined order. This modality is often used to design, optimize and tolerate lens systems, providing information about elements required in an optical system, their curvatures and ideal types of glass. An example of a sequential environment in Figure 4-26, where it was simulated the path of the laser beam for the system of focusing of the diode.

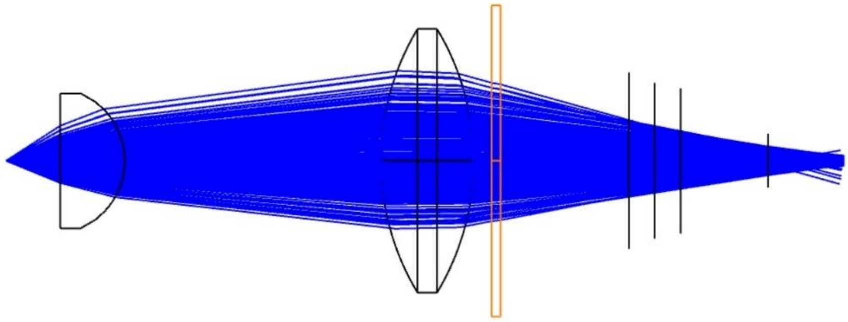


Figure 4-26 – Example of Sequential Environment in a ray-tracing software: Ray-tracing of the System of focalizing lenses.

- In the non-sequential environment, a ray can hit the same surface and the same body an indefinite number of times. The rays can meet the surfaces in a not defined order, allowing to behave in a more similar way to reality. It is used for more complex models. As the Figure 4-27 shown, the rays can hit the sample more than once, and the sequence for hitting objects is not pre-established.

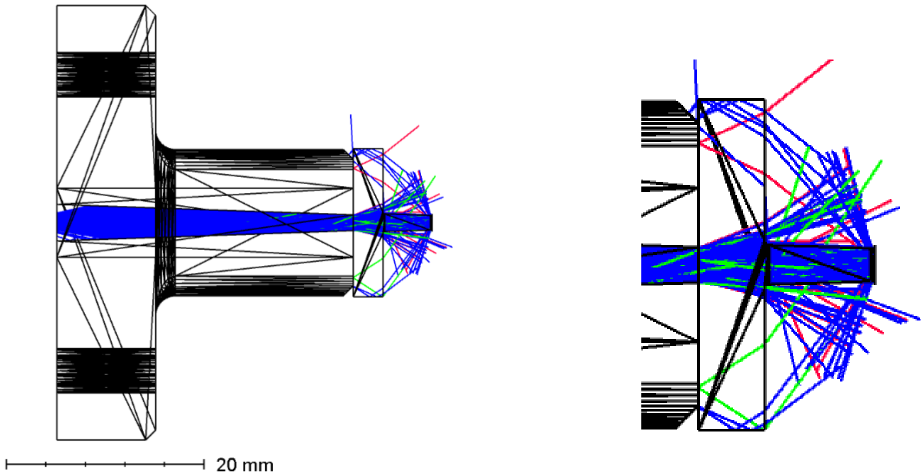


Figure 4-27 - Example of Non-Sequential Environment in a ray-tracing software: Ray-tracing for a metallic waveguide and a sample with T-Shape

4.5.2 Ray-Trace Model of the system components

In order to proceed with the study of homogenization, it was indispensable to model the complete system in the software. Therefore, for every single element an OpticStudio Zemax model is created.

There are four main components to analyse:

- Output of ferrules of the bundle;
- Hollow core waveguide;
- Laser transparent material;
- Welding interface or laser absorbent material.

The main elements for the model will be analysed below, focusing on the attention to the exit of the beam from the ferrules.

- **Output of ferrules of the bundle.** Defining the wave characteristic of the output of the ferrules beam is the most delicate part and it took a lot of work. It is the main part to describe the model in the software, as it represents the input of the welding system. Having an optimal model allows to have a better design and to define the energy distribution on the weld joint.

  As mentioned in 4.3, the end of optical fiber bundle is divided into a determinate number of ends. From 5 to 15 subdivision of ferrules the model will be the same, such as the output model of 1 and 2 ferrules.

  The measurements and the shape of the power profile is been shown in 4.4. The data indicate in good approximation the match with a gaussian profile. In the software is easy to choose a source with a Gaussian profile.

  To carry out this characterization, the steps taken were:

  1. Characterization of the beam coming out from a single ferrule with Beam Profiler or lens. The objective was used to frame a wider area of the Beam Profiler sensor and, therefore, 100% of the beam.
  2. Search in OpticStudio Zemax for a source suitable for simulation based on the characterization carried out.
  3. Verification of the coincidence of peak values and diameters between points 1 and 2 (Figure 4-28).

  In the ray-trace software, it is possible to find a model with a Gaussian profile amongst the functions used as optical sources. It is important to define the parameters of the Gaussian to obtain a faithful match to the experimental data.

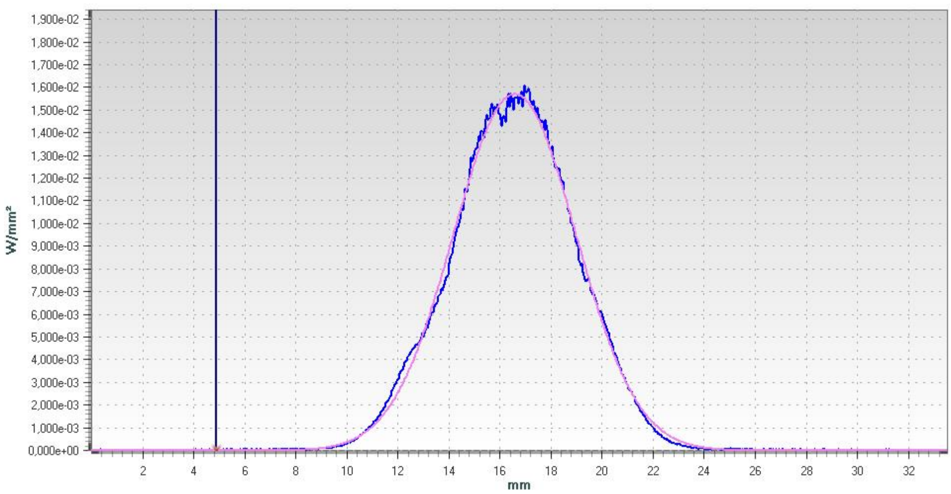


Figure 4-28- Overlap between the experimental data (blue line) and model in OpticStudio Zemax (red line)

The model data obtained has to be verified by means of welding tests. These proofs have been realized with the beam coming out of the wave guide and verification of the coincidence between the distribution detected with the Beam Profiler and the OpticStudio Zemax simulation. Other tests are conducted with the beam coming out from the PMMA lens fixed on the wave guide and verification of the coincidence between the detected distribution and the simulation.

- **Hollow core waveguide.** The optical waveguides were made of metal. This choice is due to a good workability of the material and to the possibility of making mirror surfaces. Metal such as aluminium and steel can be polished. It is also possible to carry out surface treatments to improve the degree of reflection. Some surface treatments increase resistance to chemical attack.

  To make surfaces 99% reflective [76], it is often used to coat with a thin layer of gold. Furthermore, the patina allows prolonged use as gold has a greater resistance to corrosion and oxidation than other metals. However, aluminium also reaches high percentages of reflectivity, so this material was used for experimental tests.

  Optically the metallic wave guide is modelled as a complete reflective mirror.
- **Laser transparent material.** In the first phase of the study, the specimens used were in PMMA. This material has high levels of transparency, however in ray-tracing software it is common to find features already present in the material libraries. On OpticStudio Zemax it was possible to select this material from its library. In Figure 4-29 and Figure 4-30 the characteristics of the PMMA commonly used in welding tests and applications are shown.

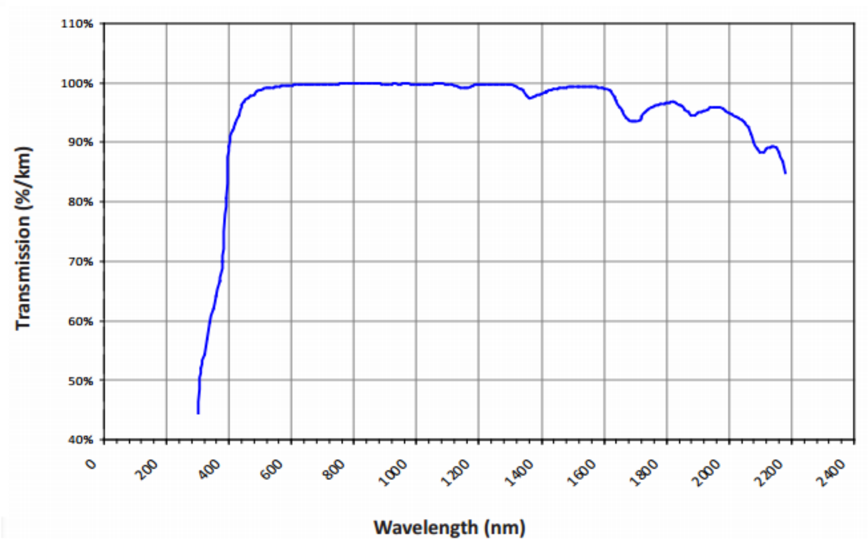


Figure 4-29 – Spectrum of Transmission of a natural PMMA

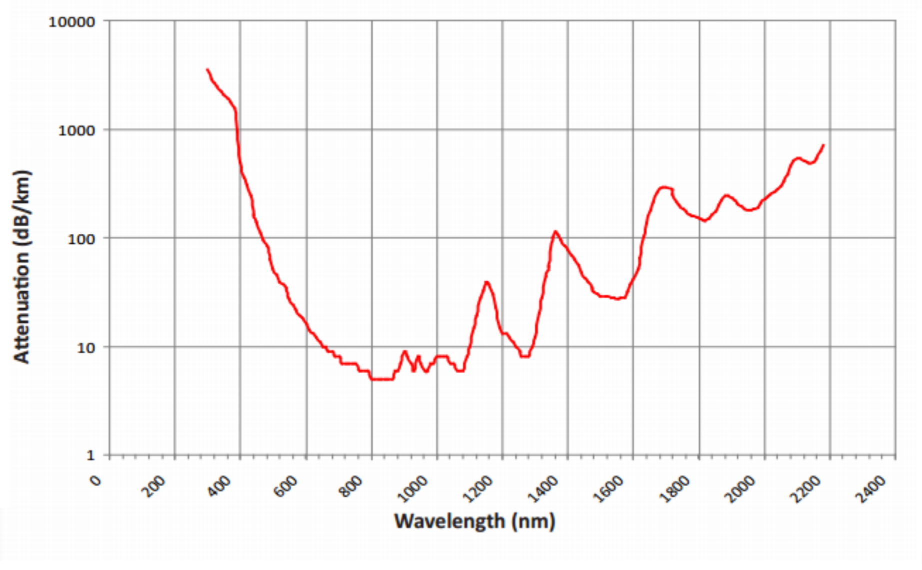


Figure 4-30 – Spectrum of Attenuation of a natural PMMA

Some PMMA compounds behave slightly different than the curves. It depends on dyes, colorants and other dispersions. In this case, it was necessary to measure the features and adjust the curves.

In the next phase of the tests, other materials were used. Therefore, it was necessary to carry out the characterization of the material and create a new software library. For the treatment of other materials, it will be analysed in the following chapters.

- **Laser absorbent material.** On the welding interface, it is possible to arrange the detectors for evaluating the power density arriving on the absorbent material. The detector will have pure absorption properties.

Chapter 5

5. Metal hollow core wave guides for simultaneous laser welding

A waveguide has the task of guiding the electromagnetic waves along a certain path with minimal energy losses. In general, it is used to carrying any kind of waves. The wave confined by the structure is forced to propagate along certain directions defined by the waveguide design. This element must be adequately designed in such a way in order to minimize power losses in wave propagation.

Guiding the light allows distributing it in a specific area. Optical fibers are waveguides, however, they are not very suitable for applications with large extension of the surfaces, because of the Gaussian emission of a single fiber doesn't allow the power density uniformity as required by the application. Making solid-core wave guide components is more expensive, so hollow elements are used. Polished metal surfaces permit total internal reflection with minimal loss of intensity for electromagnetic waves such as laser radiation. With a good degree of polishing, the losses do not exceed 5%, that is, the light propagates in the air space inside the structure. Every time the beam hits a metal surface and is reflected it is attenuated of a small quantity. The light propagates in the air space inside the structure and undergoes a total internal reflection when it hits the metal walls. Furthermore, in these components, the laser path is mainly in the air where the losses are negligible. These reasons have led the choice of metal hollow core waveguides.

Usually, the waveguides are used for transport, but in the application of simultaneous joining in through transmission laser welding have additional functions such as the homogenization of the beams and a structural function of pushing during the joining process. However, in this laser application, the main feature of waveguide is to homogenize the irradiation in the welding path. Homogenization has the role of improving the welding process, not only under quality aspect but also the force of cohesion. If the energy is not well-distributed, some areas could burn and degrade, while other areas could not reach the softening point, so the welding would seem to be successful, although the seal is not perfect. Another disadvantage of the incorrect distribution is the raise of cycle time. Optimizing the time of welding is another crucial issue, in fact when a factory has to produce continuously in a line, even a brief amount of time, for example only a few seconds, has a crucial impact.

This Chapter will study the characteristics and construction parameters to create metal waveguides for simultaneous welding applications. A good homogenization of the beam will be sought through a ray-tracing software. Finally, the results will be evaluated to obtain a good welding quality through laboratory tests.

5.1 Study and design of hollow core wave guide

In Chapter 4 the system, up to the ferrules, has been described and analysed. A complete characterization of the laser beam output was given. This part represents the input of the welding system. In the following study, the starting point is this energy profile, the structure of the waveguide is modelled and designed.

The energy outcoming from the ferrules has a shape of Gaussian (Figure 5-1), moreover the beam is divergent. Hence, there is a central area with a density of energy much higher than peripheric. It is necessary to avoid such an uneven distribution on the piece, the task of the waveguide is to redistribute this energy.

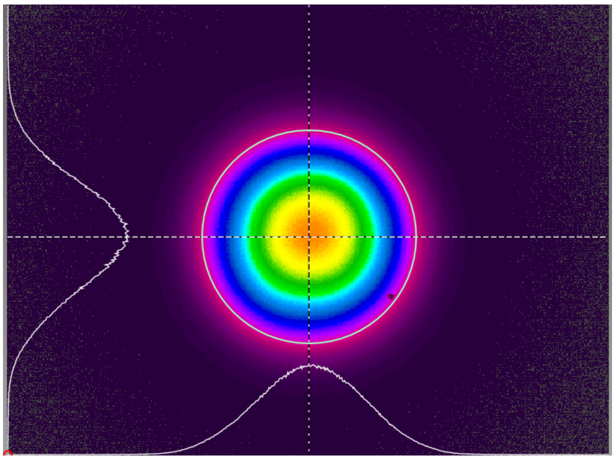


Figure 5-1 – Intensity profile outcoming from a ferrule

5.1.1 Samples for tests

Before the design of the waveguide the specimens for the tests had to be defined. The first specimens made had a T-shape. As shown in Figure 5-2, the laser transparent material was PMMA and the absorbing material was ABS filled with 0.2% by weight of carbon black.

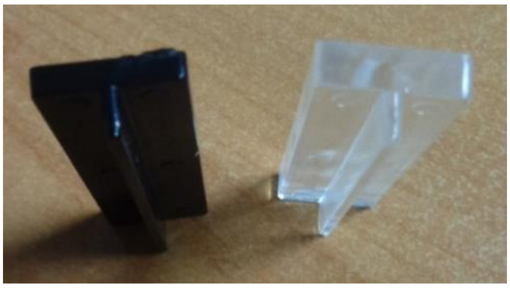
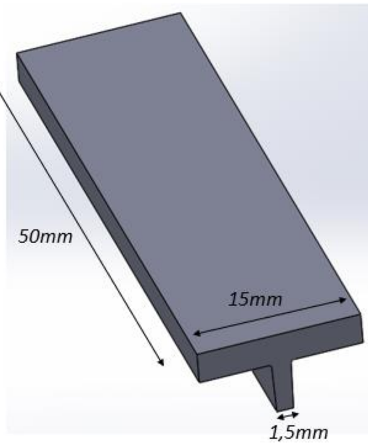


Figure 5-2 – Samples for tests in black ABS and transparent PMMA

Different dimensions of the specimen were made and tested, only the two lengths remained constant to 50x15mm. Figure 5-3 presents the dimensions that were used. The figure shows the welding configuration, where the upper part is the PMMA component and the lower is the ABS one. The width of the welding rib is 1,5mm. After the welding there could be an interpenetration of the components, and the figure represents this configuration. In automotive application this characteristic is often requested because it offers a better resistance and permits compensating for parts distortions. In fact, it is possible, in a 3D object with a complex shape and extensive dimensions, to have deformation after the molding process, hence the welding path is not in a nominal position. With the interpenetration of components, a deviation of about 0,1-0,3mm could be recuperated. For example, in some areas there will be an interpenetration of 0,5 and in others of about 0,2mm, this allows to keep the sealing of the part after the welding. Without a welding rib and interpenetration some areas could not be welded optimally.

Supported by a supplier of molding processes, a small mold was made for the injection process. The supplier has provided the specimens needed for the study. It was possible to change the raw compound in order to obtain different composition of the specimens in respect of the materials described above.



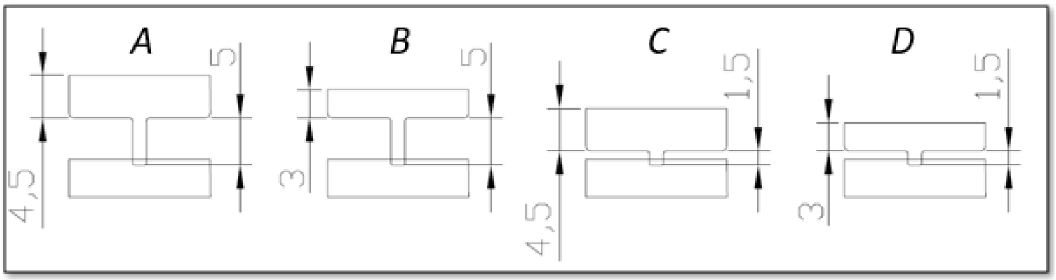


Figure 5-3 – Dimensions of the samples

5.1.2 Ferrules' step and fixing method

To avoid the discontinuity of irradiation on the welding interface, the waveguide has to be designed appropriately. To do this, another important factor is added as a homogeneity parameter: the step distance between the position of the ferrules. In fact, thanks to the superposition principle, it is possible to obtain a wave front almost regular.

Placing the ferrules side by side permits to sum of the contribution of the Gaussian and flattening the power distribution (Figure 5-4). But as result of that, a strict distance between fibers could be required.

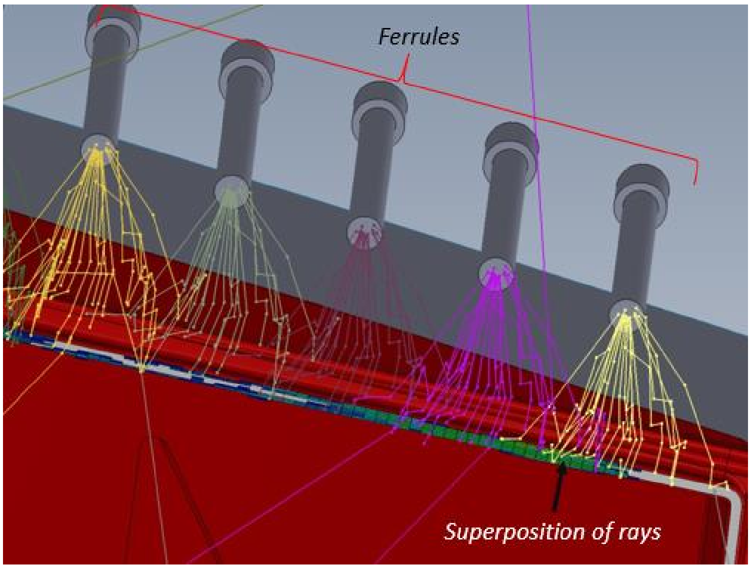


Figure 5-4 – CAD model used for the design of the wave guide, it shows the blending of the rays becoming from different ferrules to obtain a good homogeneity energy profile

Very small distances are often not possible. Usually, there is a mechanical and construction limit, the ferrules have an external diameter of 3mm, so it is not ideal to make a holder with shorter distance.

As a cheaper and more flexible solution, the ferrule housings are made from perforations in aluminium plates or blocks. These processes are mainly obtained by machine tools, so in reality it is never convenient to make holes at distances of 3mm. In fact, aluminium must resist the manufacturing process and subsequently maintain a good mechanical hold for the ferrule. The holes pass through the aluminium block, so it is necessary to have a mechanism to fix the sliding of the ferrules in the holes. Rubber quad-rings were used for this function (Figure 5-5-a). They are placed tangent to the ferrules (Figure 5-5-b), when the screw is tightened the quad-ring deforms radially and exerts compression on the ferrule in contact (Figure 5-6). In this way, the ferrule is blocked by a radial force which pushes it firmly against the wall of the hole.

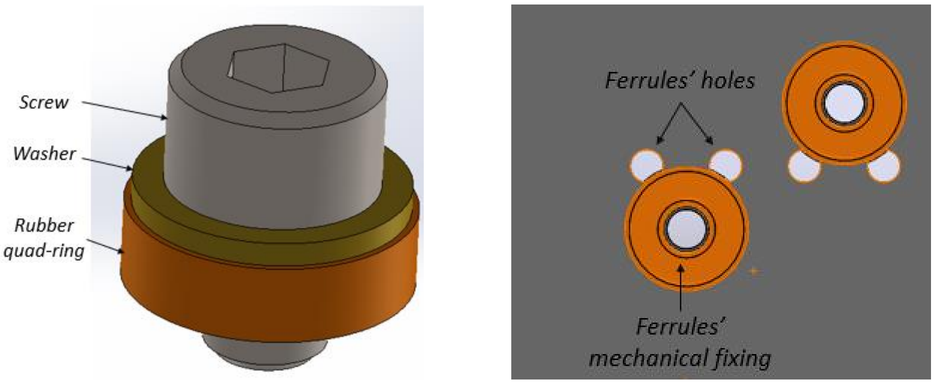


Figure 5-5 – Scheme for the mechanical fixing method for the ferrules: a) System of fixing; b) Position between the quad-ring and the ferrules

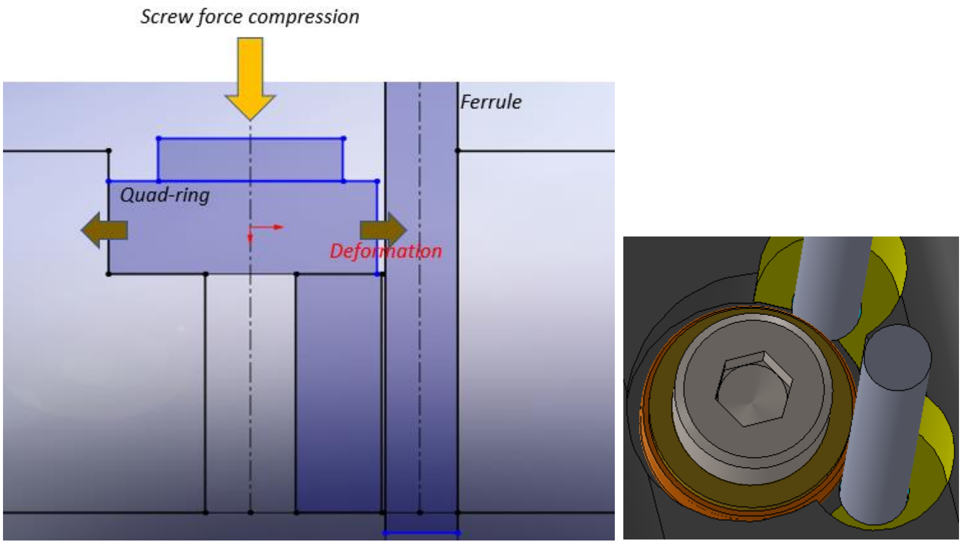


Figure 5-6 – Quad-ring principle of fixing

If the distances between the ferrules allow it, it is possible to lock two elements at the same time with a single quad-ring. In this case, the distance between ferrules must be no less than 5÷4.5mm due to the housing of the quad-ring hole. However, under the point of view of the construction and assembly it is better to keep a high step distance.

5.1.3 Wave guide parameters

A polished aluminium waveguide was chosen. The choice was guided by the advantages described in paragraphs 4.5.2 and 5.

The parameters of the waveguide are important to obtain the homogeneity of energy on the weld joint. Properties such as the degree of reflection allow to increase the efficiency of the system, however it has little influence on the distribution.

The geometric parameters allow to control and make the power profile constant. Additionally, they permit to optimize distance between ferrules and as consequence the reduction of sources number and power of the process.

To be able to polish the mirrored walls of the aluminium blocks which act as waveguides, they must be easily accessible for the surface finishing phase. For this reason, in order to create the waveguide for this application, the component was divided into two symmetrical half-shells, shown in Figure 5-7.

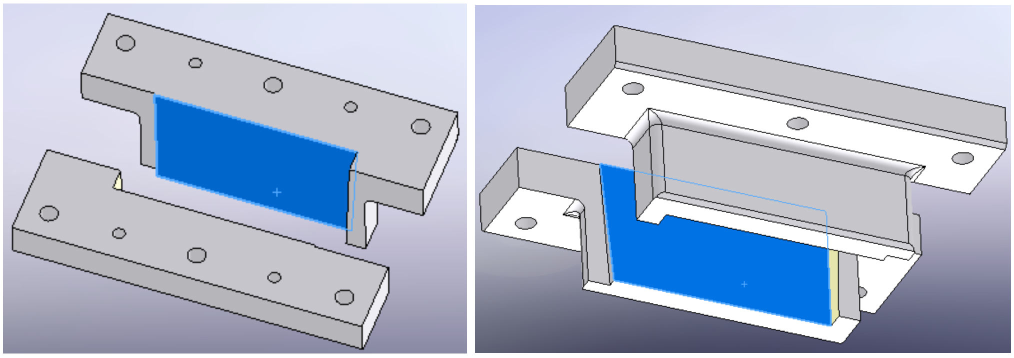


Figure 5-7 – Wave guide for T-shape samples. Blue surfaces have polished

The waveguide has axial symmetry and is linear. A good degree of homogeneity power is obtained along the thickness of the joint. Parameters such as the fiber step, height and angle between the side walls influence the homogeneity along the length of the path.

During the design and test phase of the waveguide, the parameters have been modified for the search for a good weld, were:

- Step between ferrules,
- Height (*H*),
- Angle (*c*),
- Opening width at the base (*a*).

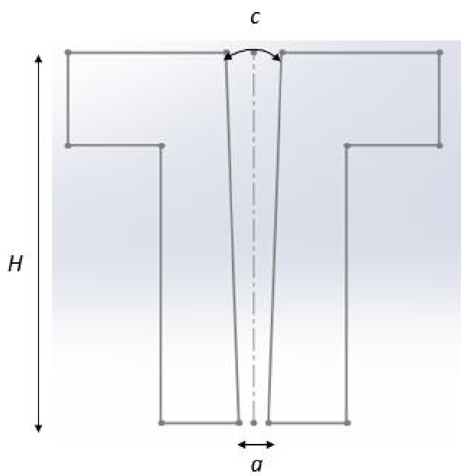


Figure 5-8 – Wave guide parameters

These factors are influenced by the divergence of the beam, although the emission is divergent per se. The expansion of the rays helps to distribute the energy and to decrease the peak of the Gaussian profile. In this way it is easier to mix the contribution of ferrules. Convergent surfaces accentuate this behaviour.

The aperture *a* defines transverse extension of the beam, this parameter is dependent on the width of the welding rib. The values are very similar to each other. If *a* was too small, it would not properly illuminate the entire welding rib (Figure 5-9-a). While a high value would burn the material outside the joint path Figure 5-9-b/c).

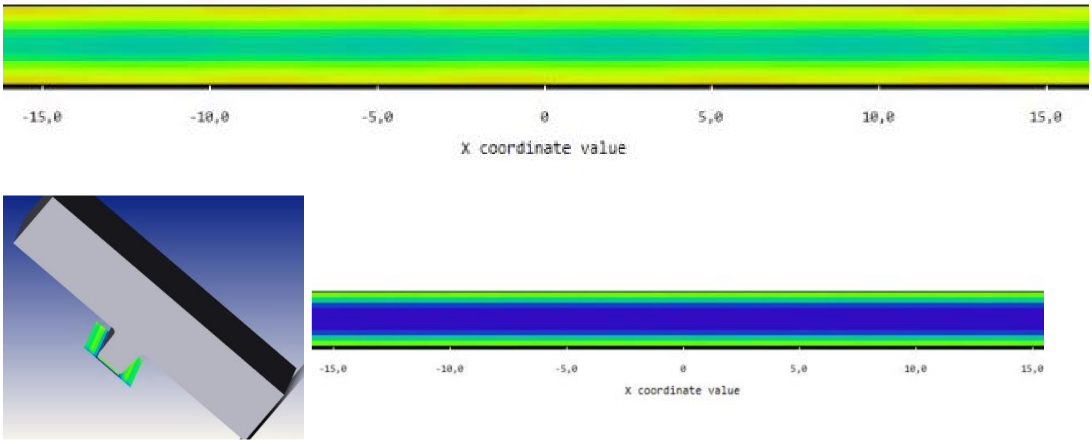


Figure 5-9 - Effect of changing the aperture: a) a=0.6mm, uneven lighting on the rib; b) and c) a=1,8mm, the flux of energy goes outside the rib.

Height is the parameter that most influences efficiency and pace between ferrules. A small height value allows for high power values to be achieved on the weld joint but creates strong power discontinuities at the ferrule position. Below the area where the ferrule is placed there is a value of power much higher than the interspaces (Figure 5-10-a). Increasing the height, this phenomenon decreases as shown in Figure 5-10-b, but the system is less efficient. The total power on the welding track decreases, passing the height from 15mm to 30mm it is lost about 2% of absorbing power. This behaviour is due to the increase in the divergence of the beam exiting the waveguide, as each reflection increases the angle of the incident rays.

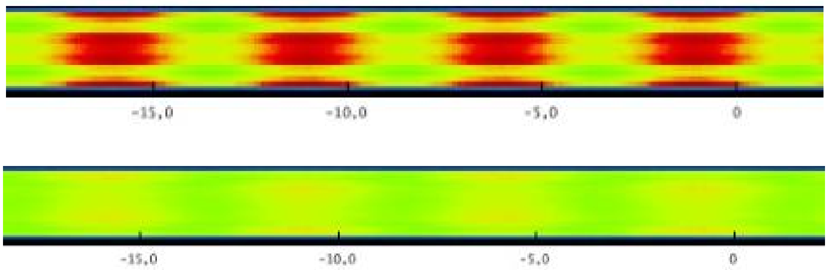


Figure 5-10 – Effect of changing the height: a) H=15mm (not homogeneous distribution); b) H=30mm (homogeneous distribution)

The angle *c* has a similar function. Increasing the angle, the effect is a better homogenization and high divergence in output but less efficiency. The diameter of the ferrule is 3mm, therefore the input opening of the waveguide must be larger. Hence sometimes the value of the angle is due to this need.

By varying these last two parameters, a homogeneity and power distribution suitable for the type of components and the type of application is sought.

A bench test tool for welding of the samples is made (Figure 5-11). In the first phase of the study, a comparison had to be made between the data found on the simulation software and the results obtained in the welding tests. In this way, it was possible to establish the power range of a good weld. The entire prototype system will be described in Chapter 6.

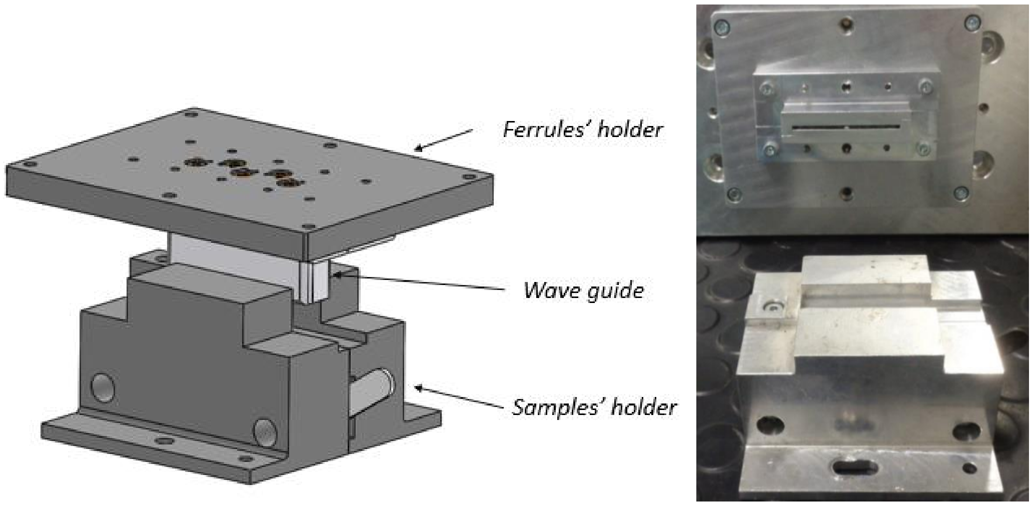


Figure 5-11 - Bench test tool: a) Cad design, b)

After some tests the parameters found, for a good distribution in T-shapes samples, are:

- $c = 4°$,
- $a = 1,8$mm,
- $H = 30$mm,
- step between ferrules = 7 mm (as consequence in the application 7 ferrules have been needed to weld the specimens).

An immediate application for these studies is the welding of car taillights (Figure 5-12-a). The materials are essentially the same: PMMA (usually transparent, coloured red, smoked, etc) for the lens and black ABS for the housing. The welding joint is also very similar (Figure 5-12-b).

The main differences with the specimen are that there is a development of the weld seam in 3D while the specimen was flat, furthermore the draft angles of the rib are different. As the geometry becomes more complicated, the study and design of the waveguide to homogenize the power are also complicated. In each section of the lamp it will be necessary to evaluate the best constructive parameters for the system, these parameters may vary. Chapter 7 will describe a valid support tool for analysis and design, which was studied and implemented during this thesis work.

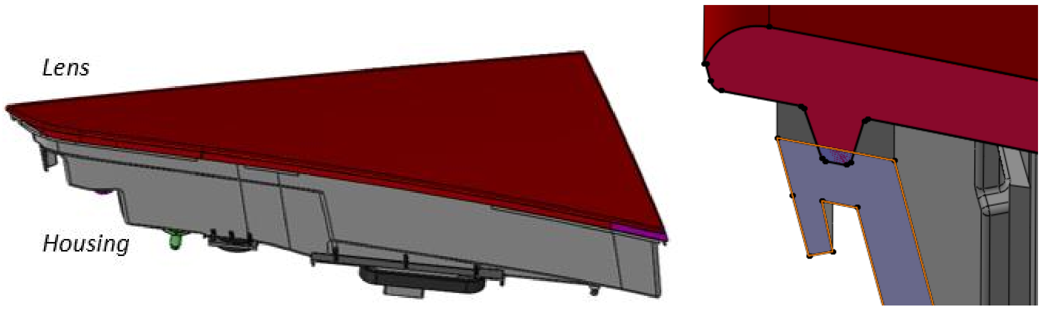


Figure 5-12 – Taillight of an automotive: a) Main components for welding; b) Section of the welding joint

5.2 Ray-tracing homogenization by commercial tool

In this paragraph, it has been investigated the target value for the simulation and parameters of the optical simulator.

In paragraph 4.5.2 the components that are part of the system have been analysed. Starting as input from these elements and from the CAD geometries (Figure 5-13) it is necessary to analyse and process the results.

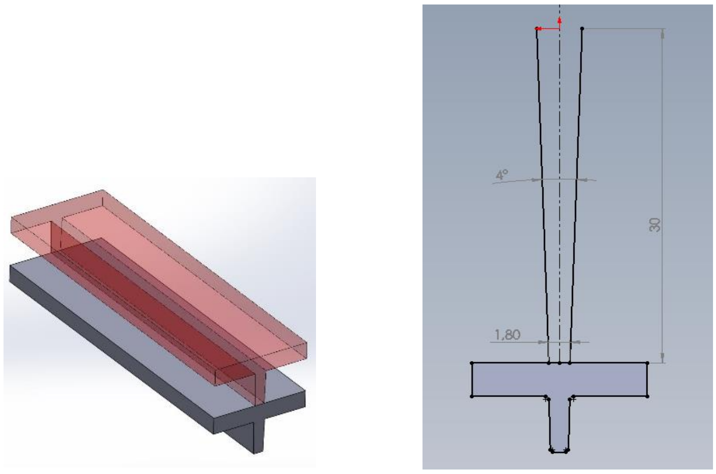


Figure 5-13 – CAD files as input of the simulator OpticStudio Zemax

Having defined and inserted the system elements in OpticStudio Zemax (the output of the ferrules or source, waveguide, transparent specimen, absorbent specimen), the simulation parameters must be set in the software: number of the pixels per mm^2 and number of rays per source.

5.2.1 Number of rays in the simulation

It is very important to find the ratio of simulated rays to the number of pixels. In fact, as the two parameters increase, the simulation times increase. As long as the system is small the simulation time is low, but if the number of sources increases up to a few hundred, the simulation time becomes very long and critical. On the other hand, by decreasing the values of radii/ pixels, information on the welding track could be lost or results are very different from reality. Therefore, the ratio was studied to minimize the time and maintain a good degree of detail on the detector.

The accuracy of the results is due to the number of rays hitting the pixels. Each cell has an error due to the statistic noise; this parameter converges to a value as the number of rays (N) increases according to the following equation.

$$\epsilon = \frac{1}{\sqrt{N}}$$

Equation 5-1

When this value converges, there is a good resolution, so the number of rays is adequate for the analysis.

Good use of smoothing is to get a high-resolution mesh with the same number of rays. It produces an improvement equal to tracing 10 times more rays. Before each simulation it is necessary to evaluate the relationship between the rays traced and the pixels of the detectors to obtain accurate results and reduced simulation and design times.

Figure 5-14 shows the effect of the smoothing in a detector: the colours are more flats, and the values of irradiance are similar.

- 20.000 rays, the peak irradiance is 34,34W/cm^2
- 20.000 rays with smoothing, the peak value is 27,4 W/cm^2
- 500.000 rays (ε is convergent) the peak value is 28,38 W/cm^2

The deviation with the simulation at 500,000 beams of the irradiance values is about 20% without smoothing and 3% with smoothing, while the times are lowered by about a half.

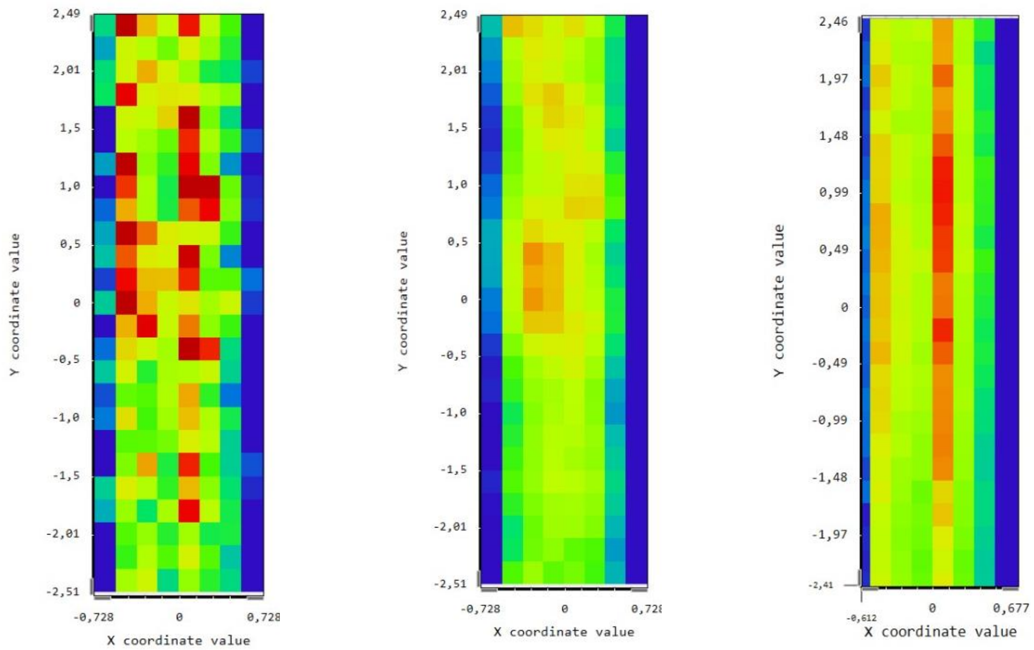


Figure 5-14 – Detector in simulation with: a) 20.000 rays, b) 20.000 adding the smooth in the results, c) 500.000 rays

5.2.2 Homogeneity results

Before defining the final parameters of the 5.1.3, numerous simulations and comparison with the experimental results were carried out in order to find the power density values necessary for good welding and short process times. A good weld is verified if the joint is fully welded, there are no cracks or burns (this is visible as bubbles), so the visual properties are good and it maintains the sealing. Usually tensile or burst tests are carried out to verify the weld.

Various tests were carried out once the elements of the welding system are imported for the specimens on OpticStudio Zemax (Figure 5-15).

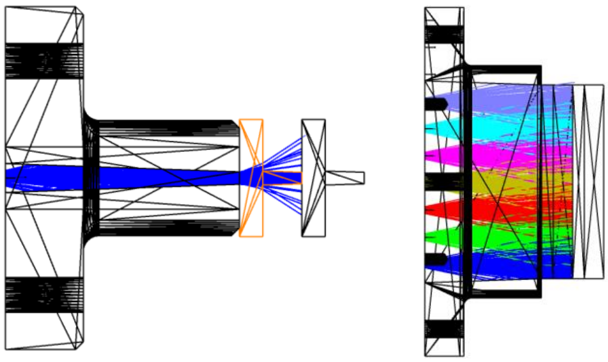


Figure 5-15 – Welding system for specimens in OpticStudio Zemax

With the variation of the source power values and geometries such as the pitch between the ferrules, the height, the angle and the opening of the waveguide, the following results were obtained (Figure 5-16)

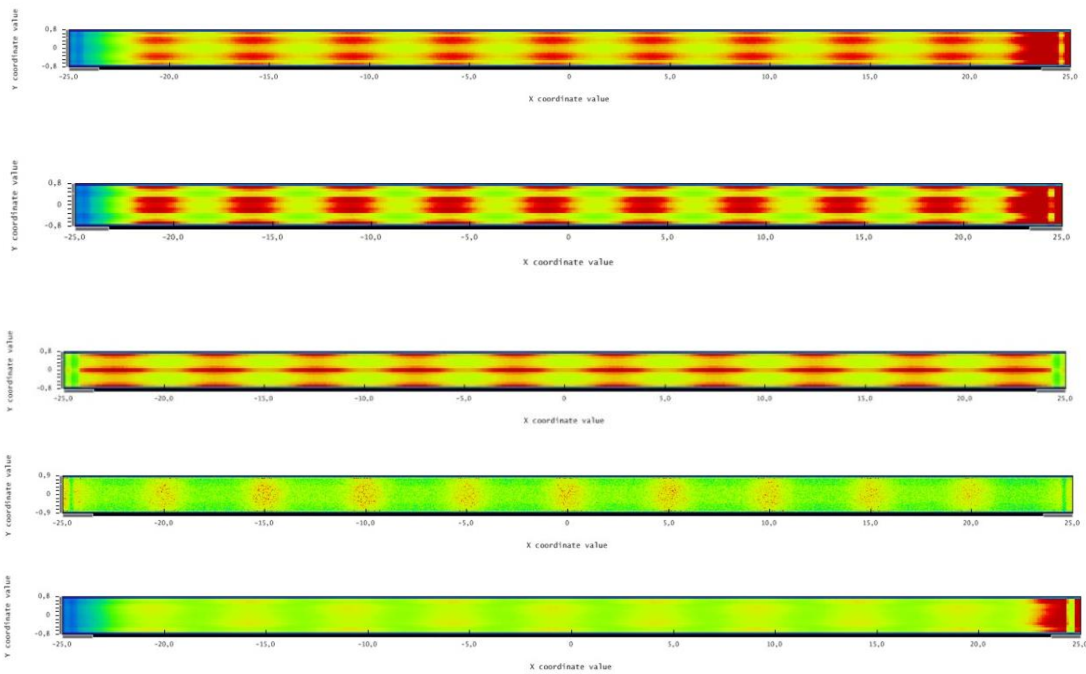


Figure 5-16 – Variation of parameters in the simulations to obtain a homogeneity profile of energy

Obviously, a complete homogenization is difficult to obtain. However, it is sufficient to have a beam centred on the rib and a quasi-flat distribution along the longitudinal section, as shown in Figure 5-17, to get a good joint.

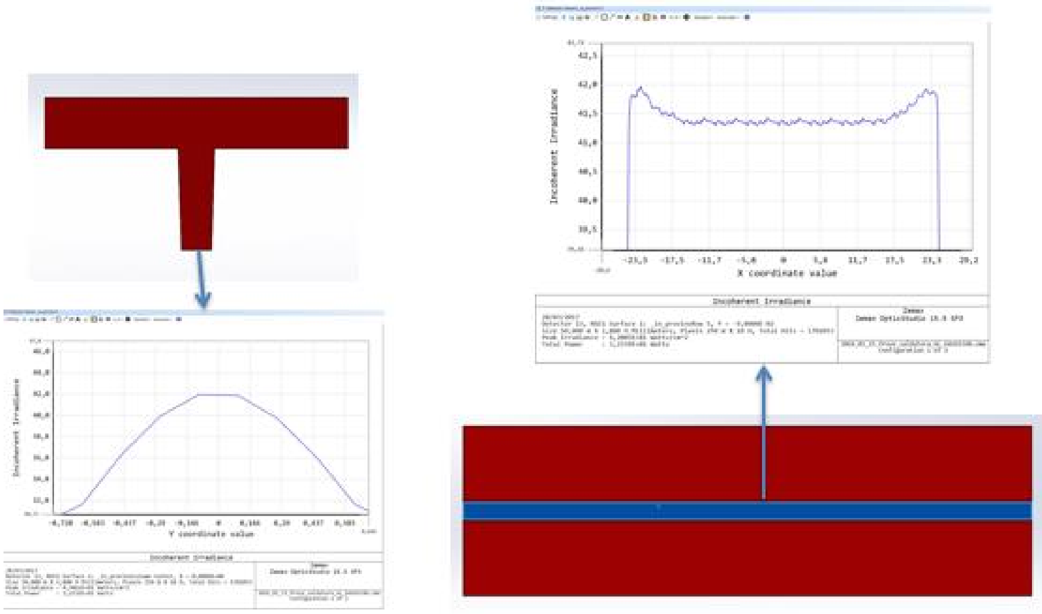


Figure 5-17 – Profile of energy along width and longitudinal section

In the simulation phase and subsequently in the tests on the specimens, a bundle with ten ferrules was used, therefore the maximum power is 6W per ferrule. Thanks to the experimental tests on the prototype it was possible to evaluate the acceptable range of power density for welding. One requirement is to minimize the power used in welding, therefore a configuration that uses fewer ferrules was sought. Seven ferrules were enough to weld a 50mm long track.

It is not convenient to use source power at 100%, as it is necessary to have power for regulation. Therefore, maximum power of about 4-5W per ferrule was used in the simulations.

5.3 Experimental tests

The fundamental phase was the study and tests to weld the PMMA and ABS specimens. It was the first approach to laser technology for simultaneous welding. It was necessary to design and build the welding system, compare experimental results with simulations and investigate the phenomena involved in the process to obtain a satisfactory weld. In addition, the welding of transparent materials has also an aesthetic function, so the needs of the final product are more demanding.

Only when the welding process with the previous materials was consolidated, it was possible to move on to the analysis of other materials such as PA66.

Therefore, in this paragraph, great importance was given to the tests on PMMA / ABS, with a subsequent discussion of PA66.

5.3.1 Tests on PMMA-ABS

The PMMA used is usually transparent to the human eye, while the natural ABS is white and slightly laser transparent. To obtain a good degree of absorption, a small amount of carbon black was added to the ABS blend.

Many tests were carried out with different waveguide and power parameters. The pressure load and the penetration sinking after welding of the specimens were kept constant.

The tests were used to evaluate the level of homogeneity necessary to obtain a good weld in the pair of PMMA/ ABS materials. For other materials the parameters used here could not lead to being optimal for the welding process.

Here in Figure 5-18 are some images with welded samples.

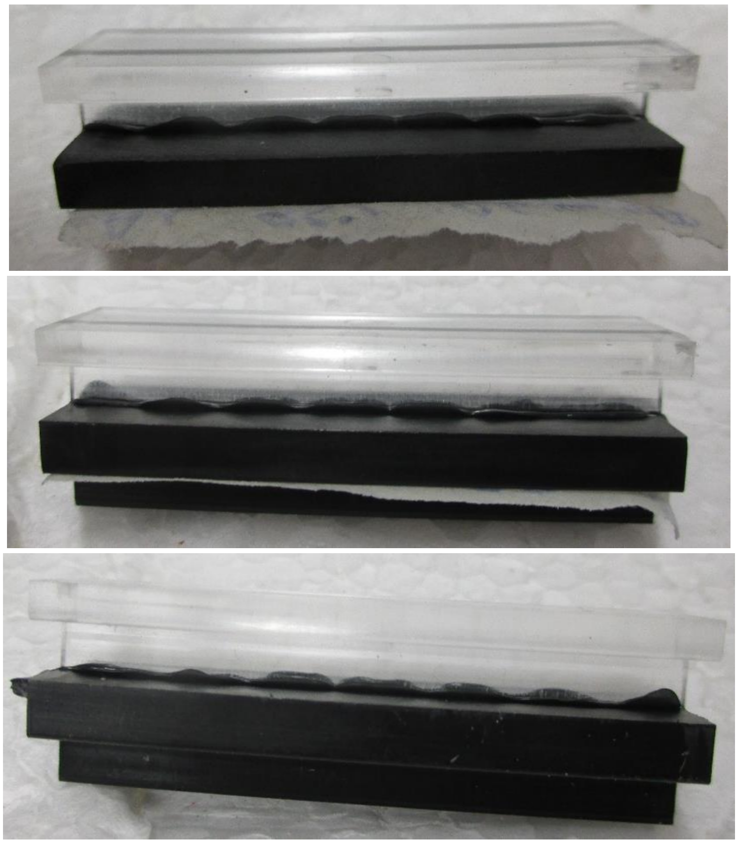


Figure 5-18 – Welded samples with proof wave guide

Despite having a good weld in terms of resistance, from the first results it was noticed that, in terms of visual quality, the specimens did not meet the aims. Therefore, better qualities of homogeneity were sought.

With the final parameters found in the paragraph 5.1.3, the results in Figure 5-19 were obtained. The welding shows good quality with a constant and uniform burr.

Repeatability tests were carried out to verify the robustness of the process. A process is stable and repeatable if keeping the input parameters constant does not change the results in terms of welding quality and cycle time.

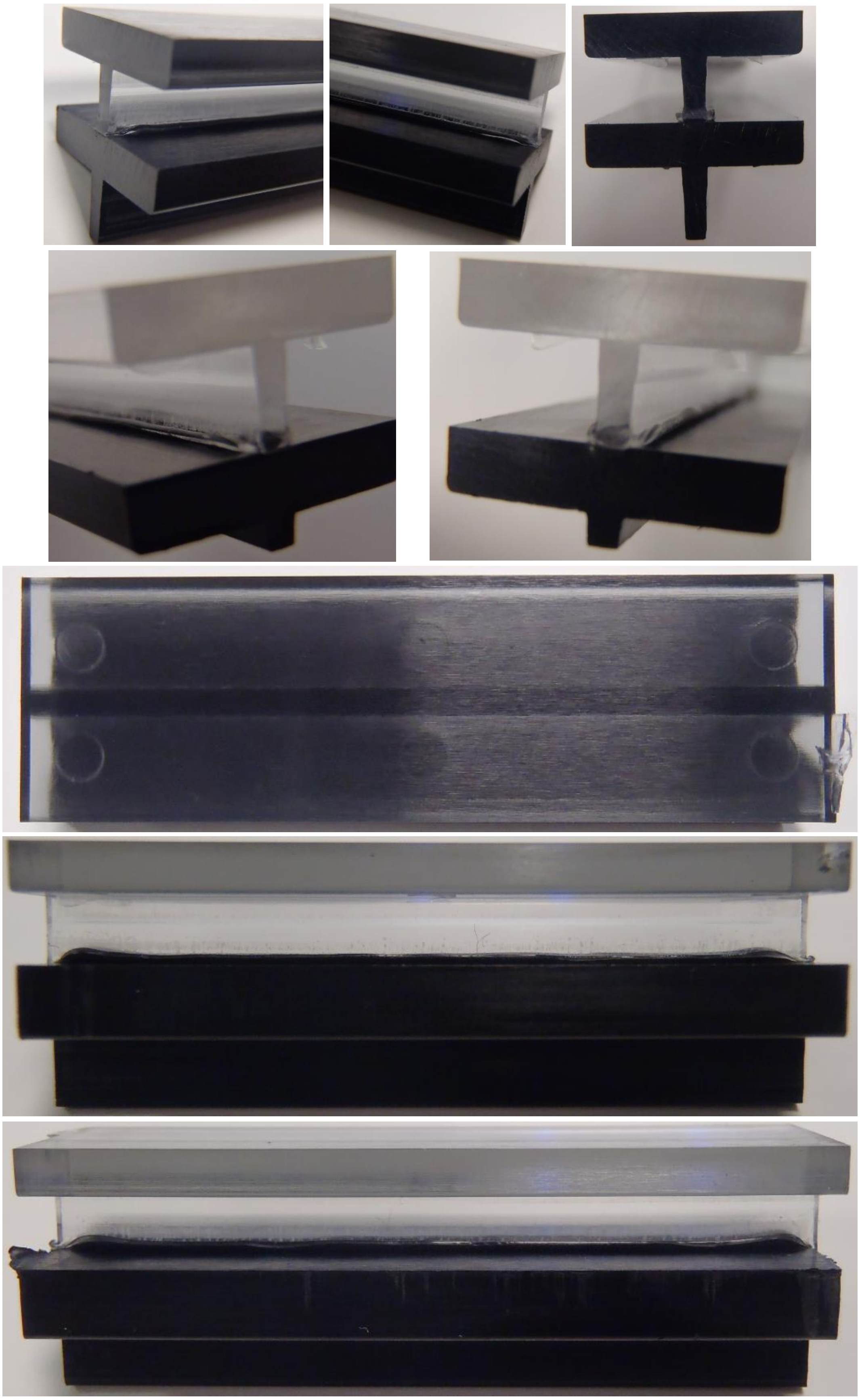


Figure 5-19 – Welded samples obtained with the waveguide

5.3.2 Results and discussion for PMMA/ABS

Based on the welding configurations in Figure 5-3, the results in Table 5-1 were obtained. The results are the mean of ten tests with the same power, the laser emission has been stopped when there was an interpenetration between components of 0,6mm.

TEST	TYPE	POWER [%]	WELDING TIME [sec]	NOMINAL POWER [W]
1	A	90	4,5	36,5
1	B	90	3,5	36,5
1	C	90	3,8	36,5
1	D	90	3	36,5
2	A	70	6,6	28,5
2	B	70	5,5	28,5
2	C	70	6,2	28,5
2	D	70	5,1	28,5
3	A	50	9,1	20
3	B	50	7,6	20
3	C	50	8,7	20
3	D	50	7,6	20

Table 5-1 – Results of welding process of PMMA with ABS

The nominal power per unit of area varies between 0.25÷0.5 W/mm^2

Although the specimens are welded correctly in terms of quality and sealing, a difference in welding times can be noted. The welding time depends on the real power incident on the joint. Increasing the optical path and the number of reflections also increase the losses. In every reflection the beam is partially scattered, this causes the decrease of power that goes through the transparent part. This explains the time differences in specimens with a high rib.

Another datum to be noticed is that with decreasing power, the welding time increase. Although the nominal interpenetration can be achieved, the joint presents a substantial difference, the quantity of PMMA increases in the burr. It can be seen in the Figure 5-20, where the burr seems to sparkle. In fact, a greater cycle time favours the heat exchange by conduction between the components and therefore a greater quantity of transparent material reaches the softening point. The composition of the welding joint increases by the latter and a layer of PMMA is clearly visible. It is not the aesthetic quality desired.

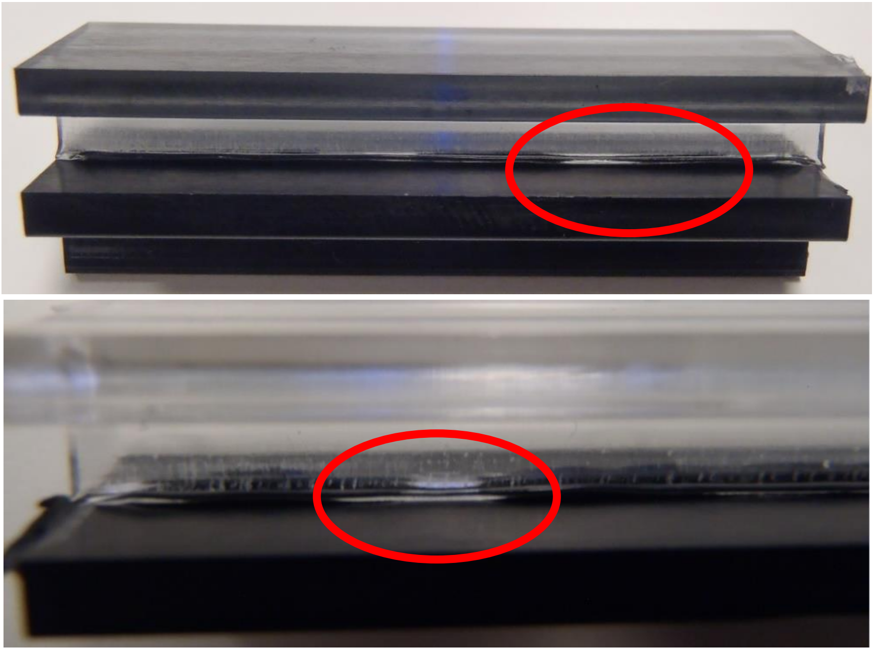


Figure 5-20 – Welding result in the test 3-B (Table 5-1), sparkle in the burr

Different blends of PMMA and ABS were tried for simultaneous welding. The Table 5-2 summarizes the tests performed with the configuration B of Figure 5-3.

TEST	Transparent Material	Absorbent Material	Welding Time [s]	Power [%]
1	PMMA Colorless	ABS Bulksam TM-20H	5,1	40
2	PMMA Colorless	PC/ABS CYCOLOY C1200 HF	5,2	43
3	PMMA Colorless	ABS Novodur H802-	4	42
4	PMMA Light Smoked	ABS Novodur H802-	6	42
5	PMMA 8N GRAU 7V265 Smoked	ABS Novodur H802-	8	45
6	PMMA 8N GRAU 7V272	ABS Novodur H802-	6,7	45
7	PMMA Colorless	PC/ABS Mablex S 280-S22523	5,2	42
8	PMMA Colorless	ABS. SINKRAL A23	4,8	40
9	PMMA Colorless	PC/ABS Mablex 459F-S250	4,8	41
10	PMMA Colorless	PC/ABS CYCOLOY C1200 HF	5,3	41

Table 5-2 – Tests on PMMA/ABS of different brands and blends

Smoked PMMA blends were tested (Figure 5-21). In Table 5-2 (test 5) can be noted how the addition of additives to make the material slightly opaque increases the welding time.

Figure 5-21 – Smoked PMMA and ABS

On the welded specimens, some joint resistance tests were subsequently performed, such as thermal shock tests, by placing the specimens in the oven at 95°C and immediately after immersed in water at 3° C. All welded specimens withstood this type of test.

The types of tests on materials are linked to the needs of customers and products, so to carry out suitable resistance tests, the specimens were sent to specific analysis laboratory. For example, to evaluate the welding between PMMA and ABS, a manufacturer of car lights was contacted.

5.3.3 Tests on PA66

Other materials were tested such as PA66 glass fibers reinforced. The waveguide parameters, number of ferrules and power had to be changed in order to achieve the weld. Unlike PMMA, PA66 is an opaque material so the aesthetic properties of the joint are no longer evaluated. Being a semi-crystalline material, with the addition of glass fiber dispersions, the transmittance is much lower than PMMA. While the PMMA has a transmittance above the 90% even for high thicknesses, the PA66 is strongly influenced by this factor.

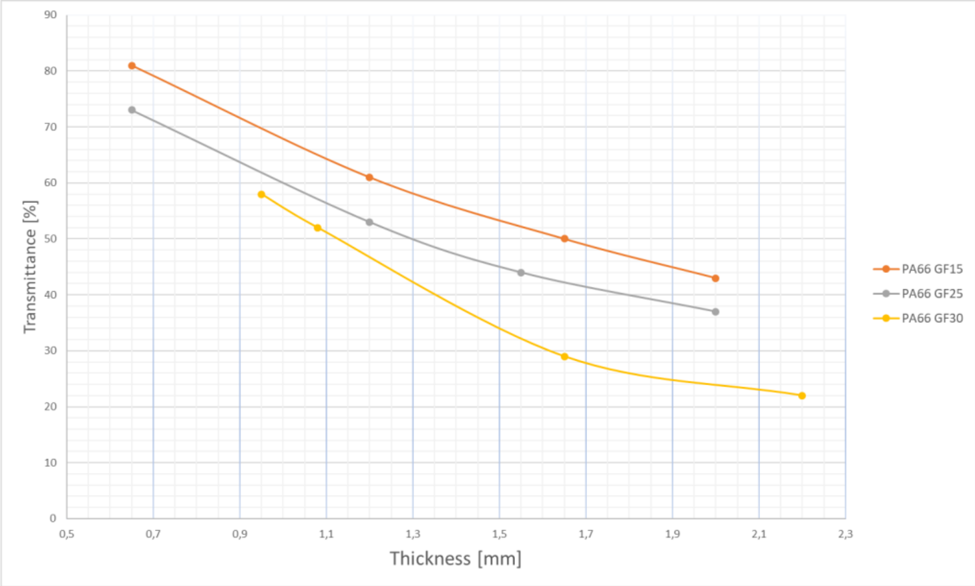


Figure 5-22 – Transmittance vs thickness of PA66 with glass fiber dispersion of 15%, 25% and 30%

In order to weld a T-shaped specimen with dimensions shown in the Figure 5-23 it was necessary to use 19 ferrules and a dedicated waveguide (

Figure 5-23 - Dimensions for PA66 samples: a) Overall dimensions; b) First configuration testes; c) Second configuration tested; d) Waveguide

-d).

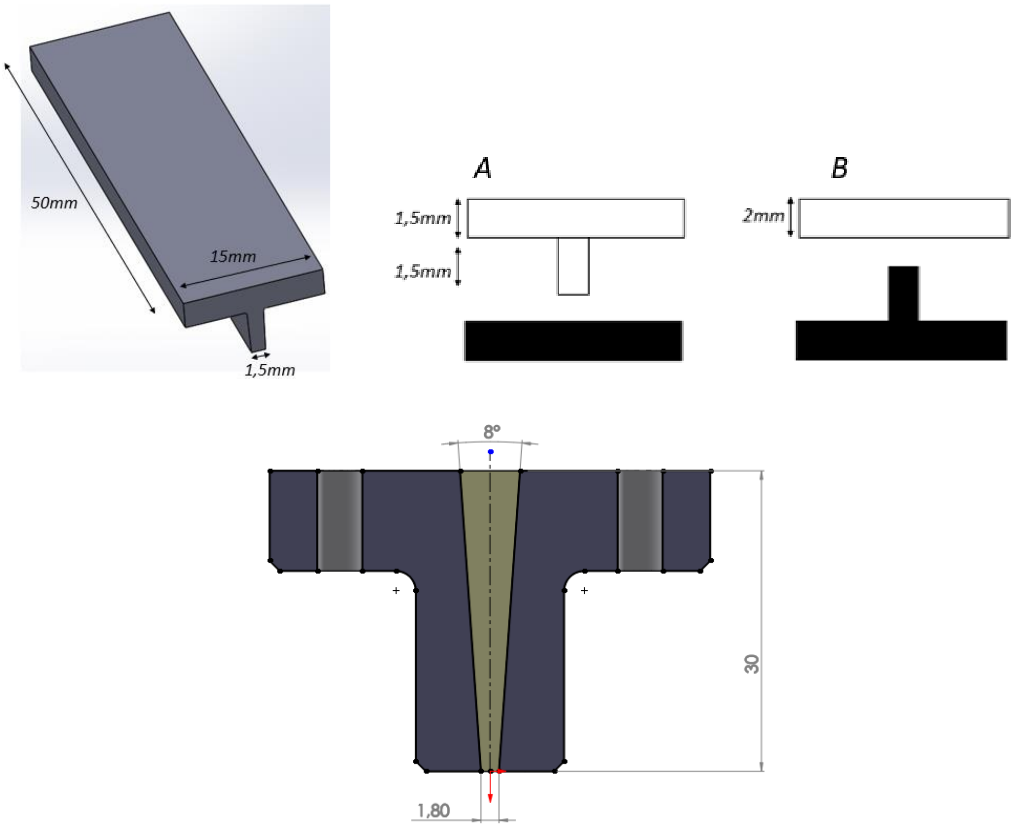


Figure 5-23 - Dimensions for PA66 samples: a) Overall dimensions; b) First configuration testes; c) Second configuration tested; d) Waveguide

5.3.4 Results and discussions for PA66

PA66 specimens with 30% glass fibers (GF) were used for the welding tests. The material used as radiation transparent is natural colour, while the coupling component is charged with a small percentage of carbon black.

TEST	TYPE	POWER [%]	WELDING TIME [sec]	NOMINAL POWER [W]
1	A	100	10	110
1	B	100	8,4	110
2	A	90	12	99
2	B	90	9,7	99
3	A	80	19	88
3	B	80	12,8	88
4	A	70	25	77
4	B	70	20	77

Table 5-3 - Results of welding process of PA66 GF30

In Figure 5-24, the PA66 specimens welded in the two configurations. If a flat specimen with a thickness of 2mm is used, less power is necessary, as the welding results show in Table 5-3.

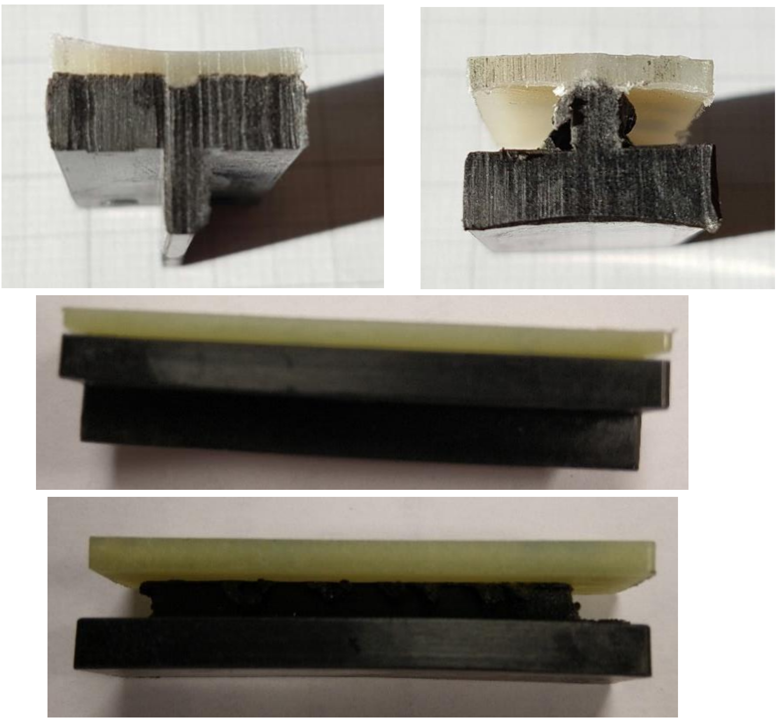


Figure 5-24 – Welded samples: Type A and Type B

In this case, the nominal power per unit area varies from 1 to 1.5 W/mm^2. A power density greater than six times is necessary to have the same welding times of the PMMA/ABS.

Having low degrees of transparency to laser radiation, it is necessary to significantly increase the power for welding. In the T-shaped specimens, internal reflections are introduced on the rib for this reason it is more difficult to get the welding. In some cases, it was not possible to weld the components, for this reason plate samples were used later in the test phase as transparent material.

PA66 welding is more critical to accomplishing than PMMA / ABS testing. To obtain good results, the thickness of the laser-transparent material must be reduced to few millimetres.

It was possible to study and carry out welding tests on an application with these materials. Collaborating with Cemas Elettra and AFT Group a small test machine was created for the component. In this case, the material transparent to radiation has a thickness of 1mm and it is black (Figure 5-25). The black colour was achieved by adding pigments which are laser transparent.

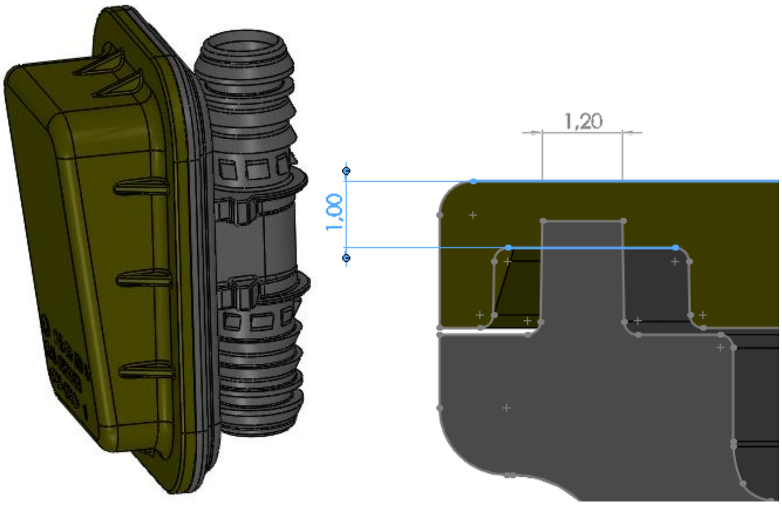


Figure 5-25 – a) Resonator welded; b) Section of the welding joint, the upper component is laser transparent PA66 GF30, the lower component is laser absorbent PA66 GF30

Test #	Power	Emission time [s]	Depth [mm]				Burst test [bar]
1	80%	6	welding	0,2	Total	0,3	11
			cooling	0,2			
2	80%	7,4	welding	0,1	Total	0,2	10
			cooling	0,1			
3	80%	7,2	welding	0,1	Total	0,5	13
			cooling	0,3			
4	80%	5	welding	0,1	Total	0,2	7
			cooling	0,1			
5	100%	4,2	welding	0,2	Total	0,3	12
			cooling	0,2			
6	100%	5	welding	0,2	Total	0,3	12
			cooling	0,1			
7	100%	4,4	welding	0,1	Total	0,5	12,5
			cooling	0,3			
8	100%	3,6	welding	0,1	Total	0,2	11
			cooling	0,1			
9	100%	3,6	welding	0,1	Total	0,2	10
			cooling	0,1			
10	80%	6,4	welding	0,1	Total	0,2	11
			cooling	0,1			
11	70%	7,6	welding	0,1	Total	0,3	9
			cooling	0,2			
12	70%	9,6	welding	0,2	Total	0,4	11,5
			cooling	0,2			
13	80%	7,6	welding	0,2	Total	0,4	12,5
			cooling	0,2			

Table 5-4 - Results of welding process of PA66 GF30 for the resonator

By lowering the thickness of the material to be crossed for the laser to 1mm, the necessary power density also decreased considerably to 0.65-1W/mm^2.

In this case, to evaluate the welding quality, the mechanical part required a more committed test, burst tests resistance.

Chapter 6

6. Simultaneous laser welding machines

To manage the welding process, it is necessary to design an appropriate system for the needs. A small prototype machine was built to study simultaneous welding of specimens, shown in Chapter 5. After gaining the knowledge of this type of laser welding, the technology can be extended to industrial mass production.

In the following chapter the prototype, the machines and the equipment needed to weld various types of products will be shown.

For the construction and assembly of the mechanics, Cemas Elettra Srl was joined. Cemas Elettra is an international company while the headquarter is located in Piedmont, with thirty years of experience in the construction and sale of industrial machines for the welding of plastics. Cemas invested in this Industrial Ph.D. in collaboration with Politecnico of Torino to catch the laser competence in simultaneous welding.

To weld plastic components optimally certain conditions must occur:

- Adequate power to bring the materials to the transition temperature to the state of viscous liquid, without having thermal degradation caused by too high temperatures;
- Contact between parts to be welded, the quality is compromised if the components are not well-compressed. This can happen if the thrust load is low. High loads lead to internal tension or cracks;
- Adequate processing time. The materials require a liquefaction time and a cooling time.

In addition to the laser sources are required a clamping/pushing system and software for controlling and managing the movement, emission, pushing, cooling and opening phases.

6.1 Prototype machine and tool

The prototype machine must include all the functions listed above that are needed for the welding process.

The components that allow to manage the process completely and safely are listed below:

- Source box, containing: the diode, lenses, cooling system with forced air finned exchanger (the entire system has described in Chapter 4).
- A protection cabin containing elements for the welding. It is sealed, in the way that laser irradiation cannot leak.
- The tool composed of the waveguide with ferrules holder and nest for the specimens. Tool has the function to hold the samples, to couple nest with waveguide and transfer the load.
- Pushing system, two pneumatic cylinders are used. They permit to load up to 400N.
- Sensors, to evaluate the sinking of the parts and the closing of the cabin for safety.
- The control panel and drivers for the system operations.

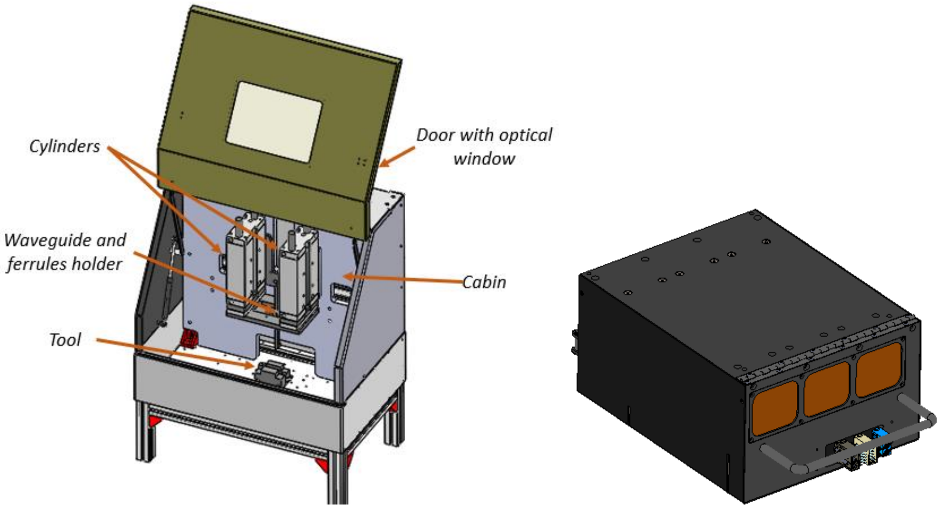


Figure 6-1 – a) Prototype structure; b) laser source box

In Figure 6-1 is possible to see the main components listed above. All the electrical management and powering components of the system have been placed in a dedicated box, placed under the machine, as can be seen in Figure 6-2.

Figure 6-2 – Pictures of the prototype realized

The bundle of optical fibers comes out of the source box and enters the cabin. The ferrules are fixed in the nest. The ferrules housing and waveguides are mounted on a movable plate, carried by the cylinders.

The pneumatic cylinders open the holding for the insertion of the specimens (Figure 6-3). Once the specimens have been positioned and the cabin has been closed, the cycle can be started. Thanks to the arrangement of the waveguide on the cylinders, there is a uniform thrust over the entire surface of the specimens during the welding process. The pressure between the interfaces of the samples allows to better transfer the heat into the transparent material. Furthermore, at the end of the welding, the specimens must be interpenetrated, therefore it is necessary that the cylinders exert an adequate load of the thrust. The load for the specimens during the tests has been constant, but when components with different or larger geometries are welded, the thrust must be increased. Usually, in the welding set-up phase the adequate load must be found according to the pieces/materials. Pushing force and laser power are the fundamental parameters for achieving a good result.

The waveguide transfers the thrust from the cylinders to the pieces. The welding phase begins where the materials are brought to the fusion. When the established penetration height is reached, the position sensor detects it and transfers the signal. The control system carries out the next order. The emission ends, but the push continues to keep the components compressed during the cooling phase of the plastic. Once the cooling phase is over, the cylinders return to the rest and open the nest.

Thanks to this prototype it was possible to carry out the welding tests described in Paragraph 5.3.

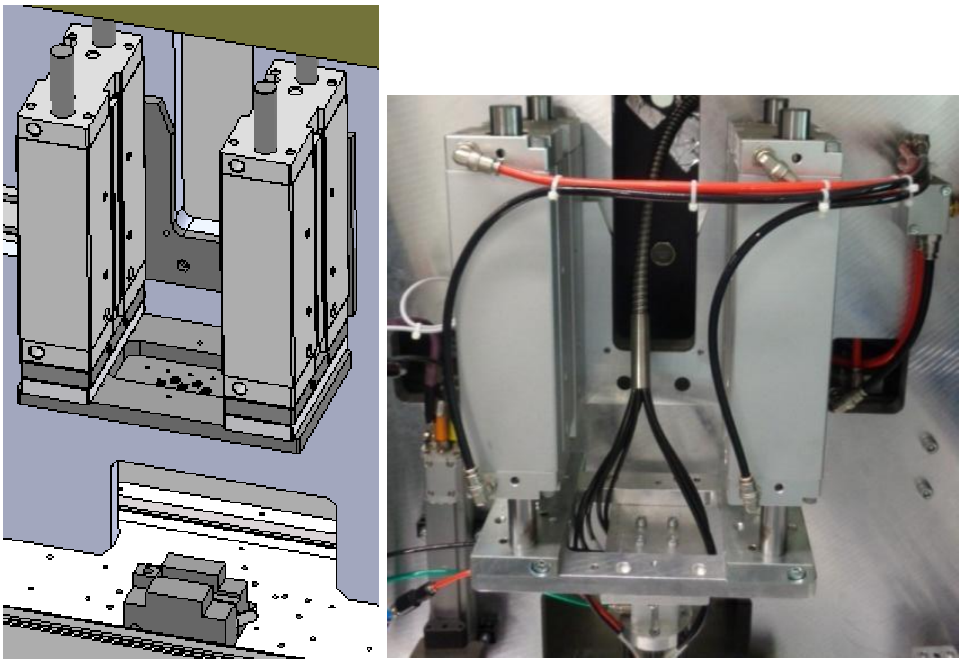


Figure 6-3 – Cylinders coupled with a plate that mounts waveguide and ferrules holder.

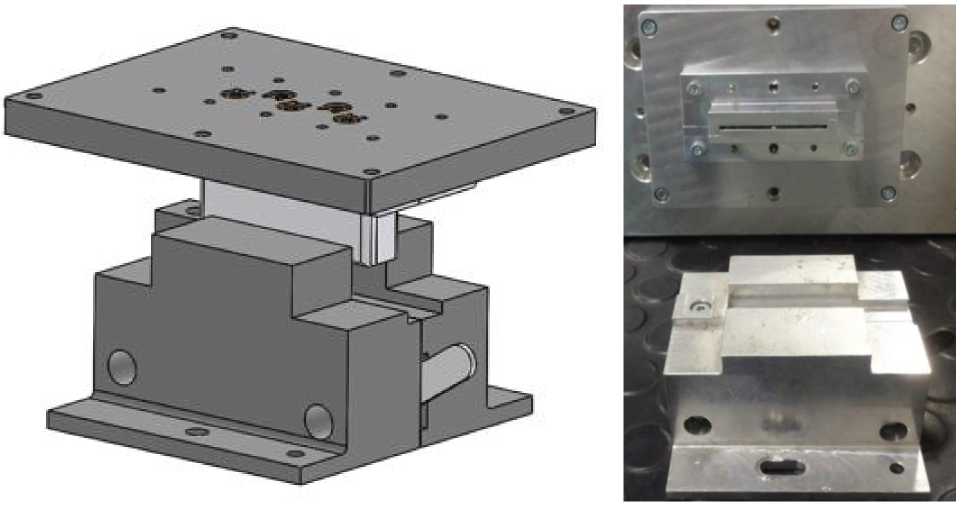


Figure 6-4 – Nest for the specimens and waveguide

6.2 Standard machine and production test

Starting from the same operating principles of the prototype machine, Cemas Elettra has developed a standard machine to simulate industrial production. The size of the machine and the number of sources that can be mounted depend on the applications they are aimed at. A machine for the welding of small components and a machine for the welding of extended components that require a large number of power will be described.

The machines have a higher degree of automation and control, this is because they are destined for production, so it is necessary to increase the number of produced batches and standardize the machine work cycle. After doing the welding set-up, all it needs is put the components in the machine and start the cycle.

6.2.1 MF120 Machine

The first machine to be described is a bench machine for the production and the test small components (Figure 6-5). The work area is about 300x350 mm. Small components can be welded, such as the sample analysed in the Paragraph 5.3.4.

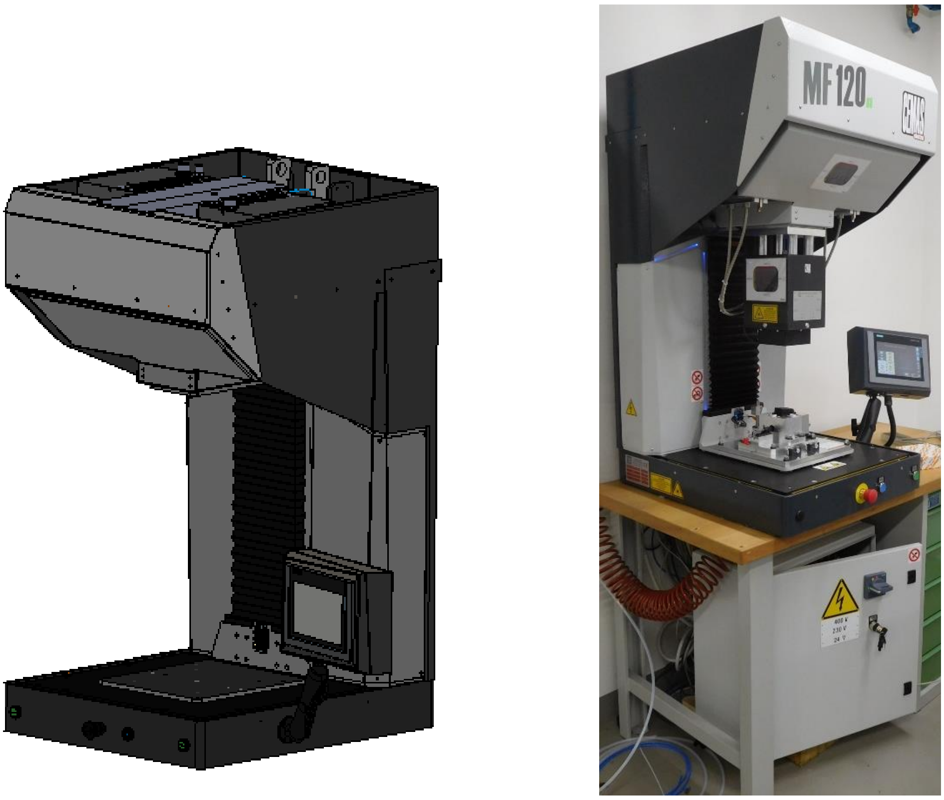


Figure 6-5 – MF120 Machine- Cemas Elettra

The starting point remains the laser source with the relative exchanger. However, three laser sources are mounted in the box (Figure 6-7), thus to obtain modularity of three sources at a time, for a maximum of twelve sources. The boxes are mounted on the top of the machine.

Being a production machine, additional safety systems are required.

When the sources do not emit and the work cycle is not active, the output from the source must be blocked, whether the optical fibers bundle is present or not. A burnished steel plate is placed outside the source, on which, in case of damage event, the laser beam will terminate and absorbed. This plate has the feature of a shutter (Figure 6-6). It is moved by pneumatic cylinders which are controlled and open by the operating system at the beginning of the cycle. In addition, sensors and systems for stopping the movement of the press and emission are placed and they are activated if an intrusion in the work area is detected.

Figure 6-6 – Shutter placed between the exit of the sources and the optical fibers bundles

The operation process is analogous to the prototype machine. The main difference is that the moving part is the lower plate, driven by an electric motor. An electric actuator is preferred to a pneumatic one as it is possible to exert great thrust forces, to control the position and the load. The motor has a greater speed of signal transmission and reactions to commands.

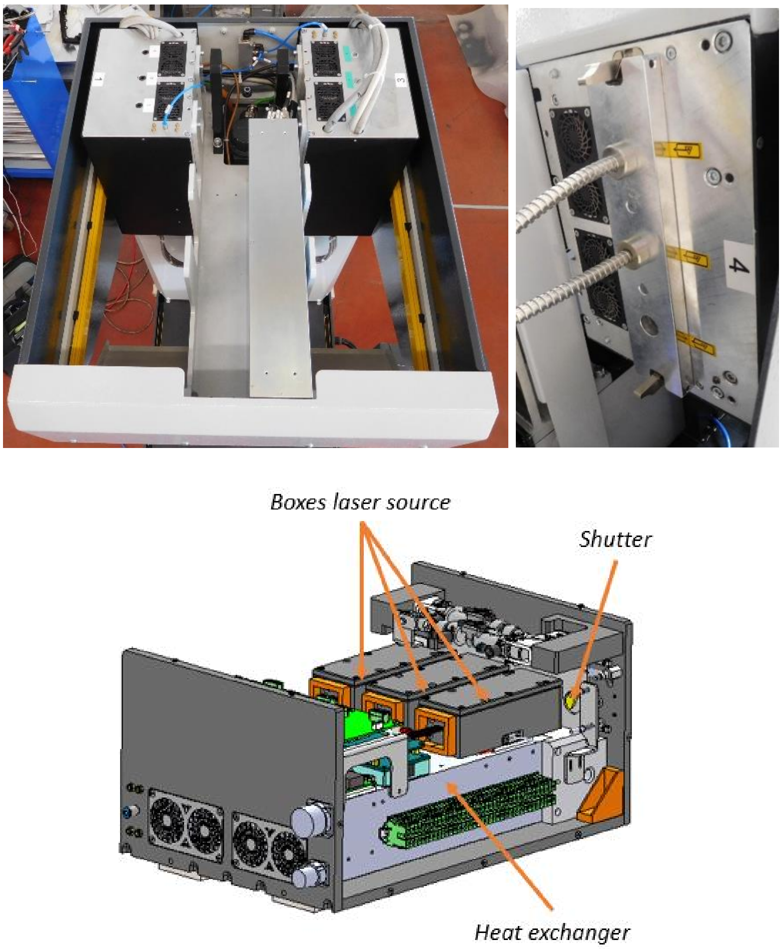


Figure 6-7 – a) Two boxes of the sources mounted in the MF120 Machine; b) Fibers optical bundles mounted at the exit of the box; c) Box of laser sources composition

It was chosen to move the lower tool, in such a way as to keep the optical fiber bundles still. Since the optical fibers are made of glass, they are the most delicate elements, hence they must be assembled and handled with care. By moving the lower plate, the risk of damage is reduced and therefore the possibility of having to carry out maintenance. The fixing system of the ferrules to the holder is the same as that described in Paragraph 5.1.2.

Fiber optic bundles are part of the tools. In fact, the process of assembling the ferrules can be long and demanding. This simplifies the process of changing tools on the machine.

The machine must allow coupling with a lot of tools (Figure 6-8). Therefore, assembly and disassembly of equipment must be quick and precise. In fact, the working life of a machine can be many years, while the tool is dedicated to a particular application and have a short time of use. If the product ends its function in the market, the tool is written off, while the machine can continue in the production of a new product.

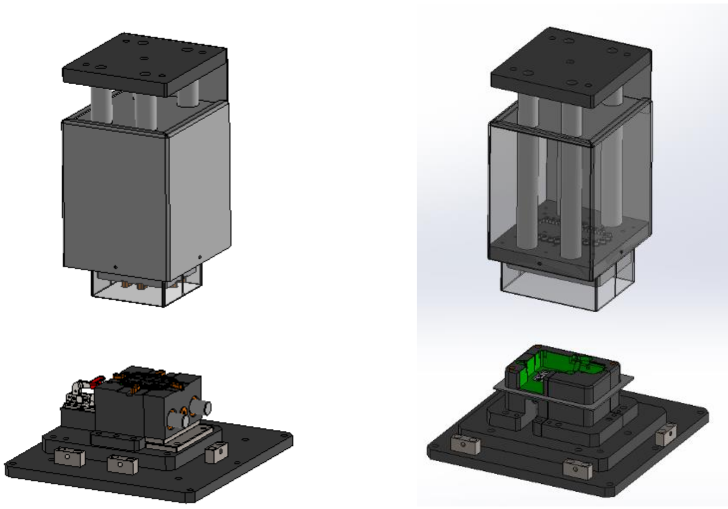


Figure 6-8 – Tools can be mounted in MF120

6.2.2 MF960 Machine

For the welding of wide components, it was necessary to design a machine with a larger work area and a high number of sources. In this case the work area is 1400x900mm. It can weld parts like taillights, manifolds, internal components for the automotive. By now some car lights reach very large dimensions (Figure 6-9), such as the rear appliques that have lengths between 1-1.5 meters. Moreover, materials with low laser transparency require very high powers per mm^2. Therefore, there was the need to have an adequate number of laser sources mounted on the machine, to meet the demand of laser power. For this reason, from 1 up to 96 sources can be mounted on the machine.

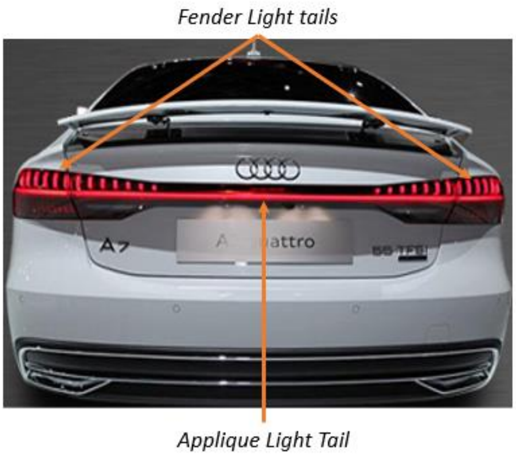


Figure 6-9 – Rear lights of a car welded with MF960

With this high number of sources, it was necessary to save space. It was decided to replace the heat exchange system for the sources. A finned exchanger requires a large exchange surface in order to subtract the heat. The most effective method is an exchanger with chilled liquid. A cold plate (Figure 6-10, Figure 6-11) is used, in which chilled liquid flows from a chiller module. It was necessary to size the system that provides for the dissipation of the heat generated by the diode and its driver.

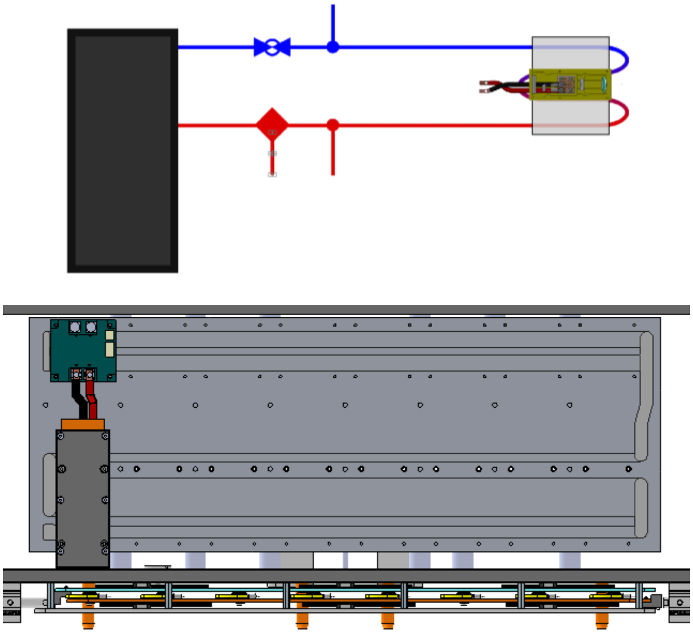


Figure 6-10 - Cooling circuit with cold plate, on which the laser diode box is mounted.

Figure 6-11 – Laser sources mounted on the cold plate

The demineralized water, that passes through the channels of the plate, is cooled by a chiller module placed above the MF960 machine.

In this machine there is also a moving table driven by an electric motor.

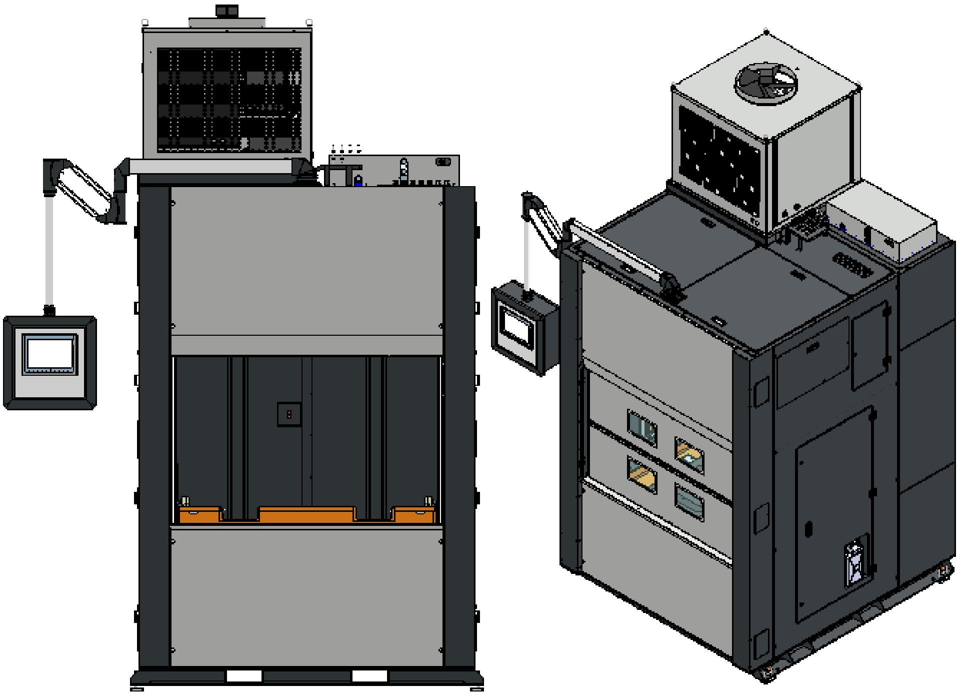


Figure 6-12 – MF960 Machine

Tools for different applications can be replaced and mounted on the machine. The tool consists of:

- nest for the lower body (Figure 6-13), which has the task of holding the component in position during the welding phase, usually the main sensors for the control of the process are mounted here;
- nest of the upper body (Figure 6-14). In addition to the function of keeping the upper component in position during the welding process, here the essential part of the technology is located, i.e. waveguide and bundle of optical fibers (Figure 6-15). In some applications, the waveguide made of aluminium can be covered by a layer of a few microns of gold which

increases reflectance, decreases losses and is more chemically stable, so there is less risk of blackening the aluminium parts.

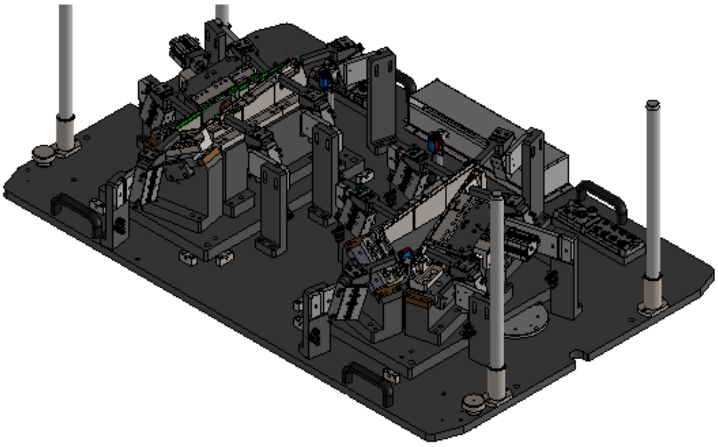


Figure 6-13 – Lower nest

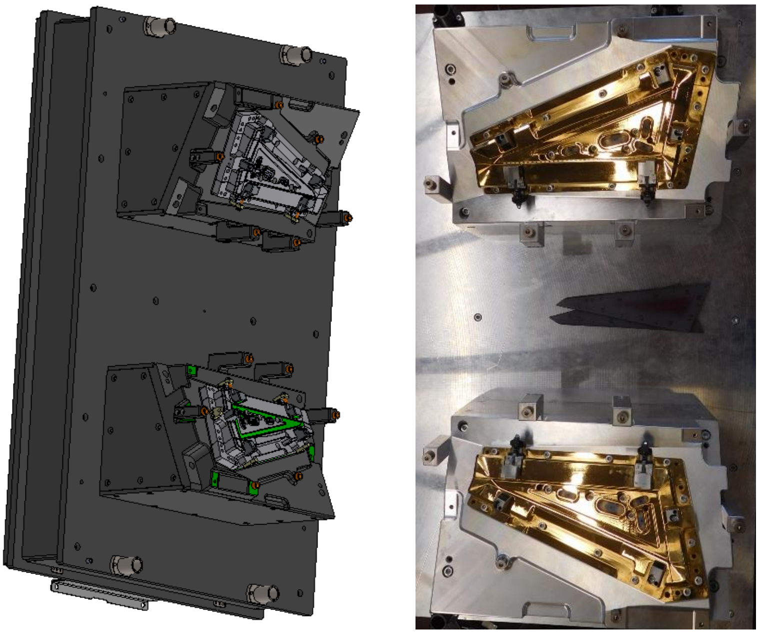


Figure 6-14 – a) Upper Nest, CAD model; b) Upper nest, final project with golden waveguide

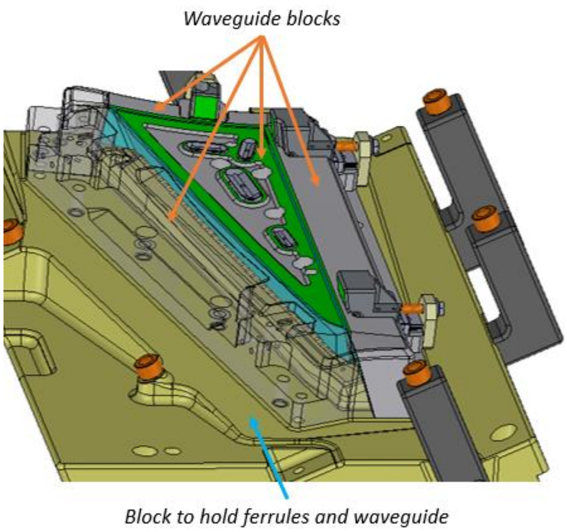


Figure 6-15 – Waveguide and ferrules holder in the upper nest

For some types of components, the tool and the waveguide become very complex. As for the tools, the complexities are due to the irregularities of the geometries of the components to be welded (Figure 6-16), the method of fixing the components in the installation, the checks that must be made in the cycle (e.g., presence of the pieces, correct positioning or type of component).

For the waveguide the difficulties are due to guiding the light through complex and non-linear geometries. A valid tool to support the design and simulation of the waveguide is given by the add-in designed and programmed for SolidWorks. This application allows to link the data and parameters of the mechanical design CAD software SolidWorks with the ray-tracing software OpticStudio Zemax. The description of this instrument is given in Chapter 7.

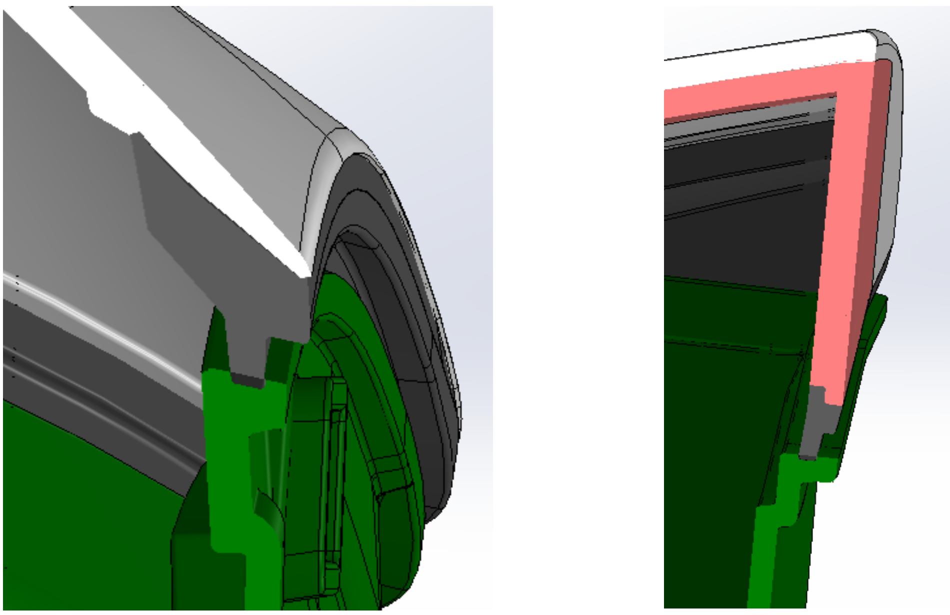


Figure 6-16 – Example of welding rib section in light tails

Chapter 7

7. Design of Solid Works add-in

The main part of this thesis has been dedicated to the study of a SolidWorks macro, created with the aim to assist the design of the waveguide. In this way, solutions for complex welding profiles are searched. The purpose is to investigate a range of possibilities and find alternative solutions in placing, orientation and inclination of the waveguide. The best optical solution may not be mechanically feasible. Therefore, a feasible solution that does not have a low optical power efficiency is looked for.

It is not always possible to guide the beam perfectly. The rib could be asymmetrical, or with side walls that are very inclined with the welding surface or the skin of the lens. These characteristics usually lead to a highly non-homogeneous distribution if the laser beams are not treated with a suitable waveguide.

Particular geometries make the positioning of the waveguide complex to obtain the required characteristics (in terms of feasibility, efficiency, power profile on the joint, dispersion, etc.). It was considered appropriate to seek a method to simplify the search for the positioning of the waveguide.

The program performs repeated simulations to optimize the times and efficiency of power distribution in the welding path.

This section is a fundamental part on the research work, since it allows to simplify the waveguide design, to have a feasible solution that meets the needs, and finally to obtain more efficient solutions, therefore fewer sources used. Multiple solutions that a designer would take too long to test individually are analysed.

It is possible to achieve an integration of the two software used for the design, SolidWorks and OpticStudio Zemax. So, this application is the fulcrum of the waveguide design for most of the components that the company must weld. In particular, the program optimizes the positioning and design of the waveguide and the ferrules that enclose the optical fibers.

The chapter describes the characteristics of the add-in, method of operation, management and analysis of the results.

7.1 Principle of operation

The software used for the design are SolidWorks and OpticStudio Zemax. The first one is a CAD program for the design of mechanical components, the second one is a ray-tracing and optical simulation program.

Through the SolidWorks environment, it is possible to write a macro which, through API (Application Programming Interface, shown in Figure 7-1), allows to execute instructions that interface the two software. The SolidWorks API is a programming interface. There are functions that can be linked with other programming languages and allow direct access to the functionality of SolidWorks and other software with which a link is researched.

So, the development environment adopted is that of the VBA provided directly by SolidWorks. To connect to OpticStudio Zemax, the API of the program were consulted through the connection with DDE. Python has been used to be able to use some functions of OpticStudio Zemax directly from the web. Python is a programming language and some developers have made available a library of features that allows to interface OpticStudio Zemax with this language.

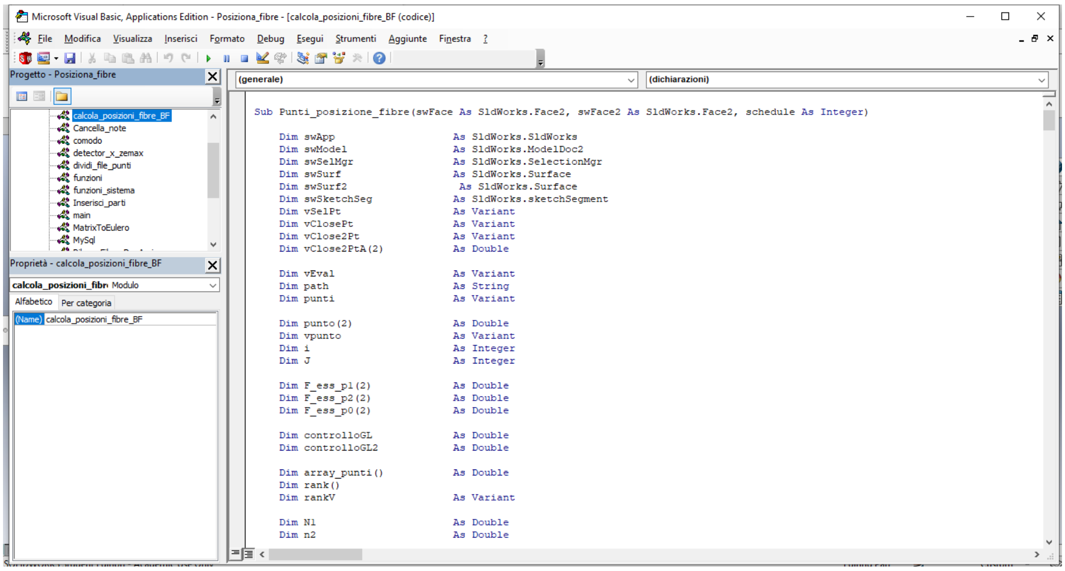


Figure 7-1 – API environment of SolidWorks for macro editing

Once the programming and code editing phase is finished, the program looks like a SolidWorks add-in (Figure 7-2) and a user interface (Figure 7-3) helps to set the parameters and plan the calculation process. The programming code cannot be made public in the Appendix section as the intellectual property belongs to the company Cemas Elettra which prohibits its dissemination.

The program analyses the angle of entry of the beam on the upper component, it will be possible to obtain the best inclinations in terms of efficiency on the welding seam, therefore an efficiency classification can be drawn up. This optimization will be carried out on reference points in the component. Collected data on all reference points, it is possible to define the waveguide.

To show the features and operating options, the work done on a taillight is taken as an example.

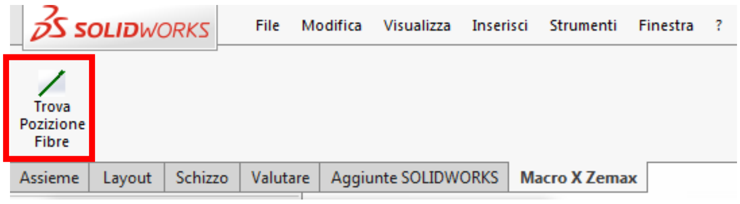


Figure 7-2 – SolidWorks tabs, button to launch the add-in

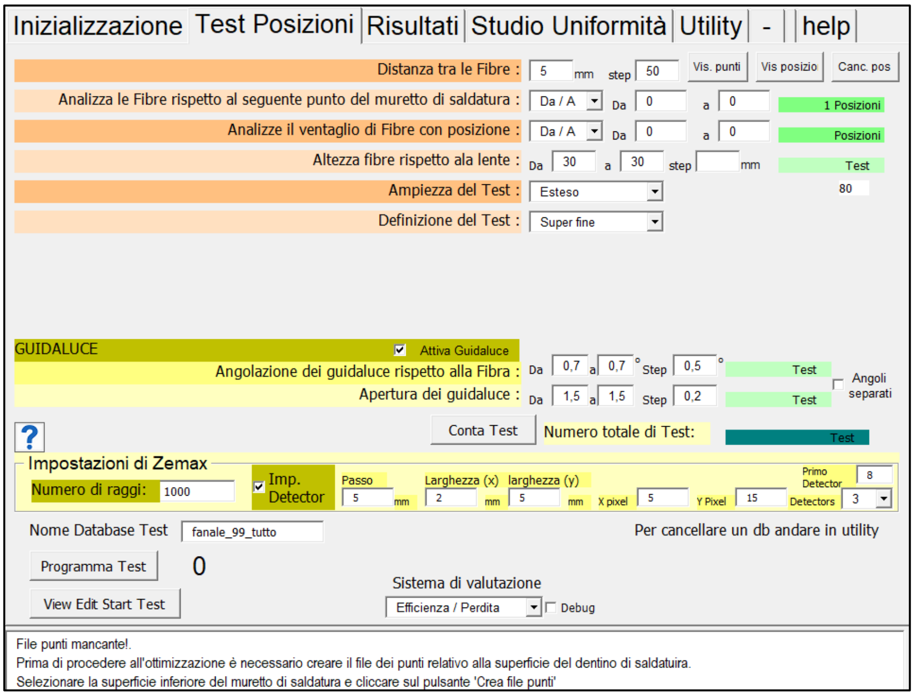


Figure 7-3 – Interface of the SolidWorks macro

7.1.1 Parameter interface

Initially, it is necessary to identify the welding path which, in this case, is represented by the rib of the lens in the lamp (Figure 7-4). Sometimes the welding rib could be in the body. Subsequently, on the welding path the detectors will be positioned in the ray-tracing software.

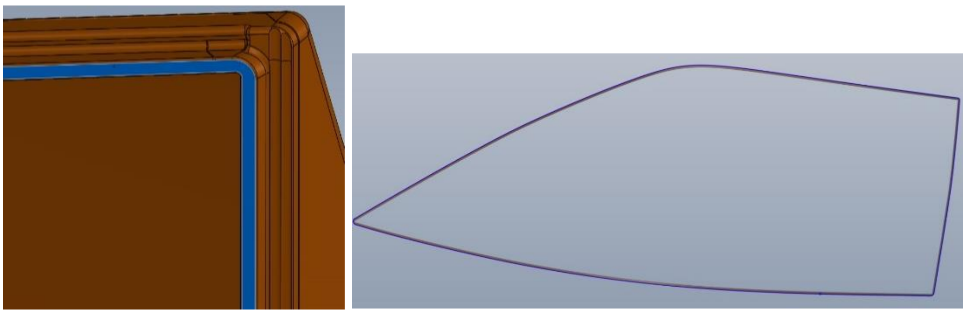


Figure 7-4 – a) Welding rib individuated in the light tail; b) Off-set of the entire welding rib

Once the path has been found, a file that identifies it is created. The file is unique for the project and also serves to recognise the positions that are reference points (Figure 7-5) for the program and the operator. It is possible to increase the resolution of the points in the path (Figure 7-5-b).

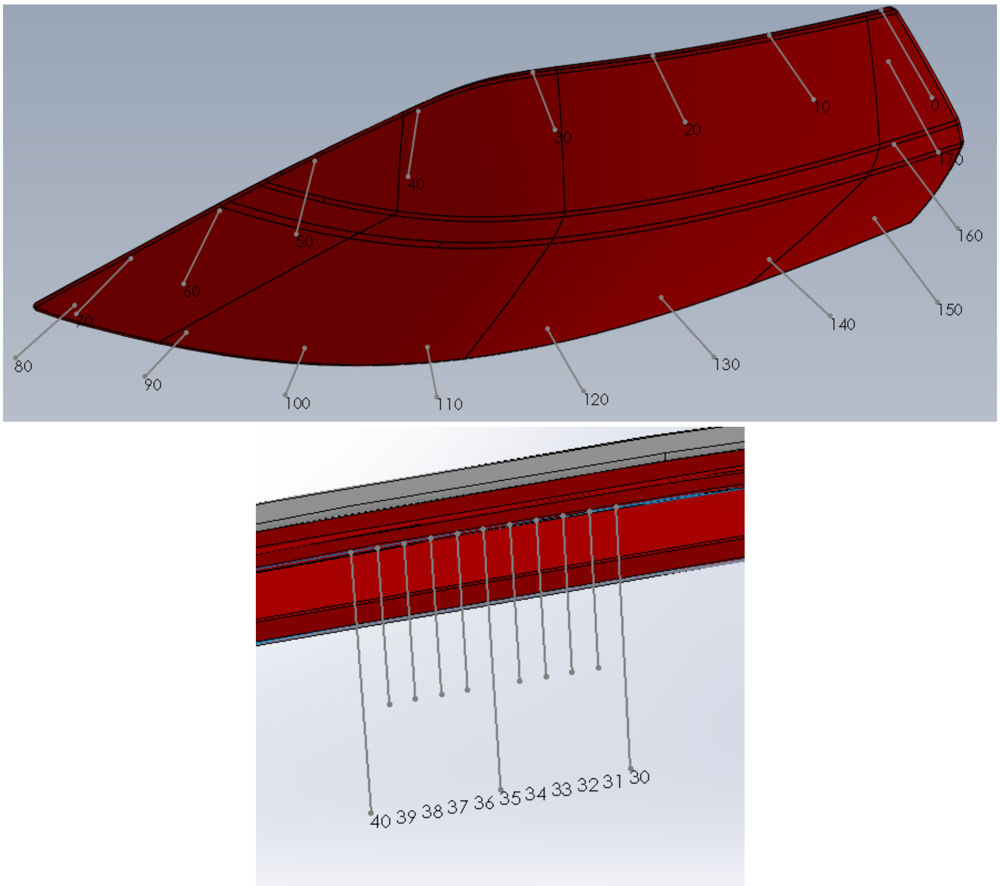


Figure 7-5 – Reference points on the welding rib of a light tail: a) General disposition; b) Increased points resolution.

From a mechanical point of view, it is convenient to have a regular and continuous waveguide. This is possible if the welding rib or the skin of the lens maintain continuity and regularity. In the case of the example in the Figure 7-5-a, these properties are present so the waveguide is predicted that it will be regular at portions (positions between 0-70, 70-150, 150-170). In these three ranges, some points are chosen to carry out the analysis with the program, e.g. position 150, 130, 110, 80. These points will be pivot points for the design of the waveguide walls.

On each point chosen, the optimization process is carried out.

One source at a time is simulated in the optimization process. So, at the end of the entire analysis process with the macro, a repetition of the ferrules still has to be set and the step that allows for a good homogenization has to be studied. In fact, considering valid the principle of superposition of effects, it is considered that source, adjacent to the one studied with the macros, will have a similar behaviour. The only constraint is that the profile of the body has gradual variations and that there are no discontinuities. In case of discontinuities, the designer must evaluate the best way to proceed with project management. In some cases, if there are clear discontinuities on the part, it is possible to break the waveguide in multiple parts (Figure 7-6).

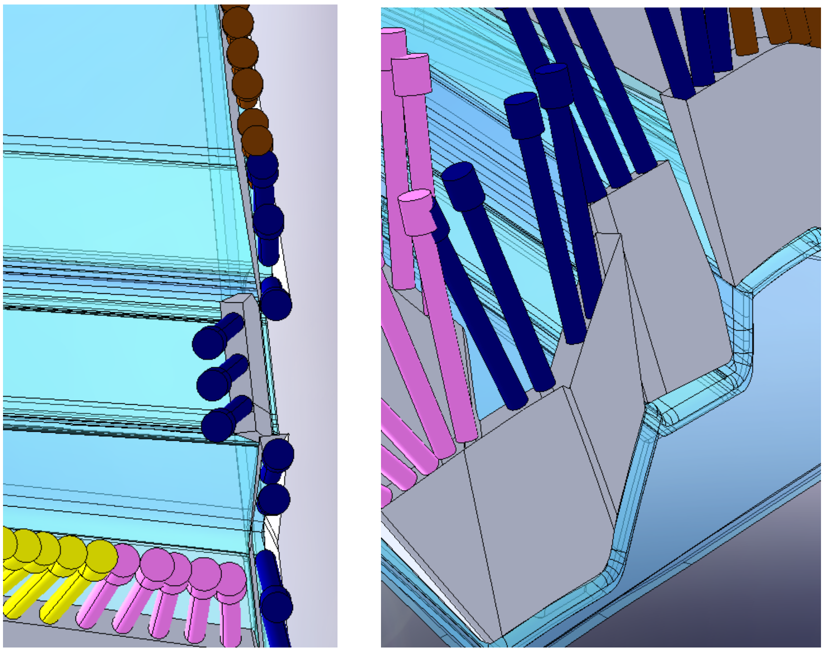


Figure 7-6 – Waveguide divides into parts

The optimization that is carried out in the individual positions is a repeated simulation process, in each simulation a parameter changes. The parameters are set in the window of the macro before the simulation is launched. At the end of the entire process, the most efficient simulations in terms of power incident on the detector are classified.

To set up the optimization process, the analysis range for the pivot point to analyse is printed. The fan allows to choose the tests.

The first simplification must be made: the laser beam is treated as a single beam with a direction coinciding with the axis of the ferrule. This simplification is only constructive, actually in the ray-tracing software the beam is modeled as described in the Paragraph 4.5.2.

On the welding joint, a fan pattern is plotted, following the refraction laws and delimited by the walls of the rib. The initial point belongs to the centre of the rib, from this point some rays are traced and go toward the skin of the lens. The rays pass the skin and they are refracted, so in the preliminary phase it is necessary to set the refraction coefficient of the materials. In this way, the entire fan is plotted.

The positions with a numbering indicate the positioning ranges of the waveguide and ferrules, all the portions inside the selected range are simulated and analysed. For example, in the Figure 7-7 the interval from 525 to 756 has been selected, so only the waveguides whose starting point is in this range are tested.

Although it is possible to test a very wide range of positions, the aim of these tests is to choose which is the best position respecting: mechanical structure of the welding machine, the geometry of the plastic component and possibly the positions already selected of the other pivot points. This allows to preventively eliminate some simulations that would be mechanically unacceptable. A narrow-selected interval permits to have short simulation time.

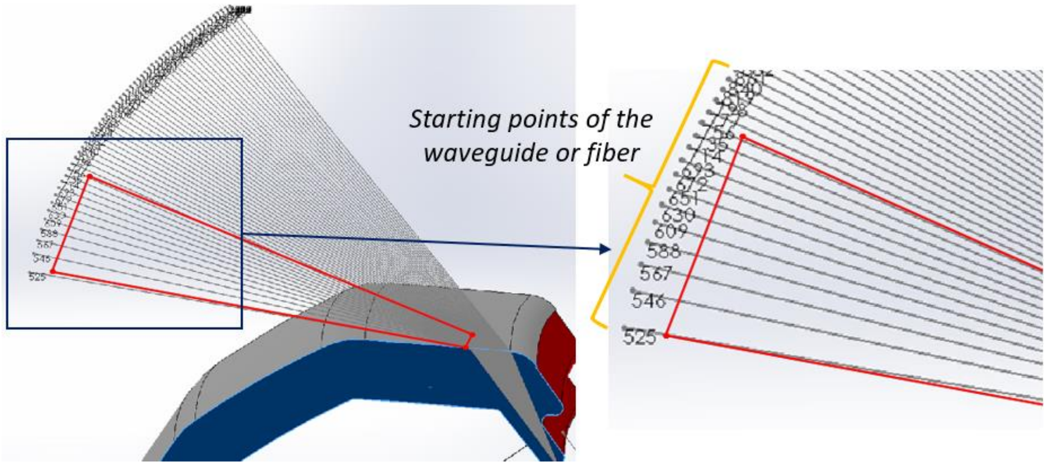


Figure 7-7 – Fan of possibilities may be analysed

Only the axes that follow Snell's law are represented, but during the test phase other positions are tested. In this way any solutions that exploit multiple internal reflections inside the welding rib are explored.

There are various options within the macro to further refine the range, it follows that a great number of tests will be carried out.

Summarizing the input parameters for the position that it is possible to set in the dialog box of the macro (Figure 7-8):

- Reference point of analysing;
- Range of reiterations in the fan;
- Discretization of the range. There are two drop-down lists that allow to define the dimension of the range or the discretization of the range.

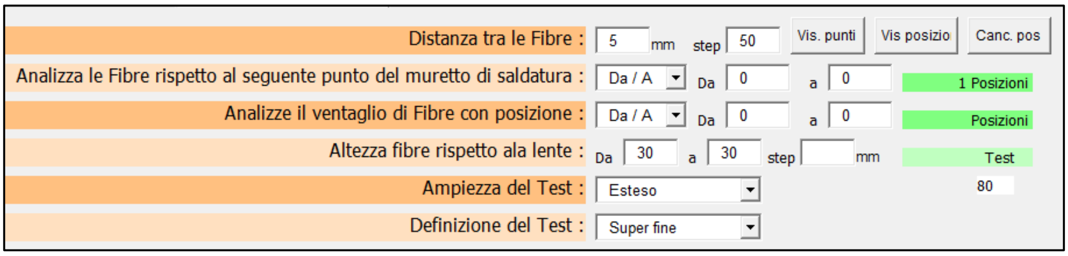


Figure 7-8 – Window to set the input of the position for the calculation

Consecutive tests on several reference points can be programmed during a work cycle of the program. This helps to save time, as the program can run autonomously even without the supervision of an operator.

Once the range for the test has been defined, the simulation parameters must be chosen and set.

7.1.2 Mechanical data

It is necessary to identify which are the components and the geometric parameters to be recognized and managed in the program.

The efficiency analysis is carried out on a point identified on the weld joint. All assumptions, analysis and plotting of the results are done on a section perpendicular to the profile in the analysis point.

Initially it is necessary to define whether to use the waveguide, in fact in some cases (i.e., high walls of the body as shown in Figure 7-9) it could be convenient to use ferrules directly facing to the transparent body. Because the plastic walls substitute the function of the waveguide in mixing and homogenising the contribution of the different ferrules. In this case, no other geometric parameters need to be set in the macro. At the end of the calculation process, the best ferrule axis positions will be found.

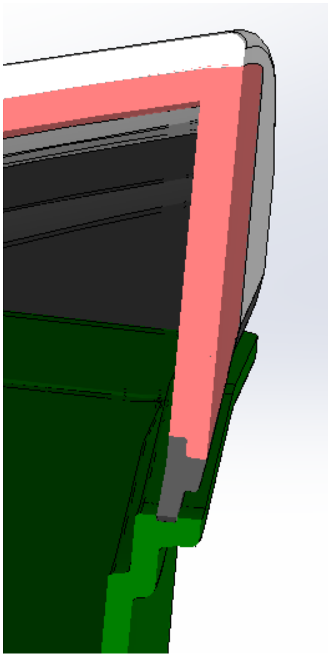


Figure 7-9 – High walls in a light tail, usually a waveguide doesn't need

Instead, if a waveguide is considered necessary, the characteristics must be set. The features are the same analysed in Paragraph 5.1.3: height, angle and aperture.

For the tracing of a provisional waveguide for reiterated simulation, a simplification is carried out: two flat surfaces tangent to the profile and with the axis coinciding with the axis of the ferrule are taken as mirroring surfaces (Figure 7-10). In fact, usually the profile of the components does not have very high curvature, so as the first estimation a non-extended waveguide closely approximates a waveguide that follows the profile.

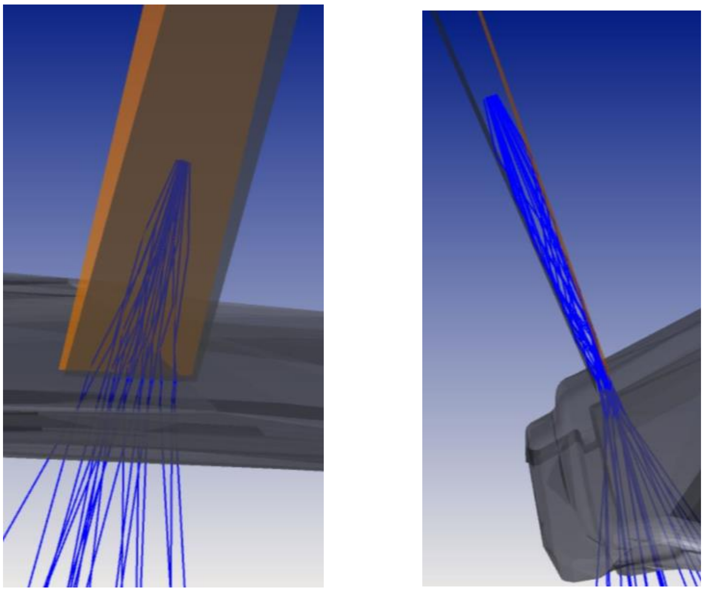


Figure 7-10 – Approximation of the waveguide with two flat mirror surfaces

The program in the reiterations can change the axis of the source, consequently the axis of the waveguide follows it.

For the parameters it is possible to insert a reiteration phase, that is to test the waveguide at different heights, or with variable angles and aperture.

The geometric parameters that can be set on the program dialog box for a single source or for a source with a waveguide are listed below:

- Height of the waveguide or distance between the ferrule and component. It is possible to choose a range of height and the step in changing;
- Semi-angle and step of reiteration;
- Aperture and step of reiteration.

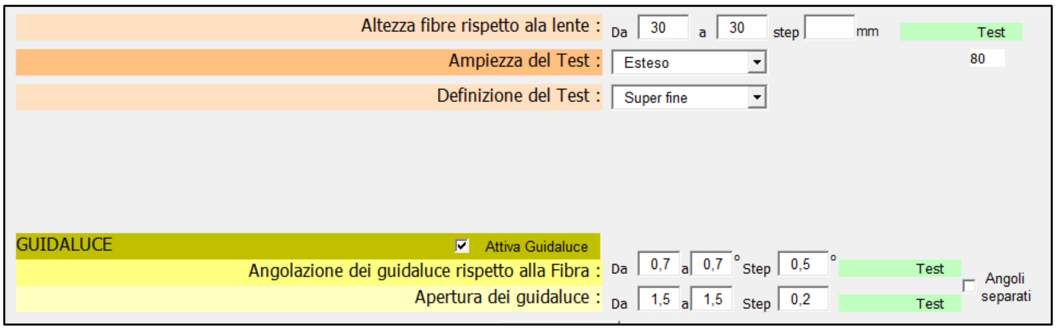


Figure 7-11 - Window to set the input of the waveguide

7.1.3 Optical data

Once the mechanical and geometric section has been defined, the parameters for the optical simulator must be defined. The simulation parameters that can be entered the appropriate dialog box (Figure 7-12) are:

- Number of rays for the source;
- Pixel extension;
- Dimensions of the detector.

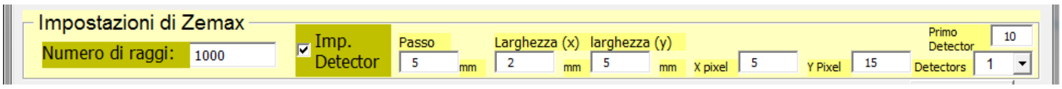


Figure 7-12 – Window to set optical parameters

The number of beams to be simulated and the number of pixels of the detector are kept constant because it has been noticed that the results are not very influenced by their change. In this phase, only the efficiency on the welding rib is evaluated and not the homogeneity of the beam. Under these conditions, a low resolution of the detectors is set. Moreover, a limited number of beams to be simulated would give concrete indications for the purpose. Remembering that the number of rays and pixels influence the simulation times, therefore a low number of these features decreases the processing cycle.

Detectors gather information on how efficient the fiber tested is and on loss on the sides of the welding rib. A fundamental function is the size of the detector. In fact, the width must follow the dimensions of the welding track, while the length depends on how much the laser beam expands.

It was decided to put detectors also externally from the welding path, in order to collect information on the dispersed flux. This data is important to understand the risk of burns on the absorbent body.

In OpticStudio Zemax all the elements necessary for the analysis process have been set. A starting file (Figure 7-13) has been compiled. it can be used in all projects, in fact most of the elements are standard such as the source, mirror surfaces and the detectors, while the only element that varies is the body to be simulated, according to the project. Therefore, starting from this model and substituting the component to be analysed, the macro process can be started.

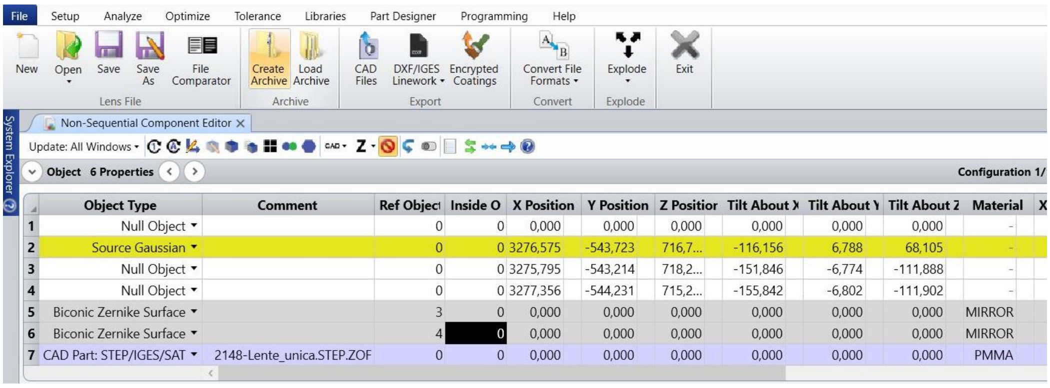


Figure 7-13 – File for the optimization in OpticStudio Zemax

7.2 Optimization results

Once all the parameters have been set, the optimization process can be started.

The tests are performed by sending various parameters, inserted in the macro, to OpticStudio Zemax. The software performs optical ray-tracing simulation and the results are stored in the database. The second group of parameters is sent to the simulator and this process is repeated until all simulations are performed. Finally, the results are classified according to efficiency. The target of these tests is to identify the best positioning for the pivot ferrules.

The results give some significant data such as: efficiency which is the parameter on which the fiber classification is drawn up and the losses that indicates the flow coming out of the welding walls and could damage the components.

To display the results, select the ‘Risultati’ tab and from the drop-down window the analysed fiber pivot can be chosen (Figure 7-14).

Figure 7-14 - Window of the results of the fibers analysed with the macro optimization process

The parameters of the simulation previously defined are shown in the specific cells (Figure 7-15): height of the waveguide or distance from the body, the aperture of the exit and half angle of the waveguide.

Figure 7-15 – Window of optimization results

A certain range of fibers analysed can be displayed (e.g., from the first to the tenth in the ranking, or the firsts hundred as shown in Figure 7-16-a) and the waveguide sketch can be printed (Figure 7-16-b). The first ranked ferrule is coloured green (Figure 7-16-c).

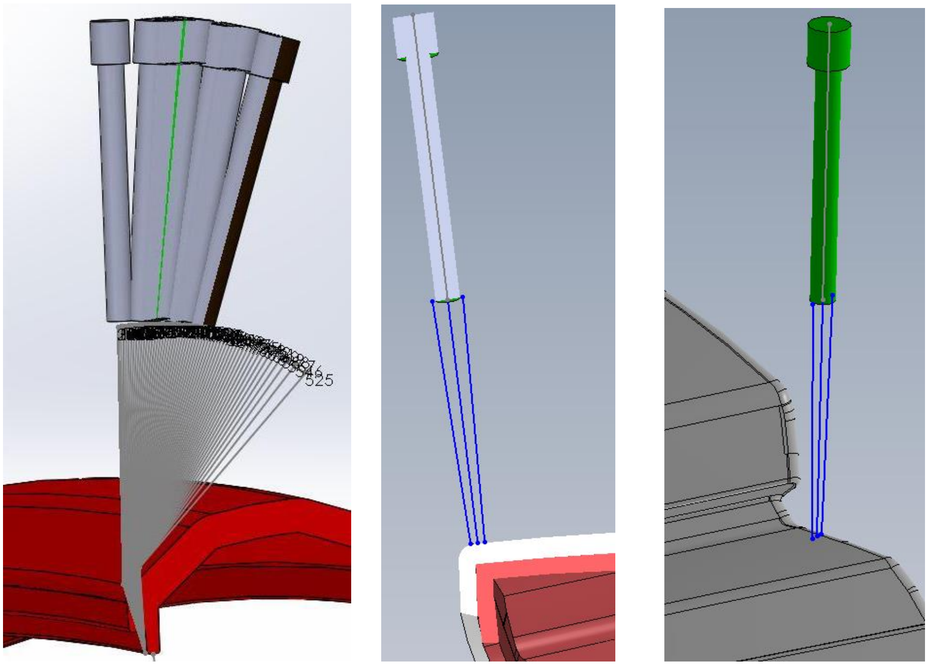


Figure 7-16 – Results in the SolidWorks environment: a) Range of sources analysed; b) Ferrule and its respective waveguide; c) First ferrule in the classification of the results.

After running a simulation, the results can be evaluated thanks to the detectors in OpticStudio Zemax. However, if a more effective visual representation is required, detectors with the corresponding power distribution values can be imported into SolidWorks (Figure 7-17-b). This is possible thanks to the import detector function (Figure 7-17-a). In fact, on the optical simulation software it is possible to view the results and perform a processing of the values, but the 3D graphics are not very developed (Figure 7-18).

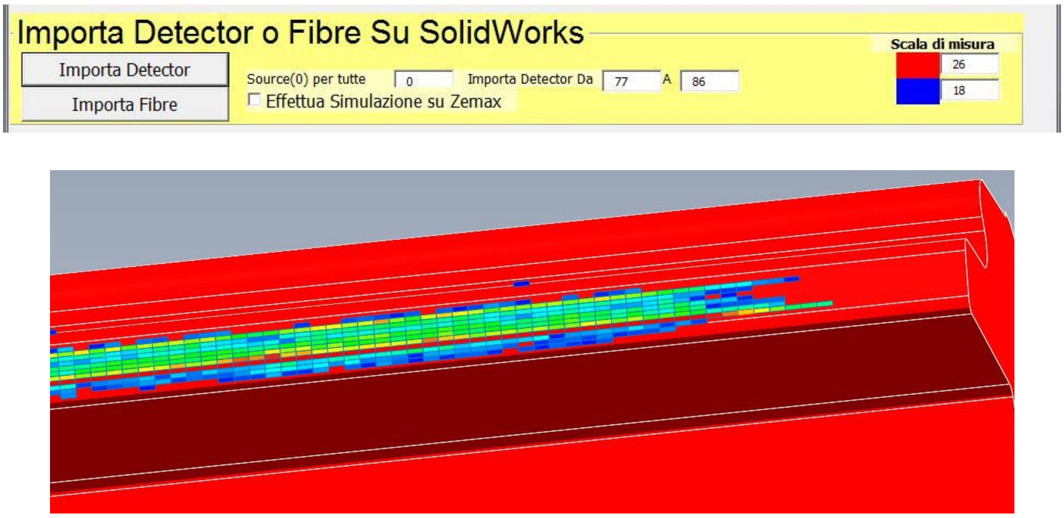


Figure 7-17 – a) Dialog box to transfer the results of OpticStudio Zemax in SolidWorks; b) Imported detector in SolidWorks

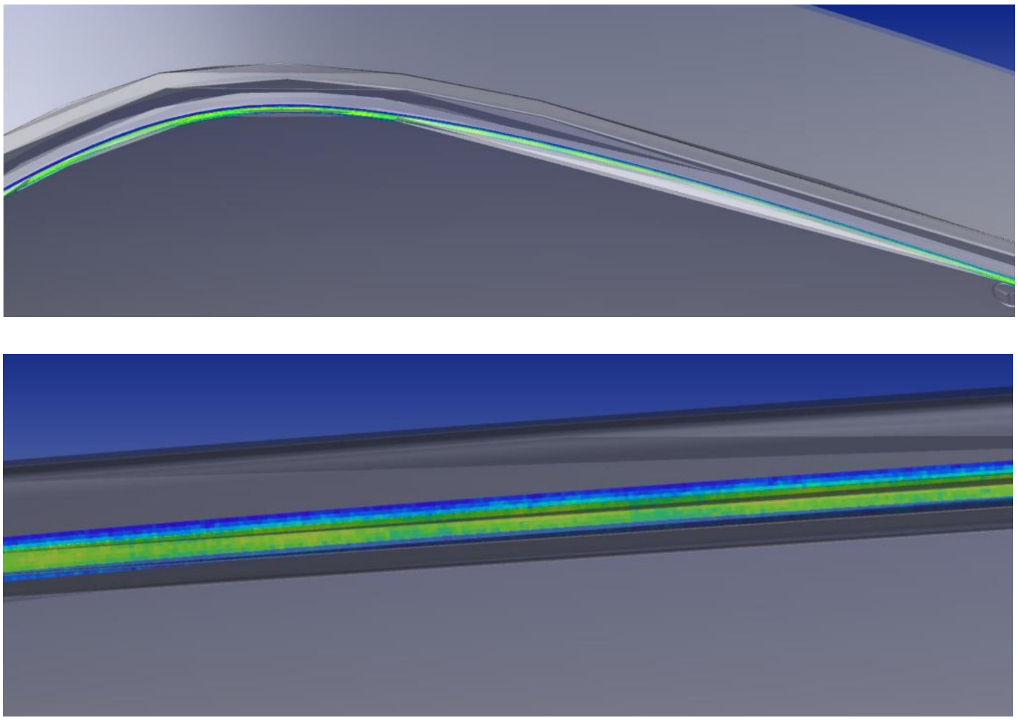


Figure 7-18 – Detector on OpticStudio Zemax

Among these analysed fibers, it is possible to choose the one that is considered best for the final positioning of the repetition of ferrules and for the design of the waveguide. If it is believed that the most suitable source is not the first but another in the ranking, the best fiber identified must be moved to the first position. This is possible through an appropriate command on the macro, shown in Figure 7-19.

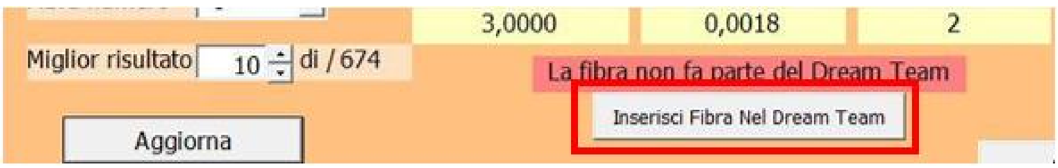


Figure 7-19 - Update ranking with the fiber chosen for the waveguide design

The choice of the best fiber depends on the designer. As mentioned above, there are many factors to consider for the choice, such as:

- Mechanical feasibility.
- High power efficiency.
- Continuity of the profile. Between nearby pivot ferrules, it is not convenient to have large differences in the entry angle inclination.
- Position of the waveguide on the body. If the waveguide is too close to the edge, the thrust may not be transmitted adequately and damage the component.
- Power profile on the welding path, which should be as symmetrical as possible.
- Low power lost outside the welding walls which could cause material burns.

It is necessary to do the optimization process and the management of the results for each pivot point chosen in the preliminary phase, until the entire perimeter to be welded has been analysed (Figure 7-20).

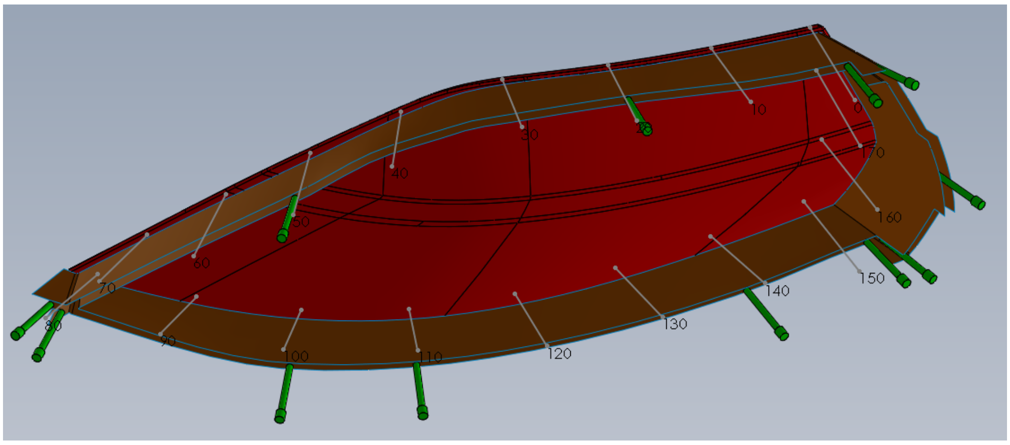


Figure 7-20 – Pivot points analysed in the project

7.2.1 Waveguide design

The macro also allows to build the surfaces of the entire waveguide in the 3D CAD model. Using the buttons (Figure 7-21) positioned in the dialog box, it is possible to draw the splines that serve as guidelines for the surfaces of the waveguide. With another command from the lines, it is possible to trace the walls that are looking for (Figure 7-22). Thus, the orange surfaces of Figure 7-20 have been created.

Figure 7-21 – Button to create the guidelines for the waveguide

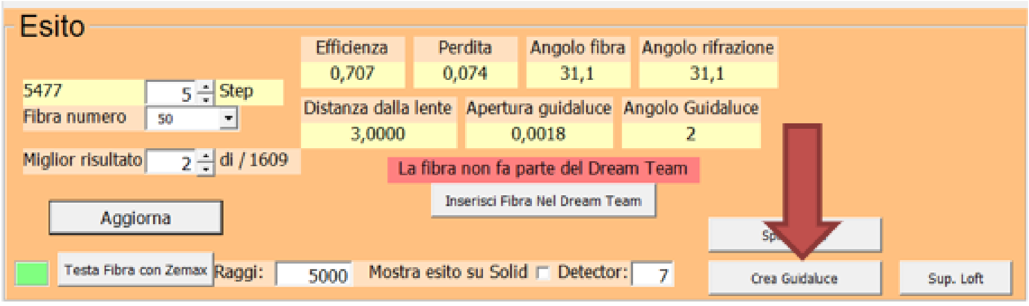


Figure 7-22 - Button to create the surfaces for the waveguide

7.3 Database development

The program to analyse the position of the ferules needs a support database where the data relating to the tests are stored.

The XAMPP software was used to compile and manage the database. XAMPP is a free multiplatform software consisting of Apache HTTP Server, the MySQL database and all the necessary tools to use the PHP and Perl programming languages. The MySQL server settings are used to connect to a database on which test results are saved. A default folder has been indicated on the user's computer to store all the data from the tests. Thanks to the software used it is possible to manage the databases of multiple users. Using the macro through the MySQL server settings, within the same LAN, it is possible to connect users of several workstations.

The default IP address is that of the computer in use. Through the available servers drop-down menu, the server to connect can be selected (Figure 7-23). By selecting a user and then pressing the 'Get IP' button, the IP number of the corresponding computer will be entered. In this way the database used will be that of the selected remote computer.

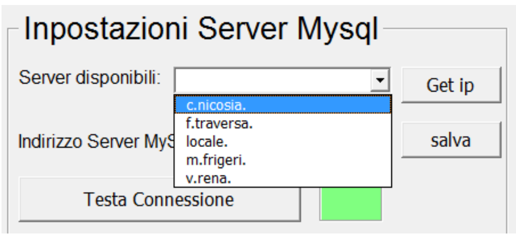


Figure 7-23 – Drop-down menu to choose the server from which to view the results

Before using the macro, the MySQL server has to be launched. XAMPP opens both a MySQL server for the database and an APACHE server.

Only after the starting of the servers, it would be possible to begin the calculation phase, because without software for saving data the macro would give errors in the script.

7.3.1 Database management

In the 'Database' section, the saved data can be managed: create new ones and make backup copies.

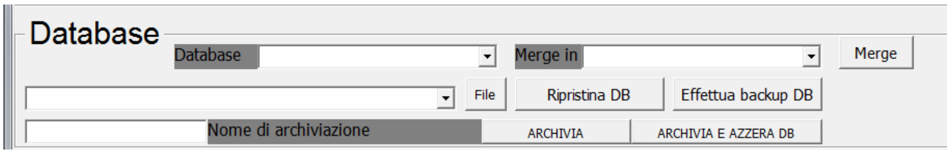


Figure 7-24 – Database dialog box

In order to manage the results for the study phase, it is possible to merge the data into an existing database or save a new one.

In fact, it might be convenient to save time by running optimization tests on multiple computers. For example, if the component to be analysed is very large or has short linear lines, the points to be optimized and the number of tests are very high. Some calculation processes may even take a few hours. Therefore, using more machines to simulate, the computing power is multiplied. The drawback is that each computer saves the results on its own database in a local folder. In order to build the waveguide described in the paragraph 7.2.1, the data must be saved in a single database. For this reason, sometimes it is necessary to create a database by merging the results of multiple databases.

From the database drop-down window, the file to be copied is selected. In the 'Merge in' cell can be chosen where the data will be saved, selecting an existing database or typing the name of a new database. The merge function can be used with archives coming from the personal server or also from the servers of other users connected to the program. The new database will be saved on the server of the computer of the current user.

At the end of the project, it is possible to make a backup archive and delete the data from the result section. To access the archive again, it can be reloaded into memory from a specific window (Figure 7-25).

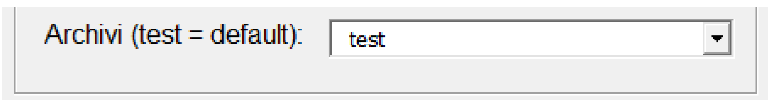


Figure 7-25 – Dialog box to select an old archive

7.4 Conclusions

The add-in created by compiling a macro for SolidWorks represents a valid support for the modeling and design of a waveguide that meets the design requirements.

Nowadays the design and production times are getting shorter, moreover the aesthetic design of the components is becoming more complex and articulated. These are the main reasons that led to the writing of the macro.

This macro has been developed by the CEMAS' working group, according to the needs of the designers, the program can be continuously improved. In case of new needs or new functions are required, the macro is editable and the script can be easily changed to implement what the end-user requires. The macro was created for various needs, such as reducing test times, evaluating solutions that would have been difficult to analyse, creating a link between the two design programs such as described in the paragraph 7.2, it may be necessary to display the results of the optical simulation on SolidWorks.

The program allows to exploit the resources of multiple computers, thus considerably reducing the computing time. However, it is up to the designer to evaluate the options and the parameters in order to take advantage of the macro and not waste time on the unnecessary calculation. Furthermore, it is not certain that a solution can be found for any profile or section of an element to be welded. The designer should be able to assess in advance whether the component is not optically feasible. The macro is in fact a support to the design work. The operator must properly evaluate the results and draw a waveguide that homogenizes the beams coming from the optical fibers of the ferrules.

Therefore, only a qualified designer who has the knowledge of optics can use the program. As errors or simulation problems are always possible, and only those who have knowledge of mechanics and optics can evaluate the best solutions or solve problems effectively and quickly.

8. Conclusions

In this study, a recent technology, i.e. simultaneous welding through transmission laser in polymeric materials was investigated. Initially with laboratory tests to understand the phenomenon and to develop a study model. Finally, a simultaneous laser welding machine was developed, in such a way that it can be used for industrial applications.

For this purpose, a customized laser source was designed and assembled. The laser path and its reshaping have been taken into account during this thesis work.

In fact, to obtain good simultaneous welding it is necessary to have a homogeneous distribution of energy on the welding path. To achieve that goal, a bundle of optical fibers has been designed and fabricated for the transport of the laser beam. Each bundle contains up to 8500 single fiber and in this way, there is a redistribution and standardization of the energy profile exiting from the fibers coupled in several groups called ferrules. Several bundles of optical fibers have been designed and tested in order to obtain the most homogeneous output. By increasing the number of fibers and dividing them with a large degree of randomization, a completely Gaussian beam is obtained and the percentage deviation in output power from the different ferrules of the same bundle is decreased, reaching down to 1%.

The laser beam coming from the ferrule needs to be guided toward the workpiece.

Subsequently, a metal hollow core waveguide was studied for the homogenization of the various beams coming from multiple optical fiber bundles. It was studied how each element affects the power profile and the quality of the welding path.

Several materials have been studied, and for each one a different power density was pointed out creating a database available for further receipt. It has been found that these parameters strongly depend on the geometries and the complexity of the optical path and the materials of the components under the welding process.

The most important study of this thesis was the design of the metallic hollow core waveguide and a complete modelling software tool as add-in of SolidWorks.

The complete laser path from the laser diode source to the workpiece was modeled on optical simulation software, OpticStudio Zemax, with which it was possible to study the geometric parameters suitable for a homogeneous power profile.

The industrial research team supported the design and fabrication of a prototype to carry out the welding tests. Thanks to the prototype it was possible to experimentally establish which power densities are suitable for welding the various analysed materials.

The best results have been obtained with PMMA coupled with ABS. The time for a complete the laser welding profile was reached down to 5 seconds, while a low optical power density is needed, nominally about 0,3 W/mm^2. The time and related optical power density depend on the material to be joined and the distance from the hollow waveguide (i.e. PMMA) to the interface with the absorption substrate (i.e. ABS). The technology is so versatile that very good results have been achieved by testing several other materials (i.e., PA66), but the time and the power have to be increased. The time can exceed 10 seconds and a nominal power of 1W/mm^2 is needed.

It is still not widely used due a lack of detailed study. But thanks to the numerous advantages, it was believed that it could spread in the industrial market and in batch production. In fact, more and more customers are showing interest.

Therefore, the technology has finally been transferred to industrial machines to test a mass production feasibility. This was the core of the thesis, where an add-in for SolidWorks has been designed, implemented and experimentally tested. The routine is able to receive in input the profile of the joining surface and guide the optical designer in the positioning of each ferrule at the inlet of the complex hollow waveguide.

The macro communicates with the two design software (OpticStudio Zemax and SolidWorks).

The implemented program allows the introduction of all optical parameters of the waveguide when the application profile is uploaded from SolidWorks. Through recurrent simulations, the most fitting parameters are carried out. However, due to the complexity of the joining surface and its polymer inhomogeneity, the input optical parameters and related results are based on a look-up table, which must then be evaluated and adjusted by the designer. Therefore, the macro up to now is a valid support to the designer in order to catch the best laser set-up for the simultaneous laser welding process.

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