LASER WELDING OF NYLON TUBES TO PLATES USING CONICAL MIRRORS

by

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ABSTRACT

Laser transmission welding of polymers is a relatively new joining technique. It is based on the fact that the majority of thermoplastics are transparent to infrared radiation. A laser beam passes through the transparent part, and is then absorbed by a part rendered absorbent by additives such as carbon black. Absorbed laser energy is transformed into heat that melts the polymer at the interface between two parts, thus forming a weld.

Many industrial applications have quite a complex geometry. This may often make it impossible to irradiate small elements of the joint interface directly. One of the possible solutions for this problem is to employ an oblique mirror to redirect a laser beam to the desired direction. In present work, transparent nylon tubes were welded to absorbing nylon plaques using a conical mirror inserted in the tube. The effects of the laser power, the angular motion speed, and the number of cycles on the joint shear strength were examined. Additionally, a two-dimensional axi-symmetric transient finite element heat transfer model was developed and evaluated. It simulated the temperature developed in the specimen during the welding cycle; the model was validated with the welding and mechanical testing results.

The experimental results demonstrated good joint strength, confirming the feasibility of this technique. It was also found that welding at a lower laser beam power and a higher rotational speed allowed higher maximum weld strengths to be achieved at the expense of longer cycle time and higher energy consumption. Simulation of the temperature demonstrated that varying of the rotational speed at constant laser power does not change the overall temperature rise trend.
ACKNOWLEDGMENTS

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This study could not have been successfully completed without the technical assistance of Mr. John Perreault and Mr. Clarence McEwen of the RMC.

The author also wishes to thank his mother Dr. Olga Kritskaya, his wife Mrs. Maria Kritskaya and the rest of the family for their help and emotional support.
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<tr>
<td>(\alpha)</td>
<td>Thermal diffusivity</td>
<td>(m^2/s)</td>
</tr>
<tr>
<td>(\Delta y)</td>
<td>Step size between two neighboring positions of the knife edge</td>
<td>(mm)</td>
</tr>
<tr>
<td>(\pi)</td>
<td>Pi (a constant approximately = 3.14159)</td>
<td></td>
</tr>
<tr>
<td>(\Psi_j)</td>
<td>Normalized power distribution of the laser beam</td>
<td>(mm^{-1})</td>
</tr>
<tr>
<td>(B)</td>
<td>Brewster’s angle</td>
<td>(^\circ)</td>
</tr>
<tr>
<td>(I_{(X=0)})</td>
<td>Radiation intensity at the surface</td>
<td>(W/mm^2)</td>
</tr>
<tr>
<td>(I_{(X)})</td>
<td>Radiation intensity at the depth (x)</td>
<td>(W/mm^2)</td>
</tr>
<tr>
<td>(K)</td>
<td>Absorption coefficient</td>
<td>([mm%]^{-1})</td>
</tr>
<tr>
<td>(k)</td>
<td>Absorptive index</td>
<td></td>
</tr>
<tr>
<td>(k)</td>
<td>Conductivity</td>
<td>(W/(m\cdot K))</td>
</tr>
<tr>
<td>(L_b)</td>
<td>Estimated length of the laser beam</td>
<td>(mm)</td>
</tr>
<tr>
<td>(n)</td>
<td>Complex refractive index</td>
<td></td>
</tr>
<tr>
<td>(n^l)</td>
<td>Refractive index</td>
<td></td>
</tr>
<tr>
<td>(n)</td>
<td>Number of the beam passes</td>
<td></td>
</tr>
<tr>
<td>(P)</td>
<td>Laser beam power</td>
<td>(W)</td>
</tr>
<tr>
<td>(p_j)</td>
<td>Power reading difference between the two neighboring positions of the knife edge</td>
<td>(W)</td>
</tr>
<tr>
<td>(Q)</td>
<td>Total line energy</td>
<td>(J/mm)</td>
</tr>
<tr>
<td>(q)</td>
<td>Heat flux</td>
<td>(W/m^2)</td>
</tr>
<tr>
<td>(R)</td>
<td>Radius</td>
<td>(mm)</td>
</tr>
<tr>
<td>(T)</td>
<td>Temperature</td>
<td>(^\circ)K</td>
</tr>
<tr>
<td>(T_0)</td>
<td>Initial temperature</td>
<td>(^\circ)K</td>
</tr>
<tr>
<td>(t)</td>
<td>Time</td>
<td>(s)</td>
</tr>
<tr>
<td>(t_h)</td>
<td>Duration of the pulse of the heat source in the model</td>
<td>(s)</td>
</tr>
<tr>
<td>(V)</td>
<td>Linear speed</td>
<td>(mm/s)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
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<tr>
<td>( w )</td>
<td>Angular speed of the beam</td>
<td>rad/s</td>
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<tr>
<td>( y )</td>
<td>Distance from the surface</td>
<td>mm</td>
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<td>CB</td>
<td>Carbon black</td>
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<tr>
<td>CCD</td>
<td>Charge-coupled device</td>
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<td>FEM</td>
<td>Finite element method</td>
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<td>HAZ</td>
<td>Heat affected zone</td>
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<td>LTW</td>
<td>Laser transmission welding</td>
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<tr>
<td>Nd:YAG</td>
<td>Neodymium-doped Yttrium Aluminum Garnet</td>
</tr>
<tr>
<td>PA</td>
<td>Polyamide (nylon)</td>
</tr>
<tr>
<td>PBT</td>
<td>Polybutylene terephthalate</td>
</tr>
<tr>
<td>PC</td>
<td>Polycarbonate</td>
</tr>
<tr>
<td>PMMA</td>
<td>Poly(methyl methacrylate)</td>
</tr>
<tr>
<td>RPM</td>
<td>Revolutions per minute</td>
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<tr>
<td>UTM</td>
<td>Universal testing machine</td>
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CHAPTER 1: INTRODUCTION

Laser Transmission Welding (LTW) is a technique for joining thermoplastic parts using a laser beam radiation. LTW joins an absorbent part to another that is transparent to near-infrared radiation. A laser beam passes through the transparent part and is quickly absorbed by the absorbent part. The dissipated energy causes melting at the weld interface and diffusion of the polymer between the two parts. A weld is then formed after the polymer has solidified. The LTW approach is made possible by the fact that majority of natural polymers are transparent to infrared laser radiation. The addition of small quantifies (a few percent) of absorbing additives, such as carbon black, allows the thermoplastic part to absorb the laser energy.

In the last ten years, significant research has been done on laser welding of polymers. The influence of process (laser power, laser speed), part (transparent specimen thickness, moisture presence), and material parameters (amount of different additives and reinforcements) on the weld strength have been studied. In most cases, researchers used simple specimen shapes [1-5]. The most common weld seam geometry was a straight line, and the laser beam was kept perpendicular to the specimen surface. However, in many industrial applications, the joint interface geometry is more complex.

Despite the complexity of the joint trajectory, it is desirable to keep the laser beam perpendicular to the surface of the part at all points along the weld seam. The more the beam is deflected from the surface normal direction, the larger the portion of power lost due to reflection. Consequently, less power reaches the joint interface. Reflected laser power, in turn, can damage surrounding parts. Moreover, the laser beam spot area
increases as the incident deviates from the normal direction. Given that the power of the beam is then distributed over the larger area, it is necessary to apply higher laser beam power to maintain the same energy intensity.

Expensive and complex robot manipulators or galvanometer-based scanning mirror systems are often used to move the laser beam along the interface. In some cases, however, the curved elements of the joint can be small, making it difficult to deliver the laser beam to the surface using conventional techniques. Thus, it might be impossible to keep the beam perpendicular to the surface in such cases. This problem was not addressed in the previous work. The simplest example of a curved joint is welding a tube to a plaque. Joining of tubes to plaques is important, for example, in the manufacturing of heat exchangers (Figure 1.1). Normally, the tube diameter is much smaller than the laser head. In this case, it is impossible to directly irradiate the workpiece from the inside, while keeping the beam perpendicular to the surface.

One possible solution in this case could be to use static mirrors. The mirror could be a polished surface on the fixture or even part of the component itself. The laser head could move over the mirror using a motion system, or alternatively, the fixture and parts could move under the motionless laser head. If the parts to be welded are relatively small, it may be possible to use a galvanometer scanning system. To weld tubes to plaques, for example, a conical mirror could be inserted inside the tube.

The objective of this thesis is to develop the process of laser transmission welding where the laser beam is redirected by a mirror. In this work, small-diameter tubes were welded to holes in plaques. A conical mirror was used to guide the laser beam along the weld path and keep it perpendicular to the tube wall. The power intensity profile and
geometry of the laser beam reflected from the conical mirror were characterized. The influence of parameters such as laser power, angular speed, and the number of passes on the strength of the joint was examined. In addition, the temperature as function of time and position were estimated using a finite element model. The results of the modeling such as the onset of welding and degradation were compared with those from welding tests.

This thesis is divided into six chapters. After the definition of the problem in Chapter 1, Chapter 2 presents background information related to this work. This information includes a review of the current plastic joining techniques, a more detailed discussion of the principles of laser welding of polymers, a background on the lasers, a review of literature on the laser welding of polymers, a background on mirrors and
reflectivity, and finally the material properties of nylon 6 – the material used in this study.

Chapter 3 presents characterization of the laser beam reflected from the conical mirror. It includes description of geometrical distortion of the reflected beam and characterization of its power intensity profile.

Chapter 4 describes experimental part of this work. It includes materials, geometry of the specimens, welding equipment, process parameters, weld strength assessment method, and discussion about the results of the experimental part of this study.

Chapter 5 presents the finite element model of the temperature distribution within a specimen during the welding process. The model is validated by comparing predicted and experimentally obtained weld widths.

Chapter 6 reviews main conclusions of this research and discusses possible areas of the future studies.
2.1. Plastic Joining Techniques

During the second half of the 20th century, plastics became widely used engineering materials. Very often, design of the products requires joining two or more parts together. Moreover, sometimes the shape of the part can be very complex. In this case it might be technically impossible to mould this part as a single piece. Therefore, the part can be composed of several simpler parts, joined together.

A number of different plastics joining techniques have been developed. In general, they can be divided into three groups: mechanical interlocks, adhesive joining, and welding [6, 7, 8, 9]. These groups, in turn, can be subdivided into various sub-groups. The variety of possible joining techniques testifies to the fact that there is no ideal assembly technique. Each technology has its advantages and disadvantages.

Mechanical interlocking can be implemented by screws or by snap-fits [7, 8, 9]. Using screws implies presence of threads in the parts to be joined. The thread can be molded-in in advance or it can be created by a self-tapping screw at the moment of assembly. An alternative solution involves using threaded metal inserts. Moulded-in threads require relatively complex moulds and, in this case, it is often difficult to make threads of small diameters. Self-tapping screws, in turn, cannot make large diameters. They also can create cracks which reduce chemical resistance of the part. Both of these thread types have the same major disadvantage: when tightened, they have a tendency to undergo stress relaxation. The screw, tightened initially, can loosen with time. In order to avoid stress relaxation, threaded inserts made out of metal can be employed. Use of these
inserts is also preferable if reusability of the joint is required. The disadvantages of using inserts are higher cost of the product, the introduction of an insertion step in the production cycle, and recyclability issues.

Another type of mechanical interlocking is the use of snap-fits. Snap-fits work by mechanical interlocking of hooks on one of the parts with slots on the opposite part. The hooks are integrated with a part. It reduces number of elements in the unit by eliminating the need for screws. Assembling with snap-fits is also fast and simple. However, more complex moulds are often needed to make the required detail on the parts. In general, these mechanical joints have disadvantages such as a non-hermetic interface between connected parts and local stress concentrations.

Selection of adhesives to join the parts can avoid many of the drawbacks of mechanical joints [6, 7, 8, 9]. Adhesives can provide hermetic seals. Moreover, the design of the moulded parts can often be simpler in this case. Adhesives can be commercially appropriate for production of single or many articles. In addition, adhesives are suitable for assembling parts made out of dissimilar materials as well as thermosets. However, adhesives have their own weaknesses. For example, some plastics have low chemical resistance to solvents used in the adhesive. Adhesives can also cause stress cracking. In addition, extra manufacturing costs are incurred due to the cost of adhesives, the careful surface preparation required, the time required to apply the adhesive, the additional material handling, as well as time required for the adhesive curing.

For thermoplastics, one of the most popular ways of joining is welding. Generally, welding involves heating of the joint interface of the parts until it reaches
melting temperature, holding the two parts together to insure interpenetration of the molten material, and cooling. This method is fast and does not require additional consumables such as the adhesive or the screws. Welding insures a hermetic weld seam and avoids chemical compatibility issues associated with adhesives. On the other hand, welding has some limitations when it comes to joining dissimilar materials. Moreover, welding techniques often require expensive equipment and their use can often only be justified in case of high-volume production. In addition, welding can produce flash (flash is a molten material that is squeezed out of the joint interface), which is often aesthetically unacceptable in the finished assembly. The current welding techniques can be classified by the way of delivering heat to the weld interface, as summarized in Table 2.1.

Table 2.1. Classification of the welding techniques by the principle of heat generation.

<table>
<thead>
<tr>
<th>Heat Delivery Technique</th>
<th>Welding Technology</th>
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</thead>
<tbody>
<tr>
<td>Heating due to heat conduction/convection</td>
<td>▪ Hot gas welding/Extrusion</td>
</tr>
<tr>
<td></td>
<td>▪ Hot plate welding</td>
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<td></td>
<td>▪ Resistance welding</td>
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<td>Heating due to viscous dissipation</td>
<td>▪ Spin welding</td>
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<td></td>
<td>▪ Vibration welding</td>
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<td></td>
<td>▪ Ultrasonic welding</td>
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<tr>
<td>Electromagnetic heating</td>
<td>▪ Induction welding</td>
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<td></td>
<td>▪ Radio frequency welding</td>
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<td>▪ Microwave welding</td>
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<td></td>
<td>▪ Laser welding</td>
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</table>

The first thermoplastic welding technique was developed during the Second World War. Hot gas was used to repair bullet-riddled airplane cockpits. The hot gas
welding of thermoplastics is similar to the gas welding of metals [6, 8]. However, for welding of thermoplastics, non-flammable gases are generally used. Most often, it is regular air. The parts to be joined are put together and a special filler rod, composed of the same material as the parts, is positioned at the joint. The gas is heated to the melting point of the thermoplastic and applied to the joint through a nozzle. The edges of the parts and the filler rod soften and form a weld seam. Advantages of the hot gas welding are its simplicity and low equipment capital cost. On the other hand, this method is relatively slow. Control of the temperature in the weld zone can also be difficult. Manual welding requires experienced operators and the quality of the weld is often not as reproducible as with automatic welders. Hot gas technique is therefore best suited for welding and repairing of large parts, and for small-series production.

In hot tool welding, the heat is transferred to the parts from a heated tool (e.g., a plate) [6, 8]. The parts to be joined are put into close contact with the plate's surface and then heated up past their melting or softening temperature. After the surfaces of the parts soften, the hot plate is removed, and the parts are then clamped together until the weld seam solidifies.

![Figure 2.1. Hot Tool Welding](image)
The hot tool method provides high joint strengths, often reaching the strength of the bulk material. The absence of vibration in the hot tool welding can be important for joining units with electronic components inside. However, there is typically more flash produced along the weld seam and this must be aesthetically acceptable for the user of this welding technique. The hot tool may have a complex geometry that represents the shape of the part. Therefore, this technique is capable of making complex three-dimensional weld seams. The use of two independent hot plates makes it possible to weld dissimilar materials with different melting temperatures. The contact hot tool welding provides one more advantage; it is not sensitive to significant gaps in the weld interface. These gaps are local imperfections on the joint surface of a part. On the other hand, the hot tool welding has a relatively long cycle time and high energy consumption. The power is permanently switched on and provides significant energy losses between the heating cycles. There are also issues with sticking of the melted polymer to the tool.

Another way to apply heat to the interface between the two parts is the use of the resistive implants placed in the joint [6]. The implants are heated by electric current which then melts the thermoplastic. Typically, the implants are made out of continuous carbon fiber or stainless steel mesh. The resistance welding technique provides better energy efficiency compared with hot tool welding. It is also suitable for joining of large parts. Equipment for resistance welding is relatively simple and does not require demanding operator skills. The resistive implant remains in the interface after welding. This makes it possible to heat the parts again later and reassemble the joint. On the other hand, the implant can reduce the strength of the weld and introduces possible problems for recycling of the product.
The next group of welding techniques is based on the principle of viscous heat dissipation. It includes vibration welding, spin welding, and ultrasonic welding.

In vibration welding, two parts are first clamped together under pressures in the range of 1 MPa. One part is not allowed to move laterally and the other is oscillated laterally at frequencies of the order of 100 Hz over amplitudes of approximately 1 mm. Heat is initially generated through friction. Once a melt layer is formed at the interface, further heating occurs via viscous energy generation in the thin liquid film. Typical cycle times for vibration welding range from 1 to 10 sec [6, 8].

This technique requires expensive equipment and is well-suited to high-volume production. The flash produced in vibration welding is often aesthetically unacceptable, forcing designers to make flash traps around weld interface. There are also limitations in the joint design. The weld interface should be straight at least in one direction in order to permit movement of one of the parts with respect to the other. Another limitation of vibration welding is the mass of the parts. Large and heavy parts require large equipment and high energy consumption. Vibration welding is not suitable for joining of the units which contain sensitive elements such as electronic components. Relative displacements
of the parts can also affect the precision of the joint for the case of strict tolerance requirements.

On the other hand this technique has number of advantages. It has better energy consumption comparing to the hot tool welding. Vibration welding is capable of overcoming large gaps in the interface which reduces the part tolerance requirements. The cycle time is shorter than in hot-plate welding. Spin welding is similar to vibration welding except that one part is rotated continuously against a stationary part.

Ultrasonic welding is one of the most commonly used joining methods for plastics. It involves heating of a polymer by vibration of high frequency, and cooling under slight compression. Compared to vibration welding; this technique has much higher frequencies and lower amplitudes. Most often frequencies vary in the range from 20 to 40 kHz and are applied normal to the weld interface [6, 7, 8]. Typical amplitudes vary from 20μm for 20 kHz to 9 μm for 40 kHz. Heat is generated in the weld interface due to viscous dissipation caused by the relative movement of the two parts.

![Figure 2.3 Ultrasonic Welding.](image-url)
Vibrations are applied perpendicularly to the interface through the “upper” part. Part design frequently includes a triangular-shaped rib at the joint interface. The purpose of this rib is to concentrate the ultrasonic energy. The ultrasonic welding is the fastest method compared to other welding techniques. The cycle time can be as short as 1 second. This method is therefore widely employed for mass production. The drawback of this technique is the need to make energy directors at the weld surfaces. As in the case of vibration welding, ultrasonic method is not desirable for electronic components. Another limitation is the size of the part. Ultrasonic welding is good for small and medium sized parts as it can be difficult to transmit vibrations to the joint interface through thick parts.

The third group of welding techniques uses alternating electromagnetic fields to heat the parts. The main difference between these methods is the electromagnetic radiation frequency that they use.

Induction welding operates in the range of frequencies from 0.1 kHz to 10 MHz [6]. Induction coils are placed along the joining interface. An alternating current passes through the coils and generates the magnetic field. The interface between the two parts contains a special composite material, made from thermoplastic polymer with ferromagnetic particles embedded in it. The alternating magnetic field creates an alternating current in these particles. This energy is then dissipated as heat and conductively transferred to the rest of the thermoplastic matrix. Melted polymer flows along the weld line and fills cavities and irregularities on the surface, forming a weld after solidification. This approach can accommodate wide tolerances. The typical cycle time is about 1 – 2 seconds [6]. Induction welding can be used to weld three-dimensional complex joints. A weld line can be continuous or discrete. Multiple weld lines can be
welded at once. In addition, induction welding, similar to all the electromagnetic techniques, do not produce any vibration in contrast to vibration and ultrasonic methods. The process has good efficiency in terms of energy consumption. Ferromagnetic particles remain in the joint interface. Therefore, the joint can be later disassembled in the same way as it was welded. The disadvantage of this technique is the necessity to produce an electromagnetic thermoplastic adhesive that will be placed at the joint interface. The mechanical performance of the weld is often reduced due to presence of the ferromagnetic particles.

Radio frequency welding operates in the range of 13 to 100 MHz [6]. The main idea of the method is to generate heat in polar materials due to intensive molecular motion. Thermoplastic parts to be welded are clamped between two electrodes which also function as press plates. The applied energy induces an alternating electromagnetic field inside the parts. Energy is dissipated inside the part by conduction. This technology uses relatively simple equipment and does not require any additional consumables, unlike in the case of induction welding. On the other hand, radio frequency welding is only suitable for the materials containing polar molecules.

Another welding technique which can be considered to belong to the electromagnetic methods is laser welding. Since this method is the subject of this work, it will be described in more detail in the next section.
2.2. Laser Transmission Welding Overview

The laser transmission welding method requires that one of the parts to be joined is absorbent and another one is transparent to the laser radiation. The laser beam passes through the transparent part and hits the absorbent part. Electromagnetic waves are absorbed by absorbing additives such as carbon black, transformed into the heat, and the material of the absorbent part melts. From the absorbent part, the heat is transferred to the transparent part. Therefore, the material in the interface of the parts melts under the laser beam path, forming the weld seam [10].

Laser Transmission Welding of polymers is based on the fact that polymers have good transmittance of electromagnetic radiation in the wavelength range from 400 nm to approximately 1600 nm [10]. This includes the near infrared (IR) wavelengths in the range of 780-1600 nm. Because of the limited range of wavelengths for which polymers are transparent, not all lasers are suitable for laser welding. The diode lasers (808 – 980 nm) and Nd:YAG lasers (1.06 μm) are the most common for this welding technique.

The total amount of the energy that must be delivered to the weld surface must account for energy lost due to reflection and absorption within the transparent part. The amount of power lost due to reflection is relatively small for all polymers (about 5-10%) [6]. Absorption in the bulk of the transparent material depends on the amount and presence of additives, thickness of the specimen, and the type of the plastic. Crystals in the crystalline phase of polymers increase absorption and scattering of the laser beam. Thus, amorphous polymers have better transparency.
The depth to which the laser beam can penetrate into the bulk of the polymer depends on the laser wavelength, presence of colourants and fillers, and reinforcing additives. Additives increase internal absorption of the energy in the polymer. Some additives, such as a carbon black, are especially good absorbents of the infrared radiation. The particle of the pigment absorbs the laser energy and rapidly releases it to the polymer's molecules due to vibration relaxation. When the polymer contains two or more mass percents of the carbon black, practically all laser power is absorbed at the surface of the part. The depth of penetration in this case is very small.

The radiation intensity distribution in the material depth is given by the Bouger-Lambert law of absorption:

\[ I(x) = I(x=0)e^{-Kx} \]  \hspace{1cm} [2 - 1]

where:

- \( I(x) \) – the radiation intensity at the depth \( x \)
- \( I(x=0) \) – the radiation intensity at the surface
- \( K \) – the absorption coefficient.

Several approaches to the laser radiation distribution at the weld interface have been developed. In contour welding, the parts are moved under the stationary beam, or the laser head is moved along the weld trajectory. Speeds of approximately 2-5 m/min are used [11]. A robot or an XY motion system can be employed to carry out the motion. The contour welding is relatively simple, flexible and efficient method. The major disadvantage of the method is absence of meltdown. At every moment of the process the
polymer is melted only in the short part of the weld contour and possible gaps in the interface may not be bridged. This technique is shown schematically in Figure 2.4.

Another technique is the *mask welding*. The parts are covered by a special “mask” with a slit in the shape of the desired weld geometry. The mask is scanned by a wide beam emitted from the diode laser bar. The drawback is that a large fraction of the laser energy is wasted, being stopped by the mask. Mask welding is shown schematically in Figure 2.5.
In order to achieve simultaneous heating of the entire weld contour, a special modular set-up of high power diode lasers can be mounted in order to reproduce the geometry of the joint. The *simultaneous welding* technique has very short cycle times. It does not require motion systems. Simultaneous melting of the entire contour allows meltdown and bridging of gaps in the weld interface. On the other hand, equipment for the simultaneous welding is expensive, complex and not flexible. Use of this method can only be cost-effective in mass production. This technique is shown schematically in Figure 2.6.
Flexibility of the laser welding techniques can be improved by using mirrors to guide the laser beam along the desired trajectory. A galvanometer scanning system combined with a laser can rapidly move the laser beam along the contour of any desired complexity in 2-D plane. The scheme of a galvanometer scanner is shown in Figure 2.7. The scanning speed can be varied widely. Scanning at low speed works in the same way as the contour welding. However, the low weight of the mirrors allows scanning speed to be increased to such speeds that the heat does not have time to totally dissipate by conduction after each pass of the beam, as the beam repeatedly travels along the joint path.

As a consequence, the temperature in the joint interface increases until the entire weld contour melts. This approach is referred to as the quasi-simultaneous welding technique. It has advantages of the simultaneous welding, but at the same time quasi-simultaneous welding is very flexible (as the beam path can be easily reprogrammed) and
requires less expensive equipment. The main disadvantage of the scanning heads is limited working area. Typical work area can be up to 200×200 mm, thus limiting the size of the parts that can be welded.

![Diagram of laser beam guiding by galvanometer scanner](image)

Figure 2.7. Guiding of the laser beam by the galvanometer scanner.

2.3. Lasers

The term laser is an abbreviation which stands for *light amplification by stimulated emission of radiation*. The first laser was made in the USA in 1960 by Theodore Maiman [12, 13, 14]. A laser comprises three major components: an active laser medium, a resonant optical cavity, and a system of medium energizing or “pumping”. Since its invention, many different designs of lasers have been developed.
They operate in a wide range of wavelengths and can be differentiated by the type of material used as a medium – gas lasers, chemical lasers, dye lasers, metal-vapor lasers, solid-state lasers, and semiconductor lasers.

The process of energy emission in the laser medium is based on the fact that the species (electrons, ions, or molecules), migrating from higher to lower energy level, emit a photon. At the same time, when the species absorbs a photon of energy, it moves to the higher energy level. The photon emission can be spontaneous or stimulated (Figure 2.8). When the species is moved to a higher energy level, it is considered to be in an excited energy state. If an external photon interacts with this excited species, then there is a high probability that it will emit a photon. This type of emission is called stimulated. The characteristics of the photon produced by the stimulated emission are identical to the photon which caused this emission. It has the same frequency, phase, polarization, and propagation direction. In other words, it is possible to say that stimulated emission leads to the amplification of the electromagnetic wave amplitude, but does not change its frequency, phase, polarization, and the propagation direction. Consequently, the stimulated emission is completely coherent with the stimulating radiation [12, 13, 14, 15].

![Figure 2.8](https://via.placeholder.com/150)

**Figure 2.8.** a) Spontaneous photon emission; b) Stimulated photon emission; c) Absorption of the photon.
The ratio of the output optical power of the laser to the input power is the efficiency of the laser. This efficiency varies depending on the laser type. Semiconductor diode lasers are among the most efficient types. They are the most widespread lasers in the world due to their high power efficiency, low power consumption, and relatively low cost. The power conversion efficiency of the semiconductor laser can be as high as 80% [12]. At the same time, the semiconductor lasers have very low voltage requirement (starting from 1 ~ 2 V). It makes them suitable for small portable devices powered by a battery such as CD players, laser pointers, and distance measurement tools.

In the semiconductor diode lasers, photons are emitted in the junction region between the p and n parts of the diode as a result of the recombination of free electrons and holes (electron acceptors) (Figure 2.9). Photons, released in the directions not perpendicular to the mirrors, do not participate in laser beam generation.

A single diode is very small and produces only a few milliwatts of power. A laser suited for material processing applications normally requires significantly more power and thus it must be made by combining many individual diodes. In order to increase the power, first, the diode elements are mounted together side by side forming a laser bar. Next, these bars are stacked one above another, forming a laser unit. These units, in turn, can be combined into blocks, capable of producing powers up to 150 kW. Since a significant fraction of the input pumping energy is converted into heat instead of light, the diode laser must have a cooling system integrated into its design. For this reason, the laser bars are mounted on special water cooled heat sinks [11].
A beam, emitted by a single laser diode is not collimated. Its light emitting area has a shape of a stripe or an elongated rectangle. The length of that stripe is typically 200-300 μm and the thickness is several micrometers. Due to these dimensions and shape, the laser light significantly diverges going out of the diode. Parallel to the stripe's long axis the full-angle divergence is about 10° - 20°, and transverse to it, in the direction of the p-n junction, it reaches up to 90° [11]. These two axes are named “slow” and “fast," respectively. To obtain a collimated beam, a micro lens is mounted close to the semi-transparent mirror of the diode bar (Figure 2.10).

Figure 2.9. Generation of the laser beam in the single diode element of the semiconductor laser.
After that, a complex optical system collects beams emitted by the single diodes into an output beam. Due to this complex optical set up, the shape of the final beam is close to rectangular and has dimensions in the range of one millimeter at the focal point. Note that the light of the diode lasers is typically not coherent when it is created by combining many individual beams. This leads to some limitations on use of the diode lasers. However, there are many applications which do not require laser light to be coherent and laser welding is one of them.

The choice of the laser type employed in transmission welding of polymers is related to the optical properties of polymers, which have different transmission values for the different wavelengths of the radiation. Today, the most common lasers types for polymer welding are the diode and the Nd:YAG lasers. The Nd:YAG laser operates at 1064 nm wavelength and the diode lasers work in the range between 750 nm and 1050 nm.
nm [11,14]. In the range of these wavelengths, polymers transmit up to 90% of the incident laser power.

2.4. Past Research on Laser Transmission Welding

A great deal of work in the field of Laser Transmission Welding of polymers has been done during the past decade. In their experimental work, researchers studied such parameters as optical properties of different polymers, influence of welding process parameters on the joint strength, and influence of various additives on the transmittance of the polymer. Theoretical work focused mainly on finite element modelling of the process.

2.4.1. Experimental Studies

One of the most important properties of plastics is their transparency to infrared radiation. It makes possible to use the Laser Transmission Welding (LTW) technique to join plastic parts together. Thus, parameters that affect optical properties of various polymers were actively studied. Kagan et al. [10, 16, 17] and Grewell et al. [18] studied the influence of short glass-fiber reinforcement, presence of different colourants and thickness of a specimen on the transmittance of several polyamides (PA or Nylon). They found that transmittance of a specimen gradually decreases with an increase in the amount of glass fibers. With high level of glass fiber reinforcement, only a small portion of the initial beam power was transmitted through a specimen. For example, the
transmittance of the 60 % glass fiber-reinforced nylon 6 specimen of 3.2 mm thickness was 20 - 25 % of the initial beam power [10].

At the same time, fiber reinforcement significantly increased scattering of the laser beam. The size of the cross-section of the beam increased with increasing amounts of glass fibers. It suggests that joining of glass-fiber-reinforced parts would require higher initial beam power in order to deliver a sufficient amount of energy to the joint interface [10].

Varying the thickness of a specimen had a similar effect. With increasing specimen thickness, its transparency gradually decreased, while the spot size of the laser beam increased [16, 17]. For example, at a 6 mm thickness, natural unreinforced Nylon 6 transmitted less than 50% of the initial beam power. Therefore, the LTW technique imposes certain limitations on the thickness of the transparent part.

Pigmentation of the material also significantly affects its transmittance. The amount of transmitted power varied depending on colour [16, 17]. Transmittance of red coloured specimens was close to that of the uncolored material. Yellow specimens showed significantly lower transmittance. White and green colourants reduced transmittance of the specimens well below 20%, showing the lowest values. High transmittance of the infrared waves through the red specimens can be explained by the fact that the wavelength of red colour is close to the infrared. From this it is clear that selection of the product colour is very important when LTW is used.

Van der Vegte et al. [19] performed comparative measurements of transmittance of different plastics. They tested specimens of the same thickness made of PC, PA 6, PA 46, and PBT. These materials are listed in the sequence from the highest to the lowest
measured transmittance. The magnitude of the beam scattering was higher for a material with lower transparency. In other words, PC showed the best transmittance and the lowest scattering and transparency of PBT was the lowest with the highest magnitude of scattering. Additionally, authors observed a reduction of transmission with an increased amount of glass fibers in the material.

Heat generation in the absorbent part occurs due to presence of absorbent pigment in the material. The most common absorbent is carbon black. Potente et al. [20] studied the influence of carbon black concentration in PA6 on the melt layer thickness ratio between transparent and absorbent parts. This ratio increased with increase of carbon black concentration and reached unity at 2 wt % of the absorber in the black part. At this concentration, the laser power is absorbed at the surface of the black part, and generated heat is equally divided between the black and transparent parts.

Chen et al. [21] investigated transmittance of polycarbonate specimens with carbon black concentration varied from 0 to 0.2 wt%. Laser absorption coefficient was observed to rise linearly with an increase in the absorber content.

In [22], Chen et al. evaluated the line energy (power divided by laser scan speed) required to cause degradation on the surface of uncolored polycarbonate. This work demonstrated that, despite high transparency of polycarbonate, there is a particular level of line energy at which energy absorption at the surface of the transparent part is high enough to cause burning. Also, it was observed that contamination or ejector pin marks on the surface of the part facilitate the onset of degradation.

Haberstroh et al. examined the influence of crystallinity on the optical properties of plastics. In [23] they studied the influence of crystallinity and glass fiber reinforcement
of nylon samples on the magnitude of scattering of the laser beam. Dimensions of the heated spots on the upper and lower surfaces of a specimen were photographed using an infrared camera. The ratio of the dimensions of these two spots allows one to estimate the magnitude of scattering. The observations showed that higher crystallinity causes more significant scattering. Higher content of glass fibers also caused an increase of the laser beam scattering, which is consistent with the results, presented in the previously mentioned works.

In [3], Haberstroh evaluated transmittance of PBT samples, injection moulded at different conditions. While the difference in the injection speed and the initial temperature of molten polymer did not show noticeable influence on transmittance, the difference in the mold temperature significantly affected the portion of power transmitted through a specimen. The specimens injection moulded with lower mould temperature had lower crystallinity. As a result, transmittance of these specimens was higher.

It is relatively easy to determine absorption coefficient for transparent specimens or specimens with low concentration of absorbent. However, the absorption coefficient of a “black” part cannot be easily detected by simply measuring a portion of the laser radiation transmitted through a specimen due to very fast absorption of the light within a small depth. Watt et al. [24] suggested the technique that allows determining a depth of penetration of the laser beam into the absorbent part. For this purpose, they welded two rectangular strips made of 30 % glass fiber reinforced polypropylene. The absorbent part was machined into the form of a shallow wedge with an angle of less than one degree. For welding, the wedge was placed between the transparent part and a piece of black Santoprene, which has a melting point close to that of polypropylene. The laser beam was
moved along the specimens and directed from the side of transparent specimen. At the thin end of the wedge, the absorbing part was thinner than the thickness of the heat affected zone. The material of the absorbing specimen was molten all the way through. As a result, the Santoprene substrate was welded to the black part. After the weld, the substrate was peeled off and the length of the weld line was observed. As the laser beam moves along a specimen, the wedge thickness gradually increases. The end of this weld line indicates point on the specimen where its thickness is equal to thickness of the HAZ.

Another parameter that affects transmittance is the incident angle of the laser beam. Rhew et al. [25] measured values of transmitted and reflected power for polycarbonate and high-density polyethylene specimens. This work demonstrates that, as the beam deviates from the direction normal to the surface of the specimen, the portion of transmitted power reduces, with an appropriate increase in reflection. In other words, placing the laser beam perpendicularly to the specimen surface is optimal in terms of power efficiency.

Usually, the power intensity of a laser beam is unequally distributed across its cross-section. From high power density in the center of a beam, it gradually decreases towards its perimeter. This results in unequal heating of a working surface. While the temperature at the center of a weld line can cause degradation of the material, the temperature at its sides may not be sufficient to melt a polymer. Caldwell et al. [26] suggested using a correcting lens to redistribute the power intensity of a beam and achieve an equal temperature distribution within the heat affected zone. Experiments and FEM analysis showed that inverted quasi-parabolic power intensity distribution of a laser
beam with minimum at the center, allows a uniform temperature distribution on the surface of a specimen to be achieved.

The main goal of welding is to achieve a strong joint between two parts. Ideally, the strength of a weld line should be close to the strength of the joined materials. Therefore, the influence of different parameters on the weld strength was extensively studied.

Bates et al. [27] examined the influence of part thickness, glass fiber content and line energy on the weld strength of the lap joints for Polyamide mXD6 plaques. It was observed that increase of the specimen thickness and glass fiber content resulted in increase of the laser light scattering. The scattered laser beam produced wider weld line, which resulted in higher failure force. On the other hand, it was necessary to apply higher line energy to achieve a strong weld. While the force at failure varied with specimen thickness, glass fiber content, and applied power, the maximum achieved stress at failure remained approximately the same.

Burrell et al. [28] studied dependence of the joint strength on absorbent concentration, specimen thickness and energy density. These tests were conducted using lap welding of polycarbonate specimens. The tests revealed that the weld strength increased with increase of the absorber concentration and/or energy density, reached its maximum, and then began to decrease. This is believed to be due to degradation of the overheated polymer. An increase of the specimen thickness also resulted in increase of the weld strength. It is possible that better performance of the thicker specimens is due to higher rigidity, which reduces bending of the lap joint during the tensile test.
Potente et al. [29] investigated optimal process parameters for quasi-simultaneous welding of PMMA and polycarbonate parts. T-joint specimen geometry was used for PMMA samples and both T-joint and butt-joint geometries were used for polycarbonate samples. It was found that weld strength increased with increase of the power intensity and joining displacement, reached its peak, and then decreased again. For some cases the weld strength increased with increased power intensity, scanning velocity and joining displacement, but never decreased at higher power intensity values. It is believed that this is due to limited range of tested powers which does not represent the whole range of the weld strength variation from cold weld to strong polymer degradation.

In laser welding of polymers, it is important to know the optimal values of power and speed needed to achieve a strong weld. Chen et al. [30] developed a technique that allows estimating optimal power and speed for contour laser transmission welding. Experiments were conducted using polycarbonate, polypropylene, reinforced and unreinforced nylon 6. For each material, a number of carbon black concentrations were tested. The black and transparent plaques were brought together but, to prevent parts from joining, they were separated by 0.5 mm metal shims. Then, for several different speed settings, specimens were scanned by the laser beam using a range of powers while keeping the scan speed fixed. This technique allowed one to identify speed and power settings at which material on the surface of a black part just began to melt, and settings, at which visible degradation appeared on the black specimen. The specimens were also welded together using the same welding conditions and then tested mechanically. The shear strength detected experimentally was compared with observations made during non-contact scanning studies. In general, it was observed that the power and speed
required to initiate visible degradation in the non-contact were close to conditions required for maximum shear strength. In addition, the shear strength of a joint increased with an increase in laser power, reached its maximum, and then dropped down again. For the specimens with a lower content of carbon black, it was necessary to apply higher laser power in order to achieve the same strength. Similarly, at higher motion speeds, it was necessary to apply higher power to keep the energy input per unit area the same and strength of a joint unchanged.

Normally, the power intensity of a laser beam gradually decreases from its center to perimeter. As the total power of a laser beam increases, the temperature at the periphery of a heat affected area reaches melting temperature and the weld line becomes wider. At the same time, an increase in the motion speed at the constant laser power reduces the width of a weld line. In other words, the width of a weld line depends on the amount of specific energy delivered to the surface of a specimen. This phenomenon was observed in [31, 32, and 33]. In [34] Al-Wohoush et al. examined the influence of the applied energy input on the weld width, the overall area of the heat affected zone (HAZ), and the ratio between the laser affected zone thickness in the transparent and the absorbent parts. They used polycarbonate as well as unreinforced and glass-fiber-reinforced nylon specimens. It was observed that increase of the energy input leads to an increase in all geometric parameters mentioned above. Light scattering in glass reinforced specimens caused a much higher weld width and larger laser affected zone area compared to the unreinforced nylon specimens. Polycarbonate specimens required less energy input to achieve a similar weld width or HAZ area. In addition, it was found that the heat
affected zone is surrounded by a thin distinct morphological zone of a constant thickness that does not change with laser power.

Prabhakaran et al. [1, 35] studied parameters of laser transmission welding of glass reinforced nylon. They conducted contour welding of T-shaped specimens. One of the results was an observation that the magnitude of meltdown also depends on the amount of energy delivered per unit length of the weld line (i.e., the line energy). Note that normally meltdown does not occur in contour welding. However, in this case, the specimens were short and the entire weld interface was molten after rapid pass of the laser beam which allowed meltdown. Results of the weld strength evaluation as a function of line energy are similar to [30].

Vetter et al. [36] conducted lap welding of unreinforced polypropylene specimens to study the influence of the line energy on the weld strength. With an increase in the line energy, the specific force at break increased, reached a maximum level, and then decreased again. The maximum value of the specific force at break reached was approximately 500 J/m. Photos of the weld seam cross-sections provided in this work showed that dimensions of the cross-section increased with increase of the line energy. At the same time, high levels of the line energy caused degradation of the material at the center of the weld seam, reducing mechanical performance of the joint. Widening of the weld seam along with an increase in degradation and voids in the center illustrates unequal distribution of power intensity across the laser beam.

In [37, 35] Prabhakaran et al. performed contour welding of unreinforced nylon 6 specimens in the T-joint configuration. The meltdown was observed to increase with increased line energy and/or weld pressure. Thickness of the weld seam decreased with
increase of the weld pressure. Varying the working distance led to a change in the dimensions of the beam spot. At the focal distance, the beam spot did not overlap the entire cross-section of the joint. As a result, unmelted material at the sides of the weld interface did not allow meltdown to occur. At the same time, the power of the laser beam was concentrated in a smaller area, causing polymer degradation at the center of the joint. A defocused beam, on the other hand, was covering the entire cross-section of the joint with more equal power distribution across it. The weld strength, weld width, and meltdown were observed to increase with an increase in beam defocusing.

Molecules of a molten polymer are actively moving in the melt pool during welding process. Fargas et al. [38, 39] came up with the technique which allowed one to visualize the melt flow trajectory and particle velocity in the weld zone during welding process. For this purpose, tracer particles were placed at the faying surface and highlighted by X-ray radiation. Motion of these particles in the melt pool was recorded by high speed camera capable of capturing 1000 frames/sec. Experiments were conducted for quasi-simultaneous and contour welding modes, using unreinforced PA6 specimens. This work allowed one to observe correlation between dynamical behavior of the melt pool with the mechanical and micro-structural properties of the weld seam. It was found that the motion speed of the particles increased with increase of the applied line energy and/or welding pressure. At given welding conditions, particles, initially located closer to the edge of the weld zone, had higher speeds than those, initially located at the center.

Knowing the dependence of the temperature at the surface of a specimen on the applied laser energy can help to determine optimal process parameters. Von Busse et al. [40] conducted a number of welding tests using an infrared camera to detect the surface
temperature of a specimen. In this work they used unreinforced nylon 6 and ABS with different carbon black content. It was observed that heating rate increased with an increase in the power density of the laser beam. It also increased with an increase in carbon black content in a specimen. Baylis et al. [41] used the infrared diode laser equipped with pyrometer to measure temperature of a specimen during T-joint contour welding of nylon to nylon and lap-joint welding of thermoplastic elastomers to polypropylene. In general, for the range of speeds tested, the temperature of a specimen and the width of a weld line rose with increased applied line energy. At the same time at a given line energy, the surface temperature was higher for higher beam power and motion speed. It demonstrates that at lower speeds, heat has more time to dissipate into the bulk of the material due to conduction.

As was previously mentioned, the power intensity distribution of a laser beam is not uniform. Frequently, it is necessary to know this intensity profile for more precise modeling of the welding process and for better understanding of heat distribution on the surface of a part. Mayboudi et al. [42] presented a method for characterizing the power intensity profile of a high-power laser beam which did not require expensive equipment. A power meter was placed under the laser head and covered by a plate with a 0.2-mm pinhole. The power meter was moved under the laser beam in 0.1 mm steps in a raster scan pattern. The power intensity values were measured for a grid consisting of 30 × 30 points. Then, measured values were normalized to the total power of the beam. The power intensity profile was characterized in the focal point of the laser beam and at several points away from it.
The pinhole method results were also compared with those obtained by a knife-edge technique. In this method, commonly used for laser-beam profiling, a laser power meter is partially covered by a plate with a straight edge which is then incrementally moved across the beam cross-section. This technique is less labour-intensive than the pinhole method but only produces the beam profile across one dimension. The knife edge was moved under the laser beam in 0.1 mm steps from the point where the beam is completely covered to the point where it is completely open and power was measured at each point. To obtain intensity values at each “stripe” of the power profile, the value of the previous power reading was subtracted from the reading at the next step. Results from both approaches showed good agreement with each other.

In high-volume production, parts frequently have some gaps at the joint interface. In case of contour laser transmission welding of polymers, only small segment of the joint interface is molten at any given moment. Therefore, gap bridging due to meltdown is not possible. Chen et al. [43] investigated the gap bridging due to thermal expansion of the material in the absorbent part. They examined the influence of laser power, carbon black concentration and gap size on the shear strength of PA6 lap welds. It was found that lower content of carbon black caused better volume expansion at the expense of higher laser power requirement. Gap thicknesses that could be bridged by thermal expansion without a dramatic reduction of the shear strength was under 0.2 mm. In high-volume production, this tolerance may be insufficient. To address this problem, attempts were made to create special design of a joint interface which would ensure tight contact between parts [44, 45]. In [45] Xu et al. used burst pressure tests of two hemispheres welded together to study efficiency of a number of joint designs. In addition, they
examined displacements and stress concentrations in these joints using Finite Element
Modeling.

A joint interface often has a complex 3-D geometry. Haberstroh et al. [46] employed robot manipulator to move the laser head along the 3-D weld path. In this work transparent covers were welded to absorbing housings. The strength of the joints was examined by conducting burst pressure and leakage tests. Experiments were repeated for several different materials. In general, this technique demonstrated the feasibility of forming strong welds.

2.4.2. *Process Modeling*

Traditionally, engineers conduct experiments to find optimal process parameters. However, computer simulation of the heat conduction during laser welding can help to reduce the amount of experimental work. Researchers have presented a number of finite element models of quasi-simultaneous and contour laser transmission welding. One can note that the models become more detailed as the computers and FEM software have developed during the recent years. It allows a more precise estimation of heat distribution within the specimen.

One of the earliest thermal models was presented by R. Prabhakaran [35]. He developed a simplified one-dimensional finite difference model of heat distribution during contour welding of unreinforced nylon 6. Equations of the model were solved using Excel solver. The model assumes one-dimensional heat conduction along the laser beam direction. Heat loss due to convection between the parts and the surrounding air is
neglected. The power intensity distribution within the laser beam cross section was assumed to be uniform. The absorption coefficient, thermal conductivity, and density of the material were set to be temperature independent. The absorption coefficient in the transparent part was determined experimentally. For the black part, it was fitted based on the available experimental observations of the HAZ thickness. The model allowed one to estimate the minimum line energy needed to achieve the melting temperature at the joint interface. The model showed that, even at constant line energy, the maximum temperature depended on the motion speed. Welding at lower beam power and motion speed provides more time for heat dissipation, which results in a lower temperature at the joint interface.

Another interesting observation in this work related to the temperature predicted at the incident surface of the transparent part. Even though the absorption coefficient of the transparent part was relatively low, its surface was predicted to reach the melting temperature in less than one second when exposed to the laser beam. Therefore, this factor may be a limitation when selecting the process parameters.

Potente et al. [47] developed a 2-D finite element model to simulate simultaneous butt welding of polymers. Physical properties of nylon 6 were used for the primary calculations. The model, created using ABAQUS© 6.3 program, predicted temperature and polymer flow profiles. The plane of the model represented the sectioned view of the parts, located perpendicularly to the weld path. The model accounted for the heat loss from the surface of the parts to the surrounding air due to radiation and convection. Heating by the laser beam was modeled as an internal heat source in the black part. Power intensity of this heat source through the depth of the black part was described by
the Lambert-Bouger law. The power intensity distribution across a typical laser beam is frequently described by the Gaussian distribution. In this model, the Gaussian distribution was replaced by two power intensity gradients, higher intensity in the center, and lower intensity closer to the perimeter. Heat absorption in the transparent part was neglected. The model predicted the joining displacement as a function of time for a constant joining pressure. The predicted temperature profiles showed that the highest temperature was achieved not at the joint interface, but slightly below the black part surface.

Huang et al. [48] employed SIMPLER® software to create the 3-D model of heat conduction during contour laser welding of the transparent 30%wt glass-fiber-reinforced polypropylene to the black Santoprene. The model assumed a Gaussian power intensity distribution of the laser beam. The absorption of the laser energy was presented as an internal heat source in the black part. It was assumed that 90% of the energy is absorbed in the uppermost element of the black part. Remaining energy was assumed to be absorbed within a thin (0.019 mm) layer. The model had rectangular mesh with the finest node spacing along the beam direction. The thermal conductivities and the specific heat capacities of the modeled materials were set to be constant and temperature-independent. Latent heat during phase transformation was neglected. All external surfaces of the model were insulated. The heat absorption in the transparent part was neglected similar to [47]. Similar to observations in [35], the temperature profile and the maximum achieved temperature were found to depend on the motion speed, even while the line energy was kept constant.

Mayboudi et al. [49, 50, 51, 52] developed a number of FEM models of a contour laser transmission welding. In these works, the authors gradually increased complexity of
the models, while trying to improve the accuracy of thermal distribution. The most recent work [52] represents a 3-D, transient, thermal finite element model of a contour laser transmission welding for a lap-joint geometry. Physical properties of unreinforced nylon nylon 6 (Akulon FD223D) were used.

In this work, the laser power, absorbed by the black part, was modeled as an internal heat source. As the beam propagated in the absorbent part, its power intensity decreased according to the Bouger-Lambert law. The model also accounted for the heat absorption in the transparent part. The 2-D power intensity profile of the beams cross-section was modeled using previous experimental studies conducted by the authors [42]. The model assumed linear beam scattering (increase in beam width) on its way through the transparent part. For the black part, the same scattered power profile was applied through its thickness. Heat convection to the environment was allowed from the external surfaces of the model.

The thermal distribution within the model allowed one to predict the dimensions of the heat affected zone. The area where temperature exceeded melting point was considered molten. The model was validated by comparing the weld width, predicted by the model, with the data obtained experimentally under the same process parameters. It appeared that the real weld widths were somewhat greater than those predicted by the model. The authors suggested that it might be due to insufficient joint pressure used in the experiments. This is one of the most detailed models presented up to date; however, complexity of the model resulted in relatively long solution times (up to 36 hours for a single run).
The models discussed above focused on specific types of LTW (either contour or simultaneous). Wilke et al. [53] developed a model which allowed one to simulate contour, simultaneous, and quasi-simultaneous welding processes. However, in this publication, the authors use this model to analyze and compare process parameters of simultaneous and quasi-simultaneous variants. For these cases, the entire joint interface is molten simultaneously which allows meltdown. Therefore, the model considered not only thermal conduction, but also displacement of the weld interface due to melt flow and applied weld pressure. The modeled specimens were in the shape of two rectangular bars brought together. The heat conduction was considered only in the plane normal to the laser beam travel direction. Heat loss due to convection and radiation was allowed from the side surfaces of the specimens. Similar to the previously mentioned works, the model assumed an exponential reduction of the power intensity in the depth of the absorbent part according to the Lambert-Beer law. While the paper's authors believed that the absorption coefficient is a temperature-depentand parameter, in this model it was approximated as an average constant value. The power intensity profile of the beam passing through the transparent part was determined experimentally. It appeared to be close to a Gaussian distribution. In order to simplify the model and reduce computation time, the power intensity profile was transformed into a laser beam of an equivalent length but with constant power intensity in the direction of scanning motion. The model was created using ABAQUS 6.5 FEM program. It was solved using physical properties of unreinforced nylon 6 (Durethan B30S).

The calculations were performed for varying frequency, scan length, weld pressure and power. The simulation results demonstrated that, in quasi-simultaneous
welding, it is impossible to increase an average heating rate by increasing the scan frequency, if the beam power and the scan length are held constant. In this situation, higher frequency results in lower temperature increase for each pass of the beam. In other words, at a higher velocity, one pass of the laser beam delivers less energy per unit length of the weld path. On the other hand, the total number of passes proportionally increases. As a result, the total amount of energy delivered to the weld line during a particular period of time, remains the same regardless of frequency. As can be seen in Figure 2.11, the variation of the scan frequency only changes the magnitude of temperature variation, while the average heating rate remains constant.

![Figure 2.11. Temperature development as a function of time for different scanning frequencies and three different correction factors W (moving laser beam (P = 250 W)). [53]](image)

In case of simultaneous welding, there is a continuous heat flow into the joint interface. On the other hand, in quasi-simultaneous welding, the weld line loses heat during intervals between passes of the laser beam. As a result, quasi-simultaneous
welding requires higher beam power in order to keep the same heating rate. The authors introduced a correction coefficient which allows a correlation between simultaneous and quasi-simultaneous welding. This coefficient accounts for the difference of the laser power required to achieve the same heating rate for both methods.

The model was solved for the absorbing part containing 0.1\%wt of carbon black. This is a relatively low concentration [20]. Therefore, a significant part of the heat was generated within the black part. Figure 2.12 shows the peak temperature located below the joint surface, slightly inside the absorbent part.

![Figure 2.12](image)

Figure 2.12. Calculated temperature and remaining melt layer thickness as a function of heating time (material PA6, 0.1 wt-% carbon black, $P = 250$ W; $K_{eff} = 3$ mm$^{-1}$, pressure 1 MPa, scanning speed 8 mm/s, $f = 94.1$ Hz; $L_\phi = 1$ %). [53]
2.5. Reflectivity of a Mirror

2.5.1. Material Reflectivity Properties

In this work, a conical mirror is utilized to redirect the laser beam energy onto the inner surface of a nylon tube. When selecting the material for the mirror or its coating, it is necessary to consider the material's reflectivity. When electromagnetic waves reflect from a surface, part of the incident power is lost due to energy absorption. Moreover, when there are several reflective surfaces in the optical system, such as mirrors and lenses, the resulting power loss can be significant. Thus, it is essential that material for the mirror (or its coating) should possess as high a reflectivity as possible.

Material reflectivity normally depends on the radiation wavelength. The material which has acceptable reflective characteristics for one laser may be unacceptable for another laser with a different wavelength. For example, a mirror made out of stainless steel can be acceptable for a CO\textsubscript{2} laser. At 10 \textmu m, the stainless steel has about 90% reflectivity. At the same time, at a high-power diode laser wavelength of 940 nm, the stainless steel mirror has only about 65% reflectivity [54].

In general, gold, silver, copper, and aluminum demonstrate the highest reflectivity in the wide range of wavelengths, and can be recommended as mirror coating materials. However, for wavelengths below 500 – 600 nm, reflectivity of these metals (except for aluminum) decreases significantly. Aluminum possesses reflectivity above 90% in the range from 200 nm to 850 nm. Lasers that are commonly used for laser welding of polymers work at wavelengths from 808 to 1050 nm. In this range, silver and gold demonstrate reflectivity up to 98% [55, 56].
2.5.2. *Influence of the Incident Angle*

It must be noted that the reflectivity figures reported in the previous section (and normally found in references) are measured for a beam normal to the surface (i.e., with the incident angle of zero). The reflectivity normally increases as the beam is deflected from the direction perpendicular to the surface and reaches 100% when the beam is parallel to the surface (i.e., at 90 degrees incident angle).

Reflectivity is affected by the polarization of the electromagnetic waves. For the beam perpendicular to the surface, polarization does not affect the reflectivity. However, this is not the case for the non-zero incident angle. In non-polarized light, electromagnetic waves oscillate randomly in all directions transverse to the beam propagation direction. It is common to represent randomly polarized light by two components perpendicular to each other. The so called "p-polarized" light lies in the incident plane of the beam, while the s-polarized light is perpendicular to it (see Figure 2.13). While reflectivity of the s-polarized component gradually increases with deflection of the beam, reflectivity of the p-polarized component behaves differently. It gradually decreases with increasing of the angle of incidence and reaches its minimum at so called Brewster’s angle. After this point, reflectivity of p-polarized light sharply increases [55, 56].
Reflectance of the electromagnetic waves occurs on the boundary between two media. The Brewster’s angle depends on the refractive indices of these media. It is equal to:

\[ B = \arctan \left( \frac{n_2}{n_1} \right), \]  

[2 – 2]

where \( n_1 \) and \( n_2 \) are the refractive indices of the two media. For air, index of refraction is approximately equal to one. Therefore, for cases where the laser beam propagates in the air, the Brewster’s angle can be calculated as the arctangent of the mirror's material refractive index.
The complex index of refraction is a number composed with two components:

\[ n = n^l + ik, \]  \[2 - 3\]

where \( n^l \) is the refractive index, and \( ik \) is the absorptive index. For many non-metals \( ik \) is very small and can be neglected. However, for metals it can be even bigger than \( n^l \). The total refractive index of metals is a relatively large number. Thus, the Brewster’s angle of metals is usually higher than 80°.

The majority of lasers generate linearly polarized electromagnetic waves. Therefore, when designing optical systems with guiding mirrors, it is desirable to avoid situations, when angle of incidence of the laser beam is close to the Brewster’s angle of the mirrors material. If the direction of the polarization of the laser beam is coincident with its plane of incidence, and angle of incidence is close to the Brewster’s angle, then power loss in the reflected beam can be more than 50% for some metals and even close to zero for other materials [57, 58].

2.6. **Nylon**

The first Nylon (also known as polyamide) was produced before the Second World War by Wallace Carothers at DuPont Company. Nylon is a rigid crystalline polymer with very good mechanical performance. It possesses high strength, modulus, toughness, abrasive resistance, and fatigue resistance. Its low friction coefficient makes
Nylon suitable for use in gears, clutches, and other applications with mutual friction of the parts. Nylon has a good resistance to chemicals, including fuels and oils. The exception is a poor resistance to acids that cause hydrolysis. On the other hand, this can be used to recover a raw material in reprocessing of the nylon waste [8, 59].

Properties of different types of nylon vary significantly depending on their components and type of the polymerization process used to form a polymer. However, all of them contain amide (-CONH-) linkage in their backbone. The identification numbers of nylon corresponds to the number of carbon atoms in the single monomer used to produce the nylon. If two different monomers were used in the material, the nylon will be characterized by two numbers. These monomers can have equal or different number of carbon atoms. For example: Nylon 6/6 or Nylon 6/12.

The first polyamide was Nylon 6/6. It was synthesized by a condensation reaction between hexa-methylene diamine and adipic acid. When the first nylon was released and became well known, many researchers in different countries began active work in this field. A few years later, German scientist Schlack produced nylon 6 via a process of ring opening of caprolactam. In Germany it was presented under the trademark Perlon [60]. Many other types of nylon have been developed since that time. However, nylon 6/6 and nylon 6 remain the most popular and widespread grades in the world.

Initially nylon was developed in an attempt to find replacement for natural fibers. Its first commercial use was in tooth brushes. During the Second World War, nylon was utilized in production of synthetic fabrics and ropes. Due to the intensive air war, there was shortage of natural silk, which was replaced by fabrics made of nylon fibers. After
the end of the war, nylon became very popular in such civil applications as stockings, carpets, variety of synthetic fabrics, and many others.

Because of its good mechanical properties, nylon is widely employed in automotive industry and many other injection moulding applications. In addition to injection moulding, nylons are also processed by extrusion, blow moulding and rotational molding. Nylon has a low melt viscosity, which is good for injection moulding, but causes problems in extrusion and blow moulding. To increase viscosity of nylon in extrusion, it is common to use grades with higher molecular weight and to reduce temperature at the die exit [8].

The properties of different types of nylon vary significantly. Melting temperatures of nylons range from 180° to 300°C. Nylons with an unequal number of carbon atoms between the amide linkages have lower melting temperatures then those with even number of atoms in each segment. This happens because the nylons with an equal number of atoms have a better ability to pack into crystals. For example, nylon 6/6 has higher melting temperature then nylon 6/12.

The number of carbon atoms between amide linkages influences the strength and stiffness of the material. Smaller number of carbon atoms will provide higher strength, because of more polar groups per unit length along the back bone of the polymer. On the other hand, nylon with fewer carbon atoms between the amide linkages will absorb more moisture. Moisture, in turn, significantly affects properties of nylon. Dry polymer has glass transition temperature Tg at 50°C. However, absorbed moisture can reduce the Tg to 0°C. In this situation crystallization process can continue at room temperature, causing
post-moulding shrinkage. Moisture also decreases dielectric property of nylon, but improves its flexibility and toughness.

Another parameter that affects properties of nylon is the amount of crystallinity. To a large extent, it depends on the cooling rate of the moulded part – the slower the cooling rate, the higher the degree of crystallinity. Nylons with low crystallinity will absorb more moisture due to less compact arrangement of the molecules in the amorphous phase.

The size of crystals also increases with longer cooling time because the crystals have more time to grow. Special nucleating agents can be added to the material to decrease the size of crystals. It improves hardness and tensile yield strength of the material but decreases its ductility.

A variety of different additives can be utilized in order to improve nylon's properties. Strength and stiffness of the nylon can be significantly improved by adding glass or carbon reinforcement fibers. Sometimes mineral fillers can also be used for this purpose. Reinforced nylon’s mechanical performance often approaches that of metals, but at a lower cost. Rubber added to nylon will improve its ductility and impact resistance. Among other additives are light and heat stabilizers, colourants, and antistatic agents [8, 59, 60].
CHAPTER 3: CHARACTERIZATION OF A LASER BEAM REFLECTED FROM A CONICAL MIRROR

3.1. Distortion of the Laser Beam Reflected From a Conical Surface

3.1.1 Model Development

In this work, a conical mirror is used to redirect the laser beam onto a cylindrical surface of a tube. As a result, the shape of the laser beam cross-section incident upon the conical surface will be changed by the time it reaches the joining surface. The energy distribution over the joining surface can influence the weld quality and thus this distribution needs to be identified.

If we can find the location of every ray of the beam, then we can determinate the shape and the location of the complete reflected beam projected onto a vertical cylindrical wall of the tube. It is convenient to split this task into two steps: first, find the location of the projected ray point on the horizontal plane and second the height of the point where the ray hits the cylindrical surface.

Let us assume that the original beam has a rectangular profile, that the location of the beam with respect to the cone is known, and that the beam is collimated (all rays are parallel) and vertical (Figure 3.1).

Consider first finding the location in the horizontal plane. Knowing the location of the beam with respect to the cone, we can find the distances OB and AB for every point within the beam’s rectangle.
Given the distances OB and AB, we can calculate the horizontal position of this ray’s projection onto the wall of the cylinder by following two equations:

$$OD = \frac{R}{\sqrt{\left(\frac{AB}{OB}\right)^2 + 1}} \quad [3-1]$$

$$ED = \frac{R}{\sqrt{1 + \left(\frac{OB}{AB}\right)^2}} \quad [3-2]$$

Eqs [3-1] and [3-2] give the location on the horizontal plane of the projected point on the vertical cylindrical surface (OD and ED) in terms of AB and OB (i.e., the location of the incoming ray projected onto the horizontal surface) as well as the radius $R$ of the cylinder.
cylindrical surface. Projection of the points located at the perimeter of the incident beam, defines the magnitude of its divergence. From eqs [3-1] and [3-2], it can be seen that, in order to achieve minimal divergence of the beam, it is desired to have small thickness of the beam (distance AB on Figure 3.1 is a half of the beam thickness) and place the beam as far from the tip of the mirror as possible (distance OB).

For the vertical plane, we know the angles $a$ and $b$, and the height of the cone OO’. The height of the projected ray point (KE) can be calculated by summation of two distances:

$$KE = EL^i + KL^i$$

[3 – 3]

Note that $EL^i = LA$ and $LA$ can be obtained as follows:

$$LA = \tan(b) \cdot (R - \sqrt{AB^2 + OB^2})$$

[3 – 4]

The second distance in Eq [3-3], $KL^i$, can be calculated as:

$$KL^i = \tan(f) \cdot (R - \sqrt{AB^2 + OB^2})$$

[3 – 5]

In the following equations, the angle $f$ is found in terms of the known angle $b$.

$$e = f + d = 90^\circ - b; \; b = d$$

[3 – 6]

$$f = 90^\circ - b - d = 90^\circ - 2 \cdot b$$

[3 – 7]


$$KL^i = \tan(90^\circ - 2 \cdot b) \cdot (R - \sqrt{AB^2 + OB^2})$$

[3 – 8]

Note that $KL^i = 0$ for $b = 45^\circ$, $KL^i > 0$ for $0 < b < 45^\circ$, and $KL^i < 0$ for $45^\circ < b < 90^\circ$. From Eq. [3-3], the height of the projected ray point can be calculated by:

$$KE = (\tan(b) + \tan(90^\circ - 2 \cdot b)) \cdot (R - \sqrt{AB^2 + OB^2})$$

[3 – 9]
The magnitude of distortion depends on the radius of the mirror. The bigger the radius, the smaller the distortion of the beam. Also, the magnitude of distortion depends on the position of the beam on the mirror. Distortion is reduced, if the laser beam is placed closer to the perimeter of the mirror and the beam's longer dimension is oriented along the radial direction of the cone.

3.1.2 *Qualitative Comparison of Model to Experimental Data*

Figures 3.2 and 3.3 illustrate the worst-case example. In this example, the radius of the conical mirror is relatively small compared to the beam. The longer dimension of the beam cross-section is oriented across the radial direction of the cone, and the beam is placed closer to the tip of the cone. Figure 3.2 represents geometrically the predicted distortion of a rectangular beam reflected from a conical mirror to a cylindrical surface. The hatched rectangle in Figure 3.2 represents the horizontal-plane projection of the incident laser beam. Several points along the perimeter of the rectangle and at its corners were projected onto the surface of the cone and onto the cylindrical surface. These points were joined by lines and are shown in the figure. The results show that the degree of the reflected beam distortion can be significant, if the position of the beam with respect to the cone is not optimal.
Figure 3.2. General shape of a rectangular beam reflected from the conical mirror to the cylindrical surface for a worst-case condition example.

Figure 3.3. The mark made by the laser beam reflected from the conical mirror to the flat plaque clamped to the mirror rod. Worst case condition.

Figure 3.3 shows the experimentally obtained profile of the distorted beam. The laser beam was reflected from the conical mirror to a flat specimen clamped to the mirror rod (see Figures 3.10 and 3.11 in section 3.2). The specimen was made of the same black nylon 6 that was used for the welding tests. The mark on the specimen was made by a
single 0.010 sec laser pulse of 88 W. The distance from the center of the beam to the tip of the cone was 1 mm. The laser mark was photographed using an optical microscope (OLYMPUS BH2 – UMA) equipped with a video camera (SONY DXC–390). As the laser mark extended beyond the microscope’s field of view, it was photographed in parts and then these parts were put together using Adobe Photoshop 7.0.1 photo editor.

Comparison of the experimental beam profile with the theoretical prediction shows that their shapes look similar.

Figures 3.4 and 3.5 present respectively theoretical prediction and experimentally obtained profile of a good case example. Here, the beam’s longer dimension is oriented along the radial direction of the cone. The beam is placed close to the perimeter of the mirror. The experimental profile was obtained by applying 0.025 sec laser pulse of 42 W. The distance from the center of the beam to the tip of the cone was 2.2 mm. Because of the small distortion of the beam, the power concentration was high. It caused melting of the polymer on the surface of the specimen, which, in turn, resulted in uneven contour of the laser mark. The shape of the beam profile projected onto a flat surface (as in the above experiments) is slightly different than the shape which would be obtained on the cylindrical surface of a tube. However, this difference was considered to be relatively minor and it was technically easier to use flat specimens for this test. The figures show that in this case, distortion of the reflected beam can be considered small or even negligible.
Figure 3.4. The rectangular beam reflected from the conical mirror with the large radius. Optimal beam position.

Figure 3.5. The mark made by the laser beam reflected from the conical mirror to the flat plaque clamped to the mirror rod. Optimal position of the beam.
3.1.3 Quantitative Comparison of Model to Experimental Data

It is insightful to compare quantitatively the theoretical and experimental profiles assuming the beam has nominal dimensions of 0.7 mm x 1.4 mm [61]. Let us compare the horizontal lengths of the upper and lower edges of the reflected beam and the vertical dimension of the beam measured at the center. Here, it is necessary to note that in case of reflection to a flat surface, equations [3-1] and [3-2] change and look as follows:

$$OD = R$$  \[3-10\]

$$ED = \frac{AB}{BD} \cdot R$$  \[3-11\]

For the so-called “bad-case”, note that radius R combined of the radius of the mirror 3.55 mm and thickness of the tube wall 1 mm.

The horizontal length of the upper edge is:

$$2 \cdot ED = \frac{2 \cdot AB}{BO} \cdot R = \frac{2 \cdot \left(\frac{1.4}{2}\right)}{1 - \left(\frac{0.7}{2}\right)} \cdot (3.55 + 1) = 9.8\text{mm}$$

The horizontal length of the lower edge:

$$2 \cdot ED = \frac{2 \cdot \left(\frac{1.4}{2}\right)}{1 + \left(\frac{0.7}{2}\right)} \cdot (3.55 + 1) = 4.7\text{mm}$$
The vertical dimension is estimated using equation [3-9]:

\[
KE_1 - KE_2 = \left( \tan 45 \cdot \left( (3.55 + 1) - \sqrt{1 - \frac{0.7}{2}} \right) \right) - \left( \tan 45 \cdot \left( (3.55 + 1) - \sqrt{1 + \frac{0.7}{2}} \right) \right) = 0.7mm
\]

where KE_1 and KE_2 are the distances from the bottom of the mirror to the points at the top and at the bottom of the reflected beam profile.

For the so-call “good-case”, the horizontal length of the upper edge is:

\[
2 \cdot ED = \frac{2 \cdot AB}{BO} \cdot R = \frac{2 \cdot \left( \frac{0.7}{2} \right)}{\left( 2.2 - \frac{1.4}{2} \right)} \cdot (3.55 + 1) = 2.1mm
\]

The horizontal length of the lower edge:

\[
2 \cdot ED = \frac{2 \cdot \left( \frac{0.7}{2} \right)}{\left( 1 + \frac{1.4}{2} \right)} \cdot (3.55 + 1) = 1.9mm
\]

The vertical dimension:

\[
KE_1 - KE_2 = \left( \tan 45 \cdot \left( (3.55 + 1) - \sqrt{2.2 - \frac{1.4}{2}} \right) \right) - \left( \tan 45 \cdot \left( (3.55 + 1) - \sqrt{2.2 + \frac{1.4}{2}} \right) \right) = 1.4mm
\]

Theoretically estimated dimensions of the beam are plotted over the experimentally obtained photos (see Figures 3.3 and 3.5). The comparison demonstrated a good agreement between theoretical and experimental height of the beam. At the same time, theoretically predicted lengths of the diverged beam are longer than actual experimental lengths of the laser marks. The length of the upper edge of the “bad case”
did not fit into the Figure, and therefore is not shown. The reason for this disagreement is not clear. One of the probable reasons may be insufficient power intensity in the remote areas of the laser beam to mark the surface of the absorbent surface. Also, rays at the remote ends of the diverged laser beam hit the surface of the flat specimen at the angle different from normal. This might result in increased reflection of power reducing energy input in these areas. As a result, the material did not reach its melting temperature.
3.2. The Power Intensity Profile of the Laser Beam Reflected From the Conical Mirror

To be able to control the weld seam width, it is important to know the laser beam power profile density. The power density is unequally distributed throughout the beam cross section area. Usually, the power density has the highest value in the center of the cross section and gradually decreases towards its perimeter. At some power level, the perimeter areas of the laser beam have a too low power density and thus do not cause polymer melting. However, as the beam power increases the power density of the perimeter areas increases as well and consequently leads to increase in size of the weld seam.

Characterization of the power intensity distribution within the laser beam was previously done for the laser employed in this research [42]. However, after the laser beam has been reflected from the conical mirror, its shape and power intensity profile are distorted. The magnitude of this distortion depends on the radius of the mirror, the horizontal distance from the beam to the tip of the mirror, and the vertical position of the focal point of the beam. There is a large number of possible combinations of these parameters. For this work, it was decided to determine the beam power profile for position of the laser beam that was used for the welding tests. The focal point of the beam was placed on the surface of the mirror. The horizontal distance from the laser beam center to the tip of the conical mirror was 2.2 mm. The mirror was 7.1 mm in diameter, with 45 degree total cone angle.

The power profile was measured by two different techniques. First, it was characterized using the knife-edge technique [42]. In the second test, the black plaque was clamped to the mirror rod and irradiated by short laser pulses of varying power.
Characterization of the beam profile with the knife-edge technique

The basic idea of the method is to incrementally move a sharp linear edge across the laser beam, and measure the power in each position by a power meter. The measurements have been conducted from the point where the laser beam was completely blocked to the point where the whole beam was directed to the power meter. The normalized power distribution of the laser beam is given by [42]:

\[
\Psi_j = \frac{p_j}{\Delta y P}
\]  

[3 – 10]

where: \( p_j \) is the power reading difference between the two neighboring positions of the knife edge; \( \Delta y \) is the step size between two neighboring positions of the knife edge; \( P \) is the highest (total) measured power. The step size for the knife edge motion was 0.1 mm.

A special tool was made in order to measure the beam power profile. Figure 3.6 shows the schematic representation of the experimental set up while Figure 3.7 shows the photograph of the equipment. The mirror rod was fixed in the drill bit chuck, which in turn was mounted on the flat rectangular base. The COHERENT PowerMax PM10 power meter was mounted on the stationary cylindrical rod. The rod was inserted into the hole drilled through the support base. A Mitutoyo digital depth micrometer was clamped to the bottom side of the base in a way that its spindle was positioned exactly in front of the butt end of the rod. Constant contact between the spindle and the rod was ensured by gravity.
Figure 3.6. Schematic of the experimental setup for characterization of the power intensity profile of the laser beam reflected from the conical mirror with “knife edge” method.
The knife edge was attached to the power meter in a way that it was covering about one third of the sensors area, and the edge of the knife was positioned horizontally. Using the micrometer, the power meter was gradually moved in the vertical direction. Five measurements were taken at each position of the power meter and then averaged. The distance between the lens and the mirror was set to 82.5 mm, which is the focal distance of the laser. The distance along the laser beam from the mirror to the surface of the power
The diameter of the power meter sensor was 18 mm. Time of each measurement was 10 seconds. Power of the laser was set to 8 Watts.

Distortion of the laser beam reflected from the conical mirror mainly occurs in the horizontal plane. Theoretically, the beam should not be distorted in the vertical plane. However, it is likely there are minor distortions due to imperfections on the mirrors surface.

In this work the power intensity distribution was measured only in the vertical direction. Measurements in the horizontal direction would require complex and precise equipment that was not available. At the same time, power density distribution in the horizontal direction has much less influence on the weld seam width.

The measurements were conducted for two orientations of the laser beam with respect to the conical mirror. For the first case, the long dimension of the laser beam was parallel to the mirror radius and for the second case the long dimension of the beam was perpendicular to the mirror radius. Only the first case was used in welding of test specimens. However, characterization of the beam for both cases provides a better understanding of the power intensity distribution in the laser beam reflected from the mirror and allows one to compare results with power intensity distribution of the original undistorted beam [42].

The resulting beam profiles are presented in Figures 3.8 and 3.9. Figure 3.8 shows the power profile for the case, where the long dimension of the beam is oriented along the radius of the mirror (preferable orientation). Figure 3.9 correspond to the long dimension of the beam oriented across the radius of the mirror. To compare the original and the reflected beams, the power intensity profiles of the original beam were also included. The
profiles are presented in terms of the normalized power flux distribution (NPFD). They show the power intensity distribution along the appropriate dimension of the beam regardless of the total laser power. In other words, these profiles are normalized to give integral of one under the curve.

These profiles were measured at 84.5 mm working distance. This distance is approximately equal to the sum of the focal distance from the lens to the mirror and the distance from the mirror to the knife edge. The profiles of the undistorted beam were kindly provided by Mr. Mingliang Chen, the coauthor of [42]. As it was theoretically expected, the power intensity profile of the reflected beam does not significantly differ from the profile of the original beam in the vertical direction.
Figure 3.8. The power intensity profile of the laser beam reflected from the conical mirror. The long dimension of the beam is positioned along the radial direction. The dashed line represents the power intensity profile along the long dimension of the original beam and measured at the distance of 84.5 mm.

Figure 3.9. The power intensity profile of the laser beam reflected from the conical mirror. The long dimension of the beam is positioned across the radial direction. The dashed line represents the power intensity profile along the short dimension of the original beam and measured at the distance of 84.5 mm.
In this test the power profile of the beam was determined by superimposing the contours of the marks left by the laser pulses on the black specimen. The concept behind this approach is that leaving a visible mark on the black specimen requires certain threshold amount of laser energy. By starting at low powers and then progressively increasing the power for the same short laser pulse duration, the boundary contour of the laser beam spot where this threshold is achieved is expanded, thus providing an indication of the laser beam power intensity profile at the point where the beam is projected onto the specimen surface.

Figure 3.10 shows the schematic of the experimental setup. A photo of the setup is shown in Figure 3.11. A flat black specimen plaque was attached to the mirror rod. In order to approximate the conditions of the welding tests, a piece of tube was put onto the mirror rod. This insured the same distance between the mirror and the surface of the black specimen as it was in the welding tests.

To match exactly what happens during the tube welding, it would be required to irradiate the internal surface of the hole instead of a flat plaque. By using a flat plaque instead of a curved cylindrical surface of the hole, the beam profiles are expected to be slightly different. However, it would have been much more complex to obtain flat images of the laser mark left within the hole. At the same time, at small deflection angles, the difference between projections on the flat and cylindrical surfaces is expected to be negligible.
The laser beam was positioned in a way that its long dimension was parallel to the radius of the mirror. The specimen was irradiated by short laser pulses of progressively increasing power. Duration of the pulses was 25 msec. The short duration of the pulse was to minimize influence of the heat conduction on the size and shape of the mark left by the laser beam. The power of the pulses was increased from 4 to 88 Watts. After each pulse, the specimen was shifted in order to expose an unmarked area.
Figure 3.11. Experimental setup for two-dimensional characterization of the power intensity profile of the laser beam reflected from the conical mirror.

The tests were accomplished for two vertical positions of the beam: (1) the focal point of the beam focused on the surface of the mirror, and (2) the focal point lowered 3 mm below the mirror's surface. The second case was tested in order to observe the influence of the vertical position of the focal point on the convergence of the reflected beam.

The marks of the laser beam left on the specimen (see Figure 3.5) were photographed by means of the OLYMPUS BH2-UMA microscope equipped with the SONY DXC-390 3CCD video camera. Then, in the Adobe Photoshop 7.0.1 photo editor, profiles of the laser marks were superimposed in a way that smaller profile was put on top of the bigger one. After that, point coordinates of the superimposed profiles were transferred to the Microsoft Excel using the ImageJ 1.40g program. The resulting beam profiles are presented in Figures 3.12 and 3.14.
Comparing Figures 3.12 and 3.14 shows that placing the focal point of the beam away from the surface of the mirror does not improve the power profile of the reflected beam. Moreover, it leads to distortion of the power intensity profile. Note that while the beam in Figure 3.12 appears to be larger in the horizontal dimension, the area on the left side of the power profile represents a zone of very low power intensity. This characteristic of the beam power distribution was also observed in the measurements carried out in [42] for this system. The low-intensity area appears only at high powers and these powers are much higher than those used in the experiments. The effect can be observed in the image of the laser mark at 88 W shown in Figure 3.13.

For example, let us compare the contours for 13W in Figures 3.12 and 3.14. (This is the fourth contour, counting from the innermost one and 13W is close to the power range used in the experiments.) The contour in Figure 3.12 is about 0.86 x 1.46 mm whereas the corresponding one in Figure 3.14 is 1.70 x 1.32 mm. Also, the image of the laser mark in Figure 3.15 shows the distortion of the laser beam shape. It can be concluded that if a defocused beam hits the mirror surface, then the reflected beam would also be defocused. Thus, the optimal distance between the laser lens and the surface of the mirror is equal to the focal distance of the laser beam. This working distance was used in welding tests in this work.
Figure 3.12. Power intensity profile of the laser beam reflected from the conical mirror. The focal point of the beam is projected on the surface of the mirror.

Figure 3.13. Mark on black specimen made by laser beam reflected from the conical mirror for 88 W power. The focal point of the beam is projected on the surface of the mirror.
Figure 3.14. Power intensity profile of the laser beam reflected from the conical mirror. The focal point of the beam is lowered 3 mm below the surface of the mirror.

Figure 3.15. Mark on black specimen left by the laser beam reflected from the conical mirror for 23 W power. The focal point of the beam is lowered 3 mm below the surface of the mirror.
3.3. Effect of Laser Light Polarization on the Reflectivity

In laser welding it is important to know the actual amount of energy delivered to the specimens’ surface. The laser beam loses some power at the mirror. Thus, it is important to know the reflectivity coefficient of the mirror.

The laser light produced by the laser used in this research is linearly polarized. The direction of the polarization is fixed with respect to the laser head. Therefore, the amount of the laser power reflected from the oblique mirror will vary depending on the direction of the incidence plane of the beam, as described in Section 2.5. In order to evaluate the magnitude of this variation, the laser beam was reflected from a flat oblique mirror in eight different directions, while the reflected power was measured by the COHERENT PowerMax PM10 power meter. The schematic of the experimental setup is presented in Figures 3.16 and 3.17. The same experimental set up as the knife-edge beam profile characterization (Section 3.2) was used for this test. The knife edge was removed from the power meter and the conical mirror was replaced by the flat oblique mirror. The angle of inclination of the flat mirror was 45°. The flat mirror was used in order to minimize possible power losses caused by divergence of the laser beam reflected from the conical mirror. Since the direction of polarization of the beam is fixed, the experimental setup was rotated under the beam. The reflected power was measured five times in each position and then averaged. The reflectivity of the mirror was calculated as a ratio of the measured reflected power to the value of the power output of the laser (also measured by the same power meter).
Figure 3.16. A schematic of the reflectivity measurements.

Figure 3.17. Orientation of the incident plane with respect to the laser beam polarization.

Measurements were conducted with the gold-coated mirror and with the uncoated stainless steel mirror. Figure 3.18 shows that the stainless steel has much lower reflectivity in general. Average reflectivity for steel mirror was 64% compared with 91%
for the gold-coated mirror. Standard deviation values of the measured reflectivity were small and thus are not shown on the graph. Average value of standard deviation was approximately 0.002 for gold and 0.006 for stainless steel. The stainless steel mirror also showed a more significant drop in the reflectivity in the direction of p-polarization (see Section 2.5.2). For stainless steel the difference of reflectivity at p and s polarizations is approximately equal to 20 %, while for gold it is just about 6 %. However, it is necessary to account for this power loss while estimating the amount of power delivered to the specimen.

Figure 3.18. Reflectivity of the oblique mirror as a function of direction of the incident plane.
CHAPTER 4: EXPERIMENTAL

This chapter describes the equipment, procedure, and the results of experiments in which nylon tubes were welded to plates. These tests were conducted to study the influence of the laser power and angular speed on the strength of the joint. Section 4.1 gives information about shape of the specimens and materials used. Experimental setup and welding procedure are described in sections 4.2.1 and 4.2.2 respectively. Section 4.2.3 presents equipment and procedure used for the tensile tests of welded joints. Section 4.3 discusses results of the experiments.

4.1. Materials and Shape of the Specimens

The material used in this work was unreinforced nylon 6. The transparent tube was purchased from the McMaster-Carr Supply Company (product code 8359K16). The outside diameter of the tube is 9.5 mm; the inside diameter is 7.5 mm; and the wall thickness is 1 mm. The length of the tube, cut for each test, was approximately 50 mm. The 100 × 100 × 6 mm plaques were injection moulded on a 55-ton Engel injection moulder using black nylon 6 (Akulon® F223-D/BK223/55B supplied by the DSM Company). This unreinforced Nylon 6 contained approximately 0.2 weight % of carbon black. The plaques were cut into 40 mm × 40 mm square plates. At the center of each square, a 9.5 mm hole was drilled. To ensure tight contact between the tubes and the holes, the holes were made by one pass of the drill bit.
Figure 4.1. The test specimen for tube-to-plaque joining experiments.
4.2. Welding Equipment and Procedure

4.2.1. Welding Equipment

The laser used in this study was a Rofin Sinar DLx16, 160 W continuous-wave diode laser, with a focal distance of 82.5 mm. At this distance, the focal spot size of the laser is specified as $1.4 \times 0.7$ mm [61]. The laser is equipped with a CCD camera aligned along the laser beam axis.

The experimental setup is shown in Figures 4.2 and 4.3. The conical mirror was made out of a steel rod of 7.1 mm diameter. The angle of the mirror was $45^\circ$. The mirror surface was gold-coated to reduce reflective energy losses [55, 56]. The laser was positioned 82.5 mm above the mirror. The plate, tube, and conical mirror were rotated under the stationary laser using a fixture mounted on the shaft of the gear motor. The angular speed of the motor was regulated by a Leeson Speedmaster motor controller. The actual RPM of the tool was measured by SHIMPO DT-105 digital tachometer before each test.
Figure 4.2. Setup for tube-to-plaque joining experiments.

Figure 4.3. Reflection of the laser beam from the conical mirror.
4.2.2. *Welding Procedure*

The incident laser beam has an elongated elliptical profile [42]. The longer dimension of the beam was oriented along the radial direction of the mirror. This allowed the widest possible weld width to be made. For each welding test, the mirror rod was inserted into the tube; the tube was inserted into the black plaque, and attached to the fixture by two spring-loaded clamps. The fixture was then positioned under the laser head using an X-Y motion system and the CCD camera.

The welding parameters used in this study are presented in Table 4.1. Selection of the angular speed was limited by the maximum performance of the motor which is approximately 300 RPM. Within the given range, two angular speeds were selected so that one speed was double the other one. Another consideration was to make the angular speed such that a whole number of passes was completed per second. Thus, two angular speeds were chosen: 120 and 240 RPM. At each speed, three different powers were tested in the range from 8 to 23 W. This power range was determined by a series of preliminary welding tests. Power values above 23 W led to material degradation at the first pass of the beam. At the same time, at low powers, the cycle time needed to achieve a reasonably good weld was excessively long. The number of passes varied from 1 to 58.

Table 4.1. Welding parameters used for the tests.

<table>
<thead>
<tr>
<th>Angular Speed</th>
<th>Laser Power</th>
<th>Number of Passes</th>
</tr>
</thead>
<tbody>
<tr>
<td>240 RPM</td>
<td>8 W</td>
<td>23 W</td>
</tr>
<tr>
<td>120 RPM</td>
<td>8 W</td>
<td>12 W</td>
</tr>
<tr>
<td></td>
<td>16 W</td>
<td>16 W</td>
</tr>
</tbody>
</table>
4.2.3. *Assessment Method*

The strength of the welded specimens was evaluated by conducting tensile tests using an Instron® universal testing machine (UTM). The plaque was fixed to the base of the UTM (Figure 4.4). The tube was pulled upward at a speed of 5 mm/min. A cylindrical rod was placed inside the tube to facilitate gripping.

The specimens were tested until failure. The force at yield was normalized by the measured weld cross sectional area in order to calculate an apparent failure stress. To measure the cross sectional area, after the tensile test, the black specimens were cut in two across the hole centre. The weld widths were then measured by an optical microscope equipped with a camera, and then multiplied by the length of the hole circumference to obtain the cross-sectional areas (see Figure 4.5 and Figures 5.2 – 5.4 in chapter 5). Five specimens were tested for each welding condition and the average result reported.
Figure 4.4. Tensile test set up.

Figure 4.5. Weld width measurement.
4.3. Results and Discussion

Figure 4.6 shows three typical force-elongation curves from the tensile/shear test for three different welding conditions. Condition A shows typical results for an assembly made at a rotational speed of 120 RPM and a power of 16 W but after 1 rotation. Conditions B and C show similar results but for 4 and 10 rotations, respectively. Condition A shows a brittle failure. Under these welding conditions, the number of passes was not adequate to impart sufficient energy to the interface and allow enough heating and molecular diffusion to occur. Inspection of the fracture surface of welds made under these conditions showed that as the number of beam passes increased, the weld seam became wider and deeper (Figures 4.7 – 4.9).

Figure 4.6. Force-elongation curves from the tensile test (120 RPM, 16 W)
Figure 4.7. Fracture surface of the weak weld after one rotation. (120 RPM, 16 W)

Figure 4.8. Fracture surface of the strong weld after four rotations. (120 RPM, 16 W)
Condition B shows a ductile failure and a significantly higher elongation at break. This assembly was manufactured under near-ideal welding conditions in which the energy delivered to the interface was sufficient to cause melting and diffusion. Finally, at the condition C, the fracture surface of the weld resembles two stripes divided by a groove which appeared to be due to polymer degradation at the centre. In some cases, material along the edge of the weld line was joined without degradation. Upon testing, these two parallel welds did not fail at the same force and thus lead to a more erratic force-elongation curve.

Figures 4.10 to 4.14 show force and strength at failure for the tensile tests of tubes joined to plaques. The error bars in these figures represent one standard deviation. Five samples were tested for each welding condition. Figure 4.10 shows the force at failure as a function of the number of rotations for a rotational speed of 120 rpm and three different
laser powers. For each power level, the force-rotation graph can be divided into three stages. Initially, the force at failure is observed to increase sharply with the number of rotations. More passes correspond to more delivered energy and higher temperatures at the weld seam. This allows the nylon in both the tube and plate to melt and thus permits diffusion to occur. In the second stage, the force at break levels off. In the last stage, at an increasingly higher number of passes, the strength decreases as polymer degrades. This is consistent with the force-elongation data presented in Figure 4.6. The number of passes at which these transitions occur is dependent on the laser power. Lower power levels require more passes in order to deliver comparable energy to the weld interface.

It is insightful to examine the same force data that has been normalized by the measured weld area. The weld widths, from which the areas were calculated, are plotted in Figures 5.19-5.24, in Chapter 5. The resultant apparent weld strength as a function of the number of passes at a rotational speed of 120 RPM is shown in Figure 4.11. The same three regions are visible; however, the number of passes at each transition is different. Specifically, the onset of degradation appears to occur at a lower number of rotations for each power level.
Figure 4.10. Force at failure as a function of the number of rotations for 120 RPM.

Figure 4.11. Weld strength as a function of the number of rotations for 120 RPM.
Figures 4.12 and 4.13 show the force and apparent strength data for a rotational speed of 240 RPM. The phenomena observed in Figures 5.5 and 5.6 for the lower speed conditions are still visible for this higher rotational speed. Note also that the number of rotations at which the various transitional effects occur has been pushed to a higher number of rotations for the same power when compared to the results for 120 RPM. At constant beam power and twice the rotational speed, it takes approximately twice the number of beam passes in order to deliver the same total energy and thus achieve similar strength results.

Figure 4.12. Force at failure as a function of the number of rotations for 240 RPM.
A drop in the apparent strength in the above results is a clear indication of degradation. When only the force data are presented, as in Figures 4.10 and 4.12, the onset of this degradation is retarded slightly by the continued widening of the weld width. In other words, a drop in the weld strength is initially offset by an increase in the weld area. For this reason it is important to examine both raw force and normalized data.

A closer examination of this total delivered energy requires introduction of the total line energy parameter ($Q$):

$$Q = \frac{P \cdot n}{V} \quad [4 - 1]$$

where $P$ is the laser beam power, $n$ is the number of the beam passes, and $V$ is the linear speed of the laser beam. Linear speed is equal to the angular speed multiplied by the radius of the tube, which is constant in this work. With an increase of the speed of the
laser beam, the heating time per pass becomes shorter. This is then compensated by increasing the number of passes.

Figure 4.14 shows a plot of the apparent weld strength as a function of the total line energy for two speeds, two power levels and the entire range of passes presented in this study. As a first approximation, the data is collapsed and shows that 0.8-1.8 J/mm are required for optimal welding for specimen shapes and materials studied in this work. However, it is clear that there are some speed and power effects that merit further discussion.

The biggest effect is that of power. It is seen that higher power (regardless of speed) allows the maximum weld strengths to be achieved at lower total line energy levels. Higher power requires fewer passes to deliver the requisite energy. Fewer passes
corresponds to less total time and therefore less total energy loss to the surrounding polymer.

It should also be noted that the maximum weld strength achieved at higher beam power is approximately 20% less than that obtained at lower power. It is conjectured that higher power causes larger temperature fluctuations at each pass [53]. Therefore the thermal history of the material is not the same for the assemblies welded at different power levels. The incremental time that the polymer spends at these elevated temperatures during high power welding may cause some degradation and result in lower achievable weld strengths.

The effect of rotational speed is similar. At a constant power, it is observed that the higher rotational speed results in more energy required for maximum weld strength. Again, higher speed results in more passes and a longer cycle time. Some energy is lost in the extra time required for welding. Welds made at the higher speed are also observed to be stronger than those made at lower speed using the same power. Similar to arguments presented earlier, lower speeds are believed to cause larger temperature fluctuations during welding. Longer time spent at high temperatures may result in some molecular degradation at the weld.

Among the parameters used in this work, welding at 240 RPM and 8 W allowed to achieve the highest possible stress in the weld seam. However, achieving the maximum possible weld strength is frequently not the main goal. In many cases the maximum load that a joint can bear is more important. Ideally the only limitation for this load should be the strength of the base material. During tensile tests in the present work, a number of specimens, welded at conditions close to optimal, broke not in the weld seam
but in the wall of the tube just above the weld seam. At speed of 240 RPM at two welding conditions, 23 W and 6 passes of the beam, and 16 W and 10 passes of the beam, all five specimens broke in the tube wall. Among specimens welded at 120 RPM, 16 W and 4 passes of the beam, four out of five also broke in the wall of the tube. In all these cases the weld widths were larger than thickness of the tube wall and there was no degradation in the center of weld lines. Therefore, the only limitation for the strength of these joints was the strength of the base material of the tube.
5.1. Development of the Model

Computer modeling of the laser welding can help to estimate optimal process parameters. Spatial temperature distribution can provide a prediction of the weld width. It can also predict the onset of weld degradation. The finite element model for welding of the transparent nylon tube to the absorbent nylon plaque was created using the COMSOL Multiphysics® 3.3a program. The transient heat conduction and convection program module was used. The model was made in 2 D axi-symmetric mode. A schematic representation of the model is shown in Figure 5.1.

Figure 5.1. Schematic representation of the finite element model.
To reduce the complexity of computation, the model represents only part of the specimens in the vicinity of the heat affected zone. The radius of the tube and the thickness of the plaque were set equal to the dimensions of the specimens used for the welding tests (see section 4.1.).

Heat convection from the specimen to the ambient environment was allowed from the boundaries indicated by the green color in Figure 5.1. The convective heat transfer coefficient was assumed to be 5 W/K·m$^2$. The initial temperature of the specimens and the ambient temperature were set to 23°C.

The physical properties of black nylon 6 (Akulon® F223) were generously provided by Mr. Mingliang Chen [62], who used the same material in his own work. The specific heat capacity for the transparent part was measured by the author. Density, thermal conductivity, and heat capacity were defined as temperature-depandent variables. Expressions for density and thermal conductivity of the black nylon 6 were applied to both black and transparent specimens in the model. The specific heat capacity of the material was obtained by differential scanning calorimetry and then approximated as a series of linear functions over the temperature range (Figures 5.2 and 5.3). Table 5.1 shows values of linear approximations of the specific heat capacity for black and transparent parts. Thermal conductivity, applied to both parts, is presented in Table 5.2. Other parameters of the model are shown in Table 5.3.
Figure 5.2. Specific heat capacity of the absorbent part.

Figure 5.3. Specific heat capacity of the transparent part.
Table 5.1. Approximated variation of the specific heat capacity with temperature.

<table>
<thead>
<tr>
<th>Temperature, K°</th>
<th>Cp, J/(kg·K°)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transparent part</strong></td>
<td></td>
</tr>
<tr>
<td>302</td>
<td>2580</td>
</tr>
<tr>
<td>459</td>
<td>3982</td>
</tr>
<tr>
<td>474</td>
<td>5331</td>
</tr>
<tr>
<td>483</td>
<td>3250</td>
</tr>
<tr>
<td>573</td>
<td>3427</td>
</tr>
<tr>
<td><strong>Black part</strong></td>
<td></td>
</tr>
<tr>
<td>273</td>
<td>1206</td>
</tr>
<tr>
<td>463</td>
<td>2674</td>
</tr>
<tr>
<td>497</td>
<td>4895</td>
</tr>
<tr>
<td>510</td>
<td>2605</td>
</tr>
<tr>
<td>1070</td>
<td>2743</td>
</tr>
</tbody>
</table>

Table 5.2. Variation of thermal conductivity with temperature.

<table>
<thead>
<tr>
<th>Temperature, K°</th>
<th>k, W/(m·K°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>273</td>
<td>0.251</td>
</tr>
<tr>
<td>473</td>
<td>0.251</td>
</tr>
<tr>
<td>503</td>
<td>0.135</td>
</tr>
<tr>
<td>1073</td>
<td>0.135</td>
</tr>
</tbody>
</table>

Table 5.3. The parameters used in the model.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption coefficient of the plaque, mm⁻¹</td>
<td>10.4</td>
</tr>
<tr>
<td>Absorption coefficient of the tube, mm⁻¹</td>
<td>0</td>
</tr>
<tr>
<td>Melting temperature, °C</td>
<td>220</td>
</tr>
<tr>
<td>Time step used for all settings, except for (240 RPM, 14.5 sec., 10 W), s</td>
<td>0.001</td>
</tr>
<tr>
<td>Time step used for (240 RPM, 14.5 sec., 10 W run), s</td>
<td>0.0004</td>
</tr>
</tbody>
</table>

The moving laser beam is modeled as a time-varying (pulsing) heat source at the interface between the two parts. In the plane normal to the direction of motion of the laser beam the power intensity profile of the beam was measured using the knife edge technique (see section 3.2.2.). It was introduced into the model along the Z axis. To accomplish that, the total applied power was unequally distributed along the heat source.
area. The profile was approximated using 0.1-mm wide steps. Scattering of the beam in the transparent part was neglected due to its small thickness. It was assumed that, in the direction of motion of the laser beam, which is normal to the plane of the model, the power intensity distribution is uniform, and the beam is undistorted. Any redistribution of the power intensity of the laser beam along the weld path does not change the total amount of energy delivered to the weld line in one pass of the beam. Therefore, this assumption should not change noticeably the results of the modeling.

The length of the beam in the model \((L_b)\) was estimated as 1.5 mm, which is approximately equal to the average length of the distorted beam spot at the joint interface (see Figure 5.4). It was calculated in the following way:

\[
L_b = AC = 2 \cdot \left( \frac{FD}{OD} \cdot OB \right) \approx 1.5mm \quad [5 \text{ – 1}]
\]

Note that small variations of this length should not affect significantly the results of the modeling. If the length of the beam increases, its power density is decreased proportionally. However, the energy input per one pass of the beam remains the same.

Each pulse of the heat source corresponds to one pass of the laser beam. The duration of a pulse is equal to the time during which the laser beam passes through a point on the weld path:

\[
t_h = \frac{L_b}{w \cdot R} \quad [5 \text{ – 2}]
\]

where \(t_h\) is the heating time, \(L_b\) is the length of the beam, \(w\) is the angular speed of the beam, and \(R\) is the external radius of the tube.

Repeating passes of the laser beam are implemented by using the following logical condition:
\[-\frac{L_b}{4} \leq R \cdot \sin \left( \frac{w \cdot t}{2} \right) < +\frac{L_b}{4} \]  \[5-3\]

where \( t \) is time and the range from \(-L_b/4\) to \(+L_b/4\) is equal to half of the laser beam length. The heat was applied only at times when this condition was true. As the angle varies from 0 to \(2\pi\) radians, this function satisfies the given logical condition twice.

Figure 5.4. Estimation of the length of the distorted beam at the joint interface.
This would cause two heat pulses per one rotation. To account for this, the angular speed in the formula was divided by two. The laser beam length in the model was also divided by two in order to keep the heating time of one pulse unchanged.

The model assumes the Beer-Lambert law (equation 2-1) [6] for energy absorption in the black part.

The absorption coefficient of the black nylon, which was also provided by Mr. Mingliang Chen, is equal to:

\[
A = 51.9 \cdot CB \quad (\text{units of } [\text{mm} \%])^{-1}
\]  

[5 – 4]

where CB is the weight percent of the carbon black. In this work it is 0.2 wt%.

The absorption coefficient for the transparent part is unknown, and there was no opportunity to measure it. However, due to small wall thickness, its absorption coefficient was assumed to be zero. The power loss caused by reflection from the specimen surface was set to 5 % [6]. The model also accounts for the power loss at the mirror (see section 3.3). The reflectivity of the mirror was set to 0.87.

A free mesh with triangular element geometry was used for this model. The center of the mesh was located in the center of the applied heat source at the joint interface. The mesh was set to grow from its center to the perimeter. The growth rate coefficient was 1.06. A number of the model runs with fixed power, speed, and cycle time (240 RPM, 10 W, and 1 sec) were conducted to determine the optimal mesh size. The runs simulated four passes of the beam. The change of the maximum temperature achieved after the fourth pass was used as a criterion of the mesh size optimality. Figure 5.5 shows maximum temperature value as a function of mesh element size. Based on these results,
the minimum mesh element size was set to $0.8 \times 10^{-5}$ mm. The meshed model is shown on Figure 5.6.

Figure 5.5. Determining the optimal mesh element size.
Table 5.4 shows values of the speed, power, and cycle time used in the simulation. They are the same as those used in the welding tests (see section 4.2). The values of the laser power, used in the modeling, correspond to the actual laser power output measured by the power meter before the welding tests.

<table>
<thead>
<tr>
<th></th>
<th>8.05 W</th>
<th>11.9 W</th>
<th>15.8 W</th>
<th>23.1 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>240 RPM</td>
<td>14.5 sec</td>
<td>-</td>
<td>6.5 sec</td>
<td>4 sec</td>
</tr>
<tr>
<td>120 RPM</td>
<td>15 sec</td>
<td>8 sec</td>
<td>5 sec</td>
<td>-</td>
</tr>
</tbody>
</table>

5.2. Results and Discussion

Figures 5.7 – 5.16 show temperature as a function of time for a point located at the joint interface in the middle of the applied heat source. This point has the highest
temperature at the weld interface. Each peak of the oscillation curve corresponds to one pass of the laser beam. The interval between the peaks equals the period of mirror rotation. The temperature is rapidly rising while the beam passes through the point, and then drops down until the next pass of the beam. The temperature shows a rising trend over time.

Figures 5.7 and 5.8 demonstrate the influence of the laser power on the heating rate at a constant speed. As expected, a higher beam power caused faster temperature rise trend. At the higher power, each pass of the laser beam delivers more energy to the unit area. Consequently, the amplitude of the heating/cooling oscillations also increases.

Figures 5.9 and 5.10 show the influence of frequency on the temperature development. At a constant laser power and cycle time, the total energy input per unit area remains the same, regardless of frequency. Thus, the trend of the average heating rate also remains constant. However, at a lower angular speed, each pass of the laser beam delivers more energy to the surface, but the total number of passes is lower. Consequently, the amplitude of the heating/cooling oscillations is higher at lower speed. As a result, higher maximum temperature will be reached at lower speed within a given period of time. At higher speeds, it takes a longer time and higher total energy input to reach the melting temperature at the joint interface. These observations are similar to the modeling results presented by Wilke et al. [53]. Also, it can be noted that doubling the RPM in the model resulted in twice higher number of the temperature oscillations on the curve. This observation indicates that the model works properly.

Figures 5.11-5.16 show the influence of the cycle time on the temperature rise. In these figures, certain peaks, indicated by circles, correspond to the number of rotations
used in the actual welding tests. The circle color indicates the outcome observed in the welding test. A blue circle indicates that a cold weld resulted. From the simulation results it can be seen that, at this point, the temperature did not reach the melting point,
Figure 5.7. Predicted temperature development as a function of time at the point located at the joint interface in the middle of the applied heat source. Effect of power on the heating rate at 240 RPM.

Figure 5.8. Predicted temperature development as a function of time at the point, located at the joint interface in the middle of the applied heat source. Effect of power on the heating rate at 120 RPM.
Figure 5.9. Predicted temperature development as a function of time. Effect of frequency on the heating rate at 8 W.

Figure 5.10. Predicted temperature development as a function of time. Effect of frequency on the heating rate at 16 W.
and it can be assumed that a weld was not formed. For these experimental welding conditions, the specimens bonded slightly, and the force needed to break them apart was very low. Green circles indicate experimental welds that exhibited high strength with ductile failures. Comparison with the model data suggests that the temperature experienced by these welds exceeded 220°C, thus allowing diffusion and welding to occur, but did not go over 500°C. The red colored circles indicate that material degradation was visible at the weld interface of the experimental welds. The magnitude of visible degradation was shown by different grades of red color. Comparison with the model suggests that these welds were made under either extremely high temperatures or a combination of high temperatures and long times.

Figure 5.11. Predicted temperature development as a function of time at the point, located at the joint interface in the middle of the applied heat source. Angular speed is 240 RPM. Laser power is 8 W.
Figure 5.12. Predicted temperature development as a function of time at the point, located at the joint interface in the middle of the applied heat source. Angular speed is 240 RPM. Laser power is 16 W.

Figure 5.13. Predicted temperature development as a function of time at the point, located at the joint interface in the middle of the applied heat source. Angular speed is 240 RPM. Laser power is 23 W.
Figure 5.14. Predicted temperature development as a function of time at the point, located at the joint interface in the middle of the applied heat source. Angular speed is 120 RPM. Laser power is 8 W.

Figure 5.15. Predicted temperature development as a function of time at the point, located at the joint interface in the middle of the applied heat source. Angular speed is 120 RPM. Laser power is 12 W.
The model allows one to estimate a minimum number of beam passes needed to form a weld seam at a given speed and laser power. It also allows one to estimate the dimensions of the weld seam. The maximum temperature achieved at the last peak of the cycle determines the depth and the width of the melted zone. The details will be discussed in section 5.3.

In addition, it can be inferred from the figures that the onset of the material degradation depends not only on temperature, but also on the time the material spent at the elevated temperature. For example at 240 RPM and 8 W (Figure 5.11) the first bubbles of degradation appeared at a temperature below 350°C after 8 seconds of heating. At the same time, at 240 RPM and 23 W (Figure 5.13) the onset of degradation occurred at 600°C in less than 1.5 seconds.
5.3. *Estimation of the Weld Seam Width*

Weld width is an important parameter of the assembly. While the strength of the material might remain constant, the area of the weld seam determines the load that the joint can bear. In welding tubes to plaques, the length of the weld seam is constant. Therefore, only width variation defines the area of the weld line.

The dimensions of the weld seam depend on the dimensions of the melted zone. The largest size of the melted zone is reached at the last peak of the heating cycle. A profile of the maximum temperature reached at the joint interface plotted along the Z axis was used to determine the predicted weld width. It was assumed, that the length of the segment of the joint interface that reached or exceeded 220°C is the weld width. An example of the typical temperature profile is presented on Figure 5.17.

The maximum temperature, achieved at the joint interface is not the highest in the area of the heat affected zone. Figure 5.18 shows the temperature profile plotted for the same example through the center of the heat-affected zone in the radial direction. The figure shows that the peak of the temperature is located a few microns below the specimen’s surface. Similar temperature profiles were observed in previously published work [35, 53]. The temperature at the peak is more than 100°C higher than the maximum temperature at the joint interface. It suggests that the onset of degradation begins in the black part a few microns below the surface. It is possible that the initial onset of degradation might be invisible at the joint interface.
Figure 5.17. Temperature profile reached at the peak of the tenth pass of the beam at the joint interface at 240 RPM and 16 W.

Figure 5.18. The temperature profile, reached at the peak of the tenth pass of the beam at 240 RPM and 16 W. View along R axis.
Predicted weld widths were compared with the experimental data in Figures 5.19 – 5.24. The error bars in the figures represent one standard deviation of the experimental values. In order to visualize the magnitude of deviation between the simulated and the experimental data, the lengths of the specimen segments that reached the temperature of 200°C and 180°C are plotted on the same graphs. The Figures demonstrate a good agreement between the modeled widths and the widths measured on the test specimens. Based on these measurements, it is reasonable to assume that the time-temperature curves generated by the model approximate the weld conditions well. Note that the weld widths generated by the model are generally slightly smaller than the experimental results. This small disagreement in widths measurements may be due to a slight overestimation of energy lost due to reflection. In addition, due to the measuring limitations, this study neglected the possible minor scattering of the laser beam, which is likely to occur as the beam travels through the transparent specimen.
Figure 5.19. The weld width as a function of number of the beam passes. (240 RPM, 8 W)

Figure 5.20. The weld width as a function of number of the beam passes. (240 RPM, 16 W)
Figure 5.21. The weld width as a function of number of the beam passes. (240 RPM, 23 W)

Figure 5.22. The weld width as a function of number of the beam passes. (120 RPM, 8 W)
Figure 5.23. The weld width as a function of number of the beam passes. (120 RPM, 12 W)

Figure 5.24. The weld width as a function of number of the beam passes. (120 RPM, 16 W)
5.4. **Analytical Estimation of the Average Temperature at the Weld Interface**

Although the Finite Element Modeling allows a good approximation of the temperature development, the appropriate computers and software may not be always available. Model development and its tuning can take a long time. At the same time, a technique for a quick rough estimation of the temperature magnitude can be very useful for engineers. The Finite Element Model presented in this work offers such a technique. It is based on the use of the time-temperature curves generated by the Model and the following analytical expression for a heat flow in a semi-infinite body under a constant heat flux [63]:

\[
T = T_0 + \frac{2 \cdot q}{k} \left[ \sqrt{\frac{\alpha \cdot t}{\pi}} \cdot e^{-\frac{y^2}{4 \alpha t}} - \frac{y}{2} \operatorname{erfc} \left( \frac{y}{2 \sqrt{\alpha \cdot t}} \right) \right]
\]  

where \( T \) – temperature; \( T_0 \) – initial temperature; \( q \) – heat flux; \( \alpha \) – thermal diffusivity; \( k \) – conductivity; \( y \) – distance from the surface.

When modelling the welding of the two parts, the temperature at the joint interface is of the highest interest. At the interface, the distance \( y \) equals zero and the equation (5–5) can be simplified as follows:

\[
T = T_0 + \left( \frac{2 \cdot q}{k} \sqrt{\frac{\alpha}{\pi}} \right) \sqrt{t}
\]

The results of the Finite Element Modeling (FEM) were presented earlier in the form of the temperature as a function of time. However, they can also be presented as a function of the square root of time (Figure 5.25). Using this approach, the FEM results
can be easily correlated with an analytical formula. In Figure 5.25, a linear trend line was fitted to the data of the form

$$ T = 23^\circ C + 22.08 \sqrt{t}^\circ C s^{-0.5} $$

for a given laser power.

In order to make this analytical model applicable to other powers, one needs to adjust the coefficient of the square-root term to account for laser power. Let us designate this term as $K$. Values of the linear coefficient $K$ generated for the settings used in the model are presented in the Table 5.5.

![Figure 5.25. Temperature as a function of the square root of time for 240 RPM and 16 W.](image)
Table 5.5. Values of the coefficient $K$ for the settings used in the FEM.

<table>
<thead>
<tr>
<th></th>
<th>8 W</th>
<th>12 W</th>
<th>16 W</th>
<th>23 W</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>120 RPM</strong></td>
<td>91</td>
<td>156</td>
<td>226</td>
<td>-</td>
</tr>
<tr>
<td><strong>240 RPM</strong></td>
<td>91</td>
<td>-</td>
<td>221</td>
<td>351</td>
</tr>
</tbody>
</table>

Values of the linear coefficient $K$ were plotted as a function of the laser power for both speeds (Figures 5.26 and 5.27). Linear trend lines were calculated for these points to generate the expressions that allow one to determine the coefficient $K$ as a function of power for each speed.

The expressions generated for 120 and 240 RPM are almost the same. The difference in values is judged to be negligible. This confirms the assertion that the average heating rate does not depend on the frequency at a given power.

By substituting the expression for the coefficient $K$ in the equation (5 – 6), we can obtain a general expression that allows estimation of the average temperature at the joint interface for any laser beam power and for any point in time:

$$T = T_0 + \left[ \left(17 \degree C W^{-1}s^{-0.5}\right) \cdot P - \left(50 \degree C s^{-0.5}\right) \right] \cdot \sqrt{t}, \quad [5 – 7]$$

where $P$ is the beam power in watts. It is important to note, that this formula is suitable only for the material and the specimens shape used in this work. Under different conditions, a new FEM model would need to be created first. Then, the analytical expression can be easily adjusted in the way presented in this section. It also demonstrates the minimum beam power at which the average temperature would not increase. For the parameters used in this work, this minimum power is approximately equal to 3 W.
$y = 17.277x - 49.423$

Figure 5.26. Coefficient $K$ as a function of the beam power. 240 RPM.

$y = 17.423x - 49.722$

Figure 5.27. Coefficient $K$ as a function of the beam power. 120 RPM.
CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

This thesis has examined the process of tube-to-plate welding using a conical mirror and a quasi-simultaneous laser transmission welding method. A fixture for the welding tests was developed, parts were welded, and ability to make strong joints was demonstrated by mechanical testing. Finite element modelling of the temperature within the weld showed how the temperature varies over time. Model findings were supported by the weld width measurements and by correlation of the cold welds, good welds, and thermally degraded joints with the temperatures predicted by the model. Given below are several specific points summarizing the key findings of this thesis.

1. The fraction of the laser energy reflected from a mirror depends strongly on the material of the mirror. Gold, silver, copper and aluminum can be recommended as good materials for a mirror. At wavelengths close to 1000 nm reflectivity of these materials exceeds 90%.

2. The fraction of the reflected laser energy is also significantly affected by the direction of the laser beam polarization with respect to the incident plane. When polarization of the beam is coincident with the incident plane or close to it, reflection will drop near the Brewster’s angle. A circular polarizer can be used to convert linearly polarized light into a circularly polarized one to avoid the dependence on the direction.
3. The magnitude of distortion of a laser beam, reflected from a conical mirror, depends on two factors: 1) ratio between the size of the beam's spot and radius of the mirror; 2) position of the beam relative to the tip of the cone. Smaller radius of the mirror will increase distortion. At a given size of the beam's spot and the radius of the mirror, the magnitude of distortion will be higher if the laser beam is placed closer to the tip of the mirror. Thus, to reduce distortion of the reflected laser beam, it is desirable to have the ratio between the size of the beam's spot and the radius of the mirror as small as possible and keep the laser beam as close to the perimeter of the mirror as possible.

4. The laser beam converges to its focal point, where its cross section reaches minimum value, and then diverges again. Placing the focal point of the beam below or above the mirrors surface will increase the magnitude of beam divergence. Therefore, projecting the focal point of the beam onto the surface of the mirror is recommended.

5. Welding at higher beam power requires less time and fewer number of passes to achieve maximum weld strength. Consequently, there is lower energy loss to the surrounding polymer. On the other hand, the maximum weld strength achievable at higher beam powers is lower then that obtained at lower powers. Varying the rotational speed has similar results. At a constant laser power, the maximum weld strength achievable at a low rotational speed is less than that obtained at high speed. Thus, welding at lower power or higher speed allows to obtain better weld strength at the expense of longer cycle time and higher energy consumption.
6. Results of the FE modeling demonstrate that at higher beam power or lower rotational speed each pass of the beam produces larger temperature fluctuation. It is believed that these larger fluctuations may cause some molecular degradation and result in lower weld strength.

7. The FE modeling showed that at constant power the average temperature trend will remain the same regardless of the rotational speed. However, at lower speed the temperature fluctuations are larger, which results in a higher maximum temperature-peak reached in a given cycle time.

8. Results of the thermal FE model were compared with the results of the welding tests. It was observed that at higher laser power (or lower rotational speed) visible onset of degradation occurs earlier. At the same time, at lower laser power (or higher rotational speed), degradation begins later, but at a noticeably lower temperature.

9. Comparison of the measured and modeled weld widths was used to validate the model and showed good agreement.

10. Combining the modeling results with the analytical expression for a heat flow in a semi-infinite body under a constant heat flux allowed derivation of an analytical expression to estimate an average temperature at the weld interface for any laser power and for any moment of time. Such an expression can be a valuable tool for selecting appropriate process parameters for the tube welding.
6.2. Recommendations and Future Work

In this thesis, feasibility of the tube-to-plate welding using a conical mirror was demonstrated by experiments with a single tube inserted into a small test specimen. To apply this methodology industrially, the process needs to be scaled up to allow welding of a high number of tubes while achieving short cycle times. Given below are several recommendations which can be further explored in order to develop this process on an industrial scale.

1. In this work the cylindrical rod with a conical mirror on its end was inserted inside a tube from the bottom. However, this solution may not be practical in a mass-production setting for relatively long tubes. An alternative solution can be the use of a transparent insert, made of polycarbonate or glass, and inserted into the tube from the top. A conical shape would be machined in this insert and coated with reflective material. Even though this mirror is expected to reflect high fraction of the applied energy, there may be a temperature rise in the material sufficient to damage the mirror. Future work can examine the line energy limitations for this type of mirror. Different materials of the transparent insert and reflective coating can also be tested.

2. If a laser beam of a circular ("doughnut-shaped") power profile could be obtained, it could be employed for simultaneous welding of tubes to plates. Instead of moving around a conical mirror, a laser beam can be projected onto
the tip of a mirror and reflected in all directions around the circle simultaneously. This is expected to reduce the welding time.

3. Instead of moving a specimen or a laser head to guide the laser beam along the weld path, it is possible to use galvanometer scanner equipped with telecentric F-theta scanning lens. It can be used for both simultaneous and quasi-simultaneous methods of welding.

4. The geometry of the joint studied in this work was relatively simple. In the future work, more complex joint geometries can be welded using a guiding mirror.
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**APPENDIX A**

Table A: Welding parameters and tensile test results for laser welding trial.

<table>
<thead>
<tr>
<th>Run #</th>
<th>Laser power, W</th>
<th>Angular speed, 1/min</th>
<th>Number of rotations</th>
<th>Average Force at yield (N) and standard deviation</th>
<th>Weld width (mm) and standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>23.1</td>
<td>240</td>
<td>2</td>
<td>808.5 (53)</td>
<td>1.09 (0.09)</td>
</tr>
<tr>
<td>1</td>
<td>23.1</td>
<td>240</td>
<td>4</td>
<td>840.2 (34)</td>
<td>1.21 (0.13)</td>
</tr>
<tr>
<td>3</td>
<td>23.1</td>
<td>240</td>
<td>6</td>
<td>853.1 (19)</td>
<td>1.26 (0.08)</td>
</tr>
<tr>
<td>4</td>
<td>23.1</td>
<td>240</td>
<td>8</td>
<td>845.3 (6)</td>
<td>1.47 (0.05)</td>
</tr>
<tr>
<td>5</td>
<td>23.1</td>
<td>240</td>
<td>12</td>
<td>676.9 (24)</td>
<td>1.56 (0.05)</td>
</tr>
<tr>
<td>6</td>
<td>23.1</td>
<td>240</td>
<td>16</td>
<td>539.3 (74)</td>
<td>1.75 (0.05)</td>
</tr>
<tr>
<td>7</td>
<td>15.8</td>
<td>240</td>
<td>2</td>
<td>145.8 (34)</td>
<td>1.11 (0.07)</td>
</tr>
<tr>
<td>8</td>
<td>15.8</td>
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