Chapter 5

5. Engineering Case Study in the Mexican Automotive Industry.

The objective of developing a case study in the Mexican Automotive Industry is to illustrate the process of technology transfer in real companies and to give some examples of the many advantages of TT and the difficulties encountered during the process. To illustrate the latter a laser welding process has been chosen.

5.1 Laser welding. The technology transferred.

Laser technology is being used on a wide scale in many industrial sectors particularly in developed countries. Its applications include many fields in industry such as, cutting, welding, drilling, surface heat treatment and hard facing. Laser beam technology as a high energy density, low energy input, and high processing speed would also improve quality and increase productivity.

5.1.1 A Brief History of Lasers.

The principle of the laser was first known in 1917, when physicist Albert Einstein described the theory of stimulated emission. However, it was not until the late 1940s that engineers began to utilize this principle for practical purposes. At the onset of the 1950's several different engineers were working towards the harnessing of energy using the principal of stimulated emission. At the University of Columbia was Charles Townes, at the

University of Maryland was Joseph Weber and at the Lebedev Laboratories in Moscow were Alexander Prokhorov and Nikolai G Basov.

At this stage the engineers were working towards the creation of what was termed a MASER (Microwave Amplification by the Stimulated Emission of Radiation), a device that amplified microwaves as opposed to light and soon found use in microwave communication systems. Townes and the other engineers believed it to be possible create an optical maser, a device for creating powerful beams of light using higher frequency energy to stimulate what was to become termed the lasing medium. Despite the pioneering work of Townes and Prokhorov it was left to Theodore Maiman in 1960, he invented the first Laser using a lasing medium of ruby that was stimulated using high energy flashes of intense light. Both Townes and Prokhorov were later awarded the Nobel Science Prize in 1964 for their endeavors.

The Laser was a remarkable technical breakthrough, but in its early years it was something of a technology without a purpose. It was not powerful enough for use in the beam weapons envisioned by the military, and its usefulness for transmitting information through the atmosphere was severely hampered by its inability to penetrate clouds and rain. Almost immediately, though, some began to find uses for it. Maiman and his colleagues developed some of the first Laser weapons sighting systems and other engineers developed powerful lasers for use in surgery and other areas where a moderately powerful, pinpoint source of heat was needed. Today, for example, Lasers are used in corrective eye surgery, providing a precise source of heat for cutting and cauterizing tissue. (Steen, 1998)

5.1.2 Laser Principles.

Everything we see within the universe is made up of an infinitesimally large number of combinations of the 100 different kinds of atoms. The arrangement and bonding of these atoms determines what material/object they constitute.

Atoms are constantly in motion. They continuously vibrate and move. Although all atoms are vibrating to a degree, atoms can be in a different state of excitation (i.e. they can have different levels of energy). If a large degree of energy is applied to an atom then it can leave what is referred to as ground-state energy level and go to an excited level. The level of excitation is proportional to the amount of energy applied.

A simple atom as shown in Figure 5.1 consists of a nucleus, which consists of protons and neutrons and what is often referred to as an electron cloud. For a simplistic interpretation of the atom model it is easy to think of the electrons within the electron cloud following discrete paths or orbits within the cloud. This analogy suits our purpose as we can then consider these orbits to be the different energy levels that make up the atom. If we add some form of energy to the atom we can assume that electrons from the lower-energy orbitals will transfer to the higher-energy orbitals at a greater distance from the nucleus, resulting in a higher level of excitation.

When electrons reach a higher-energy orbital they eventually seek to return to the ground-state energy level. Upon returning to ground-state energy level the excess energy is released in the form of a photon - a particle of light.

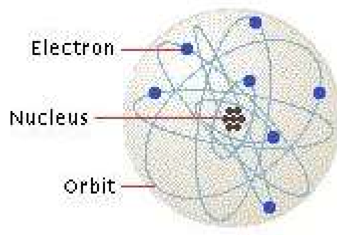

Figure 5.1 Simple Atom Model

Laser is an abbreviation for Light Amplification by Stimulated Emission of Radiation. A laser is a device that controls the way in which energized atoms release protons. There are many different types of laser available; all the different types of laser rely on the same basic elements. In all types of laser there is a lasing medium, which is pumped to get the electrons within the atoms to a higher-energy orbital i.e. to get the atoms excited. Typically, very intense flashes of light or an electrical discharge pump the lasing medium and create a large number of excited-state atoms. This creates a high degree of population inversion (the number of excited state atoms versus the number of atoms at ground-state energy level). At any stage the excited state atoms can release some of the energy and return to a lower-energy orbital. The energy released, which comes in the form of photons, has a very specific wavelength that is dependant on the level of energy or excitation of the electron when the photon is released. Two identical atoms with electrons in identical states will release photons with identical wavelengths. This forms the basis for laser light.

Laser light has the following properties:

- Laser light is monochromatic. It contains one specific wavelength of light, which as described earlier is determined by the amount of energy released when the electron drops to a lower-energy orbital.
- Laser light is coherent. Each proton moves in step with the other (i.e. all protons have wave fronts that move in unison).
- Laser light is highly directional (i.e. a laser beam is very tight and concentrated.

To ensure the aforementioned properties are apparent within the laser light the process briefly mentioned earlier, “stimulated emission” must occur.

Any photon that has been released by an atom, (which therefore has a wavelength, phase and energy level dependant on the difference between the excited atom state and the ground-state energy level) should encounter another atom that has another electron in the same excited state, therefore stimulated emission can occur. The first photon can stimulate or induce atomic emission so that the emitted photon vibrates with the same frequency and direction.

To produce laser light it is necessary to have a pair of mirrors at either end of the lasing medium. These mirrors are often known as an optical oscillator due to the process of oscillating photons between the two mirrored surfaces. The mirror positioned at one end of the optical oscillator is half-silvered; therefore it reflects some light and lets some light through. The light that is allowed to pass through is the light that is emitted from the laser. During this process photons are constantly stimulating other electrons to make the downward energy jump, hence causing the emission of more and more photons and an avalanche effect, leading to a large number of photons being emitted of the same wavelength and phase. (Hugel, 1988)

5.1.3. Types of Laser.

There are many different types of lasers. The laser medium can be solid, gas, liquid or semiconductor. Lasers are commonly designated by the type of lasing material employed:

- ***Solid-state lasers*** have lasing material distributed in a solid matrix (such as the ruby or neodymium: yttrium-aluminum garnet "YAG" lasers). The neodymium-YAG laser emits infrared light at 1,064 nanometers (nm). A nanometer is 1x10-9 meters.
- ***Gas lasers*** (helium and helium-neon, HeNe, are the most common gas lasers) have a primary output of visible red light. CO2 lasers emit energy in the far-infrared, and are used for cutting hard materials.
- ***Excimer lasers*** (the name is derived from the terms excited and dimers) use reactive gases, such as chlorine and fluorine, mixed with inert gases such as argon, krypton or xenon. When electrically stimulated, a pseudo molecule (dimer) is produced. When lased, the dimer produces light in the ultraviolet range.
- ***Dye lasers*** use complex organic dyes, such as rhodamine 6G, in liquid solution or suspension as lasing media. They are tunable over a broad range of wavelengths.
- ***Semiconductor lasers***, sometimes called diode lasers, are not solid-state lasers. These electronic devices are generally very small and use low power. They may be built into larger arrays, such as the writing source in some laser printers or CD players.

Table 5.1 Some typical lasers and their emission wavelengths.

Laser Type	**Wavelength (nm)**
Argon fluoride (UV)	193
Krypton fluoride (UV)	248
Nitrogen (UV)	337
Argon (blue)	488
Argon (green)	514
Helium neon (green)	543
Helium neon (red)	633
Rhodamine 6G dye (tunable)	570 – 650
Ruby (CrAlO3) (red)	694
Nd:YAG (NIR)	1064
Carbon dioxide (FIR)	10600

(The University of Liverpool, [8])

The output of a laser may be a continuous, constant-amplitude output (known as C.W. or constant wave), or pulsed, by using the techniques of Q-switching, Modelocking or Gain-switching.

Q-switching, sometimes known as giant pulse formation, is a technique by which a laser can be made to produce a pulsed output beam. The technique allows the production of light pulses with extremely high peak intensity, much higher than would be produced by the same laser if it were operating in a continuous wave (constant output) mode.

The basis of Q-switching is the use of a device which can alter the *Q factor* or *quality factor* of the optical resonator of the laser. The Q is a measure of how much light from the gain medium of the laser is fed back into itself by the resonator. In this technique, initially the laser medium is pumped while the Q-switch device prevents feedback of light into the gain medium (producing an optical resonator with low Q). This produces a population inversion, but laser operation cannot yet occur since there is no feedback from the resonator. Since the rate of stimulated emission is dependent on the amount of light entering the medium, the amount of energy stored in the gain medium will increase as the medium is pumped. Due to losses from spontaneous emission and other processes, after a certain time the stored energy will reach some maximum level; the medium is said to be *gain saturated*. At this point, the Q-switch device is changed from low to high Q, allowing feedback and the process of optical amplification by stimulated emission to begin. Because of the large amount of energy already stored in the gain medium, the intensity of light in the laser resonator builds up very quickly; this also causes the energy stored in the medium to be depleted almost as quickly. The net result is a short pulse of light output from the laser, known as a *giant pulse*, which may have very high peak intensity.

The Q-switch itself may be a mechanical device (e.g. a shutter, chopper wheel or spinning mirror placed inside the cavity), some form of modulator such as an acousto-optic or electro-optic device, or a passive saturable absorber material. A typical Q-switched laser (e.g. a ruby laser) can produce light pulses of around 2 nanoseconds duration with peak intensities over 25 MW/cm^2. Q-switched lasers are often used in applications which demand high laser intensities, such as dentistry and metal cutting.

Modelocking is a technique in optics by which a laser can be made to produce pulses of light of extremely short duration, on the order of picoseconds (10^{-12}s) or femtoseconds (10^{-15}s).The basis of the technique is to induce a fixed phase relationship between the modes of the laser's resonant cavity. The laser is then said to be *phase-locked* or *mode-locked*. Interference between these modes causes the laser light to be produced as a train of pulses. Depending on the properties of the laser, these pulses may be of extremely brief duration, as short as a few femtoseconds.

Gain-switching is a technique in optics by which a laser can be made to produce pulses of light of extremely short duration, of the order of picoseconds (10^{-12}s). In a semiconductor laser, the optical pulses are generated by injecting a large number of carriers (electrons) into the active region of the device, bringing the carrier density within that region from below to above the lasing threshold. When the carrier density exceeds that value, the ensuing stimulated emission results in the generation of a large number of photons. However, carriers are depleted as a result of stimulated emission faster than they are injected. So the carrier density eventually falls back to below lasing threshold which results in the termination of the optical output. If carrier injection has not ceased during this period, then the carrier density in the active region can increase once more and the process will repeat itself.

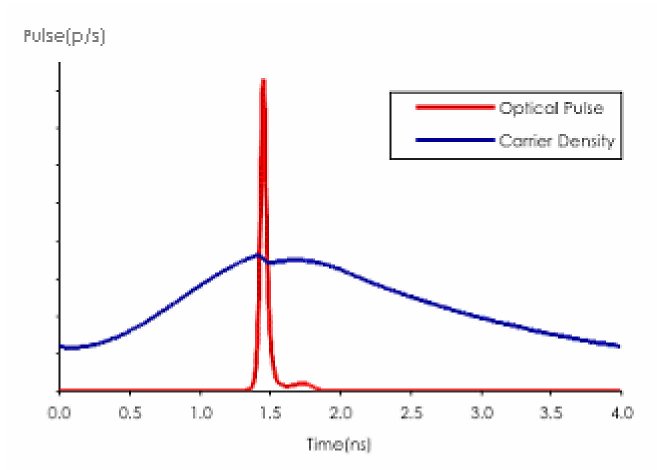

Figure 5.2 Typical gain switched pulse.

The figure 5.2 on the right shows a typical pulse generated by gain-switching with a sinusoidal injection current at 250 MHz producing a pulse of approximately 50 p/s (pulse per second). Notice the depletion in carrier density during the pulse, and its subsequent rise due to continued current injection giving rise to a smaller secondary pulse.

For solid-state and dye lasers, gain switching (or *synchronous pumping*) usually involves the laser gain medium being pumped with another pulsed laser. Since the pump pulses are of short duration, optical gain is only present in the laser for a short time, which results in a pulsed output.

The term gain-switching derives from the fact that the optical gain is negative when carrier density or pump intensity in the active region of the device is below threshold, and switches to a positive value when carrier density or the pump intensity exceeds the lasing threshold. (wordiq.com, [11])

5.1.3.1 Types of Lasers used for Welding Operations.

Generally, there are two types of lasers that are being used for welding operation: CO_2 and Nd: YAG. Both CO_2 and Nd: YAG lasers can be C.W. or Q-switched and operate in the infrared region of the electromagnetic radiation spectrum, invisible to the human eye. The Nd: YAG provides its primary light output in the near-infrared, at a wavelength of 1.06 microns. This wavelength is absorbed quite well by conductive materials, with a typical reflectance of about 20 to 30 percent for most metals. The near-infrared radiation permits the use of standard optics to achieve focused spot sizes as small as .001" in diameter.

On the other hand, the far infrared (10.6 micron) output wavelength of the CO_2 laser has an initial reflectance of about 80 percent to 90 percent for most metals and requires special optics to focus the beam to a minimum spot size of .003" to .004" diameter. However, whereas Nd:YAG lasers might produce power outputs up to 500 watts, CO_2 systems can easily supply 10,000 watts and greater.

As a result of these broad differences, the two laser types are usually employed for different applications. The powerful CO_2 lasers overcome the high reflectance by key holing, wherein the absorption approaches blackbody. The reflectivity of the metal is only important until the keyhole weld begins. Once the material's surface at the point of focus approaches its melting point, the reflectivity drops within microseconds. (Miller, [9])

High-power laser welding is characterized by keyhole welding. The laser energy then melts and evaporates the metal. The pressure of the vapor displaces the molten metal so that a cavity is formed - the keyhole. The keyhole supports the transfer of the laser energy into the metal and guides the laser beam deep into the material. Keyhole welding thus allows very deep and narrow welds to be obtained and is therefore also called deep penetration welding.

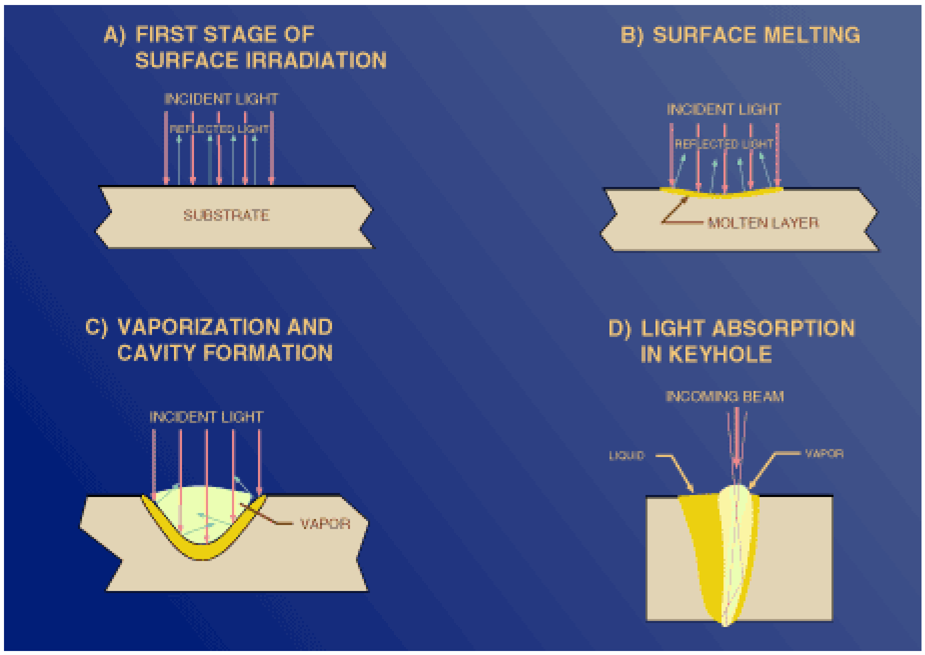

Figure 5.3 Stages of Keyhole Formation.

1.1.4 Laser Weldability

Weldability in its simplest sense is 'the ability of a material to be welded', in this case with a laser. The practical definition however goes much deeper and additionally demands that the weld be fit-for-purpose. This indicates that the weld produced has the suitable characteristics required for the application. For example a weld intended for use on a low grade container, will not be of sufficient quality to seal a nuclear fuel rod housing. In addition to this instance, Titanium alloys used in fatigue sensitive applications must not exhibit undercut as this detracts from fatigue life. Aluminum alloys are prone to excessive porosity; austenitic steels can become unacceptably hardened by martensite formation.

The American Welding Society defines Weldability as “the capacity of a material to be welded under the fabrication conditions imposed into a specific suitably designed structure to perform satisfactorily in the intended service”. It has been stated that all metals are weldable, but some are much difficult to weld than others. Taking this into consideration, it is very important that the welding process and welding procedures be considered when determining the Weldability of a particular metal. It is important to know all about the metals to be welded, the design of the welds and the weldment, and the service requirements including loadings and environments to which it will be exposed. The base metal or metal to be welded must be considered from all points of view. This includes its physical properties, mechanical properties, and chemical composition and structure.

To better determine Weldability, it becomes necessary to make several assumptions:

- The material to be welded is suitable for the intended use.
- The design of the weldment is suitable for its intended use.

Based on these assumptions, it is necessary then to study the weld joint. The desirable joint has uniform strength, ductility, notch toughness, fatigue strength, and corrosion resistance throughout the weld and adjacent material.

Most welds involve the use of heat and addition of a different metallurgical structure from the unaffected base metal. The specific case of laser welding can be with or without filler metal. Welds may also include defects such as voids, cracks, and entrapped materials. Two types of problems may occur:

- Problems of the weld metal deposit or heat-affected zone that occur in connection with or immediately following the welding operation, such as hot-cracking, heat-affected zone cracking, hydrogen-induced cracking, etc.
- Problems in the weld or adjacent to the weld that occur any time during service of the weldment. These can be any kind of defects that will reduce the efficiency of the weld joint under service conditions.

Hot cracking may result from any of the following factors: restraint, weld shape, excessive heat input, or material composition. Restraint is always present in any weld because as the weld solidifies it acquires strength but continues to cool and shrink. It is the degree of restraint that becomes critical. Restraint relates to the weld design, the weldment design and the thickness of the material being joined. Weld shape is also a function of weld design, weldment design and welding procedure. Welding procedure relates to the placement of welds or beads in the weld, the shape of the beads and the shape of the finished surface. The third factor is the metal composition. Segregation is important, however, since impurities such as sulfur and phosphorus tend to form low-melting-point films between solidifying grains of the metal. These impurities relate to weld joint detail and the welding process, since they affect the amount of dilution.

Hydrogen cracking is considered cold cracking since it occurs soon after the weld is completed, usually within 4 to 8 hours. It usually occurs in the HAZ. The four main factors that affect HAZ cracking are:

- The thickness of the base metal and the type of weld.
- The composition of the base metal.
- The welding process and filler metal type.
- Energy output and pre-heat temperatures.

The effects of these four factors are interrelated. The thickness of composition of the base metal is established by the design. The weld joint configuration, the welding process, the type of filler metal and the welding procedure all contribute to the severity of the factors that cause HAZ cracking. The input energy can be modified by the welding process; welding procedure and welding preheat temperature. These can also be changed to reduce the cooling rate.

All the factors above determine the type of microstructure that will occur in the HAZ. The two factors most important to Weldability are hardenability and susceptibility of the hardened structure to cracking. Hardenability is related to the cooling rate of metals. The faster cooling rate tends to produce higher hardness. The cooling rate depends on the mass of the metal, the welding process, the welding procedure and pre-heat temperatures. The welding process and procedure influence the energy input used to make the weld. The greater the energy input, the slower the cooling rate. In general, Weldability is very complex and all the welding factors interrelate. It is of vital importance for success of welds to give consideration to all these factors. (Cary, 1979)

Table 5.2 CO_2 vs. Nd: YAG Weldability for Various Materials.

(Source: www.lasers.org.uk)

Material	**CO_2**	**Nd:YAG**
Steel	XXX	XX
Al Alloys	X	XX
Cu Alloys	X	XX
Ni Alloys	XX	XX
Ti Alloys	XX	XXX
Zinc Alloys	X	XX
Gold/Silver	-	XXX

where	X	-Poor
	XX	-Average
	XXX	-Good

The table above shows the Weldability of common metallic elements and their alloys. Steel, Nickel Alloys and Titanium Alloys are easily welded with either a CO_2 or an Nd: YAG laser. Aluminum and Zirconium Alloys are easier to weld using Nd: YAG lasers. Highly reflective materials such as Copper, Gold and Silver pose a problem when welding is attempted using a CO_2 laser. This is due to the longer wavelength generated by the CO_2 laser being so effectively reflected due to the high reflectivity and low absorptivity of the surfaces. The shorter Nd: YAG wavelength is more easily absorbed by the aforementioned materials. (The University of Liverpool, [8]) Laser welding can be performed on a wide range of ferrous and non-ferrous alloys. Most steel alloys are very weldable either in the conduction or keyhole modes. The alloy composition and post-weld processing must be considered when selecting the welding parameters due to the high cooling rates associated with laser welding. High cooling rates can induce hardness, high yield strength, low ductility, or low toughness in the weld metal or in the HAZ of the weld. The degradation of properties is of special concern for high-alloyed steels where martensite may be formed in the weld metal or HAZ. Any coating on the steel may be a concern. The relatively low boiling point of zinc can make the laser weld unstable causing “blow holes” and porosity in the weld. This is a major problem for lap joints and less problem for butt welds. To prevent this problem in lap joints a gap may be established between the plates to allow the zinc vapors to escape. (ASDM, 2000)

5.1.4.1 Commonly found Laser Welding Defects.

Figure 5.4 illustrates a successful full penetration or keyhole weld. The relatively slim HAZ and the apparent absence of porosity are to be noted.

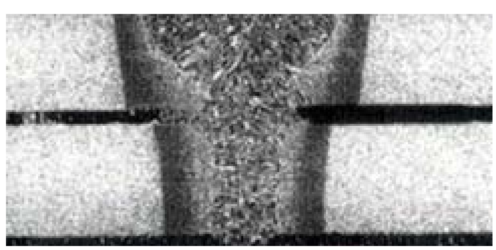

Figure 5.4 Successful weld.

Figure 5.5 is an instance of a laser spot weld failing due to fatigue. Fatigue failure is the cumulative effect that occurs when the work piece is subjected to constant repetitive stresses below the yield point of the weld or the work piece. To minimize the risk of fatigue failure it is necessary to minimize or remove the existence of sharp edges and cracks.

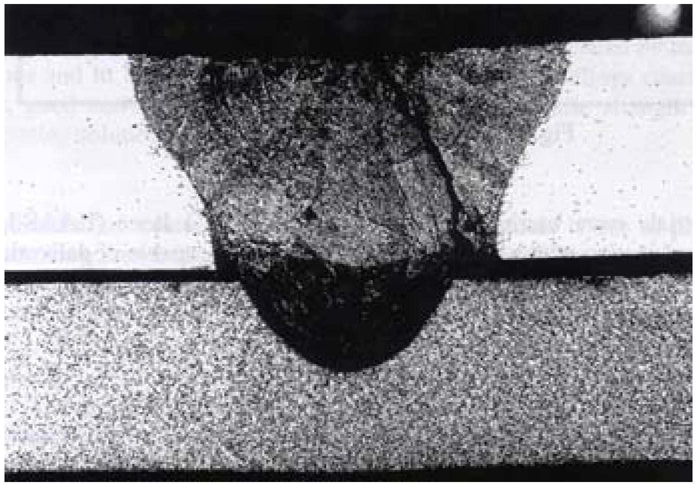

Figure 5.5 Fatigue Crack.

In figure 5.6 it can be seen that the weld displays porosity i.e. it has small pockets of unwanted gas trapped within the weld zone. If the weld exhibits excess porosity the weld can often suffer from brittleness. Porosity is most commonly caused by surface contamination prior to commencing welding. To minimize porosity within the weld effective pre-weld cleaning and the use of an inert shielding gas should reduce the likelihood of such an occurrence. It should be noted that minimal porosity up to 6% should not affect the strength of the weld and is therefore not a problem in most engineering applications.

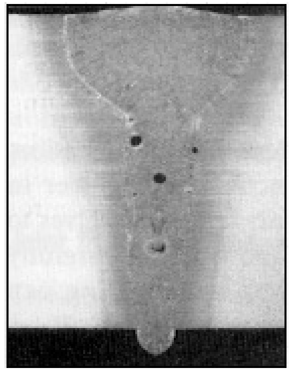

Figure5.6 Porous Weld.

The deformation shown in figure 5.7 was caused by different areas of the weld cooling at different rates, causing those areas that cool quicker to contract. Within thin specimens' plates such as the one illustrated buckling is the result, with the buckling direction and magnitude proportional to the stress through the depth. In the case of thicker plates that can restrict the buckling, residual stresses can form which can manifest themselves later by causing a reduction in fatigue life or crack propagation.

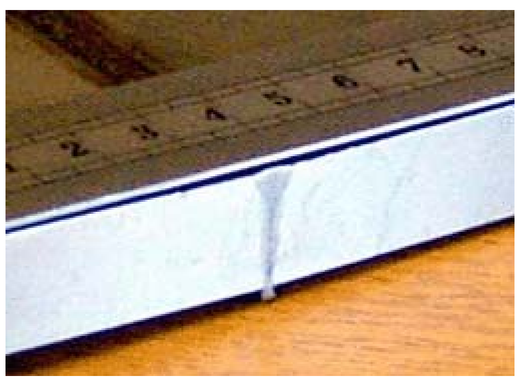

Figure 5.7 Residual Stresses.

The weld in figure 5.8 shows undercutting at both the top and bottom. This can be attributed to the two sample pieces that were to be welded together being too far apart from one another, preventing the melt pool filling the gap between the pieces.

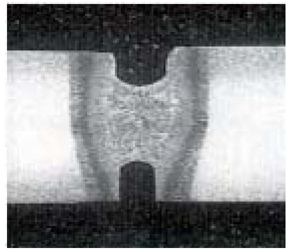

Figure 5.8 Undercut 1.

In figure 5.9, the micrograph shows a defective weld too wide to be welded in the horizontal position, the consequence of this being that due to the slow cooling gravity has exerted a vertical pull causing the solidified weld pool to undercut at the top and overfill at the bottom. Welding in the vertical plane can rectify this problem.

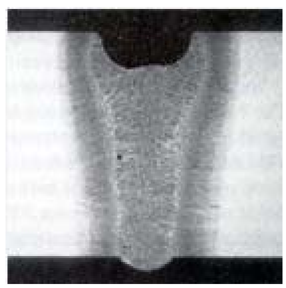

Figure 5.9 Undercut 2.

(The University of Liverpool, [8])

5.1.5 Laser Welding Considerations.

There are two different approaches to laser welding. One is the low-power method for relatively thin materials; and the other is the "brute force" high-power approach that generally involves key holing. In both cases, since filler material is rarely used, a tight fit up of the parts being welded is necessary. For butt and seam welds, the laser energy is applied to the junction of the materials, minimizing heat input and distortion and permitting high processing speeds. However, these butt joints must fit accurately, which often limits laser butt welding to circular parts which can be turned to close tolerances and press-fit together prior to welding.

For lap joints, the tolerances for seam alignment are somewhat looser. The width of the weld is the major consideration. The upper material forms most of the fusion zone so that a good laser-weldable material could be welded to less suitable material by putting the former material on top. (Miller, [9])

It is not as simple as just buying a given laser welding system or a complete automated or semi-automated welding station, at least not if you are to achieve the best possible yield and throughput. Indeed, it may not be possible to make the assemblies at all. The key to addressing these issues is applying the appropriate planning in the definition and implementation of the laser system. This planning will be exemplified with the case study and further analysis. The key process parameters for laser welding include laser power, weld speed and focus optics. All these parameters are interactive. For a given focusing optic and material thickness, and assuming that full-penetration welds are desired, the higher the power, the faster the weld speed. Selecting the appropriate focusing optics is essential for achieving optimal welding performance for each different application. The heat source provided by the laser beam is highly concentrated and most advantages offered by the laser welding process stem from this feature. These advantages include high productivity, low heat input/low distortion, deep penetration, repeatability and ease of automation.

As mentioned before, the welding energy is obtained by focusing the laser beam on a small diameter spot on the surface of the workpiece. Plasma generated by the metal vapors is formed at the point of interaction between the beam and the metal. Various techniques can be used to prevent or at least reduce the formation of plasma but these are not always easy to implement in practice. A way of limiting the formation of plasma is to use the suitable shielding gas. The shielding gas has three main roles:

- To protect the molten metal from oxidation.
- To minimize the effect of plasma, as the formation of plasma depends on the nature of the shielding gas.
- To minimize the effect of plasma by expelling it from the joint: plasma control.

Helium is the best gas for laser welding. Because of its high ionizing potential and its high heat conductivity it preserves the transparency of plasma and it does not cause any metallurgical problems. The performances of argon are not as good as those of helium. Owing its lower ionizing potential than that of helium, argon can result in absorbent plasma. Like helium, it does not cause any metallurgical problems. Nitrogen must be used with care as it can cause metallurgical problems with certain materials. Furthermore, it results in serious spattering which means that not only must the spatter be removed from the welded part but, also, there is a risk of damage the focusing optic. Carbon dioxide is not suitable as the laser beam has very high absorption rate which prevent much of the laser power from reaching the workpiece to be welded. (Air Liquide, [12])

5.1.6 Advantages of Laser Welding.

Many of the advantages offered by laser welding are in the actual manufacturing process, due to the reduction in throughput time. These include faster weld rate and the ease of automation of the process. In addition, the same welding station can be used for several laser processes, such as cutting, welding, drilling, recovery and surfacing.

The full potential of laser welding is frequently not realized for several reasons. In most cases, products are designed to be manufactured with more conventional welding methods, instead of laser welding. The advantages which laser welding offer the designer include:

- Minimal distortion compared with ordinary welding methods.
- Weld is narrow in relation to depth, and leaves a much smaller Heat Affected Zone (HAZ). This makes it possible to weld close to heat-sensitive components with no danger of damage.
- Laser welding gives consistent quality.
- A large number of different materials can be welded together.
- Most types of joints used in conventional welding can be used for laser welding. Further joint types, unique to laser welding, can also be used.
- Most materials can be welded together, in thickness down to thin foils, or bonded to form thicker components.
- Can be used in pone air.
- Can be transmitted over long distances with a minimal loss of power.

- No filler metals necessary.
- No secondary finishing necessary.

(EBTEC Corporation, [10])

A major advantage of laser welding is the ability to weld disparate metals together, which has previously been difficult to do. This has become possible thanks to the nature of the keyhole technique and the geometric shape of the weld. This means, for example, that expensive high alloy steel only needs to be used in locations where it is absolutely necessary. The most common problem in welding components of different thickness is to get the thicker component to melt without vaporizing the thinner component. Using laser welding, this is not a big problem, since it is possible to melt a thick component by using a relatively small amount of heat. (The University of Liverpool, [8])

Weld distortion of the work-piece is considerably lower with laser welding than with conventional welding methods. This reduces or eliminates the need for subsequent finishing. Laser welding can thus become the last manufacturing operation in many cases.

Table 5.3 Advantages of Laser Welding Compared to Other Processes.

Competing Process	**Advantages of Laser Welding**
Gas Metal Arc	Faster welding rates by an order of magnitude; low distortion; no filler metal required; single-pass two-side welding
Submerged Arc	Faster welding rates; low distortion; no flux or filler needed
Resistance Welding	Non-contact, eliminating any debris buildup; can reach otherwise inaccessible locations; faster welding rates
Electron Beam	Does not need to be performed in a vacuum; on-line processing; shorter cycles and higher uptimes; welds magnetic materials; does not require radiation shielding

5.2 Need of Laser Welding in the Automotive Industry.

Competition in an increasing global marketplace and the furious pace of technological advancement are having profound effects on the automotive industry. They are forcing manufacturers to develop their resources differently and change the way they transform raw material into finished products. The challenge to manufacturers has been to develop technology and operating strategies that complement one another so as to respond rapidly to changes in demand in any part of the world.

The European metallic welding equipment market for automotive applications is expected to expand against a backdrop of strong price pressures and intensifying competition. In this market-valued at $626.4 million in 2001 and projected to rise to $746.6 million in 2008-the fast-advancing arena of laser welding technology offers exciting opportunities for growth. Currently, metallic welding equipment manufacturers are grappling with rising competitiveness based on the twin demands for lower prices and enhanced product quality from end-users.

Falling prices have been a consequence of escalating competition and advances in manufacturing techniques. Also, with end-users increasingly clamoring for lower prices, leading players have been forced to pursue aggressive pricing policies. This presents a challenge for manufacturers to maintain profitability while adapting to declining prices. Price leadership remains important. Companies unable to compete on price will struggle to win business.

Competitiveness is also growing, on two parallel fronts. On the one hand, manufacturers of metallic welding equipment are contending with increasing usage of substitutes to welding, such as clinching, riveting, and gluing. On the other hand, opposing technologies within the field of welding equipment are competing with each other for market share and revenues.

The most prevalent example is laser welding, which is successfully competing in a growing number of markets due to its superior performance characteristics. This technology has been continually advancing over recent years, enabling improved performance and an expanded range of applications. High growth in this segment is expected to continue, to the detriment of rival welding technologies such as resistance welding.

In serving the automotive sector, innovation is seen as being critical in addressing end-user demands for increased product value and performance. Already, equipment quality is improving as manufacturers continue to develop innovative features aimed at increasing the value of their products. In turn, end-users are receiving more value for money than before. The growth in high-specification instruments and newer technologies such as mechanized equipment, weld sensors, software integration, welding simulation programs, and improved power sources has further underlined the importance of innovation.

The use of new metallic materials such as aluminum and magnesium alloys in the automotive industry is also creating new applications and market opportunities for metallic welding equipment. Increasing demand for sophisticated welding equipment that can produce quality results with these materials is growing, making it a key requirement for manufacturers to develop advanced technologies, or face the risk of losing market share.

In future years, ensuring global availability of products and services is likely to be a key challenge for equipment suppliers. In order to retain their competitive edge, manufacturers will also need to provide complete solution packages augmented by comprehensive before and after sales service. While there is good scope for advancement in the sales of welding equipment to the automotive sector, the pressure the industry faces means that all suppliers will have to ensure they focus on more effectively servicing user needs with a broad and affective range of cost effective technology.

5.3 Case Study.

In this case study, a major transnational company will be referred to, for it transferred the laser welding technology to its Mexican subsidiary. It is important to mention that this subsidiary did not decide to transfer this technology to their plant in Mexico on their own, it was a decision imposed by its headquarters.

5.3.1 Background.

Company “X” is a very popular and large vehicular firm within the assembly plant segment. Its headquarters are located in Germany. For proponents of laser welding of automotive structures, it is to be admired or a company that provokes tremendous jealousy. In Germany, “X” has been working with lasers on body-in-white applications since 1993, with the first application on a roof joint occurring in 1996. In 1997, three car models had laser welded roof joints. Then, as time went on, there were more applications and more cars added to the mix.

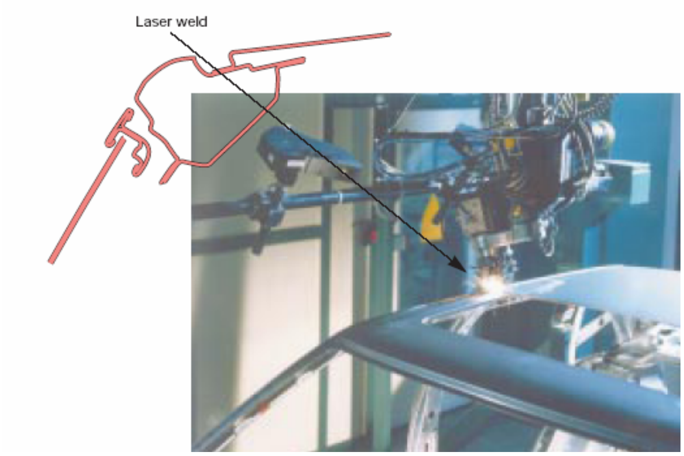

Figure 5.10 Typical joint geometry for roof laser welding. (Source: Larsson, 1999)

“X” plant in Puebla started working with laser welding in 1998. They used two or three laser welding systems for assemblies in the B-pillar and the groove of their previous model. These systems were not automated.

The process to weld the sheet metal parts before laser were spot welds and resistance welding. The advantages of laser welding compared to these processes were already mentioned in section 5.1.6.

5.3.2 Equipment, Tooling and Material Specifications.

The laser welding systems in “X” include a laser generator, fiber optics, robots, optics or welding heads, monitoring system, fixturing devices and cooling systems. All the equipment used is standardized on consortium level.

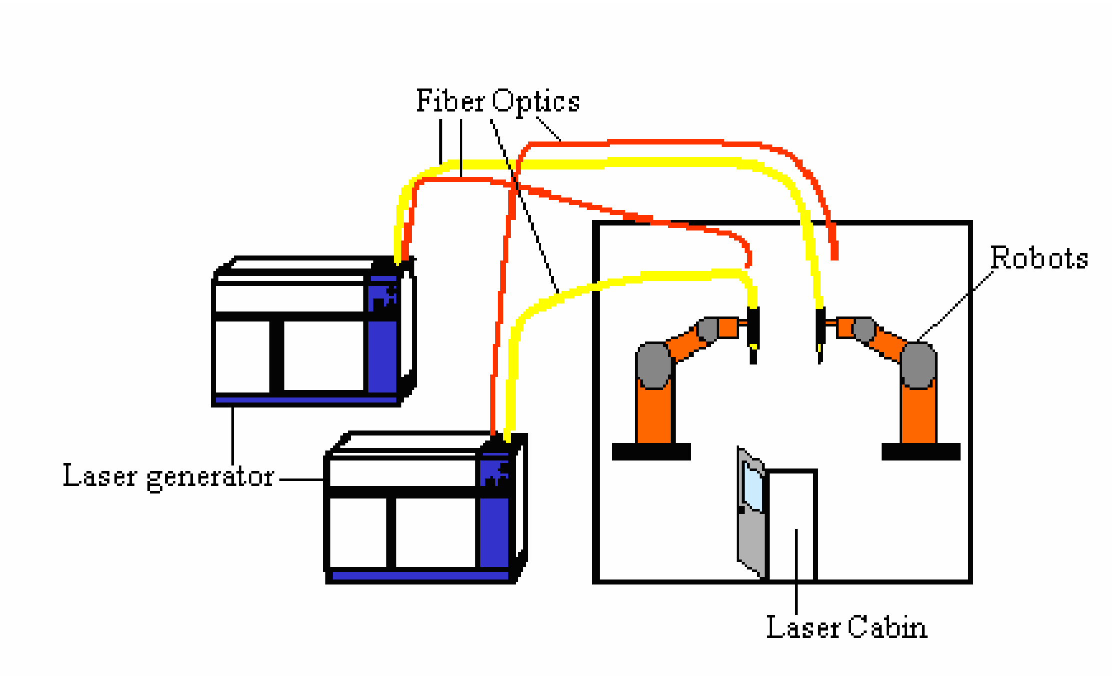

Figure 5.11 Sketch of the Laser welding installations seen in company “X”.

The laser generator is a 4kW Nd: YAG laser. This laser has 8 cavities to produce the 4kW laser power (500W each). It has a C.W. mode, because a constant source of high power is required.

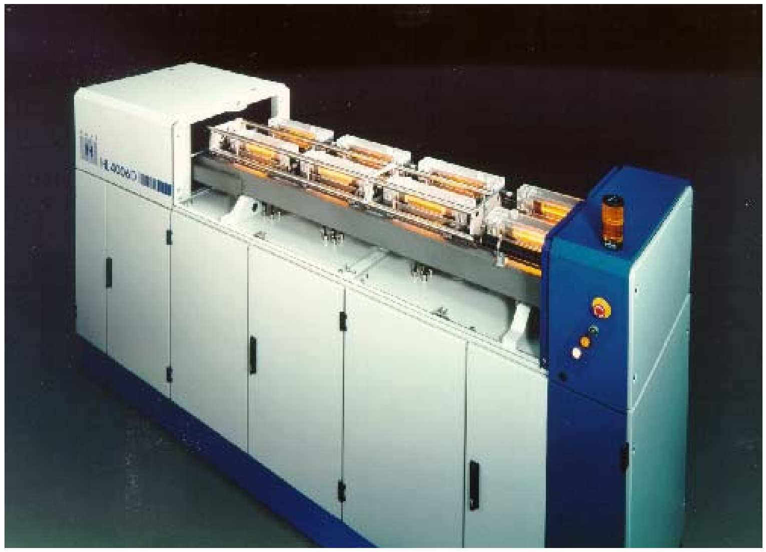

Figure 5.12 Nd: YAG laser with 8 cavities and 4kW power (Source: www.trumpf.com)

The “YAG laser” used in “X” is a solid-state laser. It produces laser lights with a wavelength of 1.06µm. This lies in the infrared spectrum, which is very close to the range of visible light. For this reason, the beam can be guided through laser light fiber optics.

Fiber optic laser cables consist of a core (optical fiber), a sheath and a protective covering. The cable is about 12.5 mm thick and its core has a diameter of 0.6 mm.

Figure 5.13 Fiber optic cable construction (Source: www.arcelect.com/fibercable.htm)

Laser robots are employed along the main production line. These jointed-arm robots have six or seven axis. They have a mechanical and electrical part and a controller.

Figure 5.14 Laser welding robot for a car body. (Source: www.kuka.com)

The laser heads employed have integrated fixturing. The fixturing types include: wheel, double wheel, splitter wheel, and single and double fingers. The optics used are to cut and to weld, with or without filler metal. The filler metal used is $Cu\ Si_3$ or steel wire.

Figure 5.15 Laser welding optic (Source: www.highyag.com)

There are cooling systems for the laser generator and for the optics. These use demineralized water and normal water. The monitoring systems are optical web inspection systems for 100% monitoring of technical surface quality including complete classification and documentation of each visible defect.

The material welded is zinc-coated steel and its thickness varies from 0.8 mm to 1.6 mm. The sheet metal comes from a prior stamping process and the vast majority of it is imported. Table 5.4 shows the material specifications and requirements and figure 5.16 shows the typical geometry of a B-pillar. In general, the geometry of the welded parts are surfaces.

Table 5.4 Material specifications and requirements.

Material Specification			
Quality	***Quality according to standard***	***Tolerances according to standard***	***General Dimensions (mm)***
DC04 + ZE 50 / 50 BPO	DIN EN 10152	DIN EN 10131	0.80 x 1690 (+6.00) x 0 (+0.00)
Roughness	***Process***	***Type of Zn***	***Zinc-coated sided***
1.1 - 1.6 µm	Zinc-coated	Electrolytic	2 (5.0 µm)
Material Requirements			
Desired Thickness	***Width Tolerance***	***Yield Point***	***Tensile Strength***
0.82 mm	0.80 +/- 0.08	< 160 N / mm^2	< 350 N / mm^2
Elongation	***Coefficients***	***Phosphatized according to standard***	***Phosphate Layer***
> 40%	r > 1.9 n > 0.20	Granodine 5854	0.8 - 2.0 g / m^2

Figure 5.16 Typical B-pillar geometry. (Source: www.gom.com)

All the equipment mentioned above is inside a laser cabin for security reasons. There are fourteen laser cabins and fifty two laser generators. It is difficult to measure the area occupied by the laser welding equipment, but considering just one robot and just one welding application, a space of 4 m^2 would be needed. The local conditions of the “X” plant in Puebla will be described and analyzed in the next chapter.

5.3.3 Process Parameters.

Among the processing parameters, the laser parameters are among the most important. Above all, these are: laser power (4kW), polarization, focusing ability (beam quality) and focus position (Focus diameter = 0.6 – 3.2 mm). By the same token, welding speed (2.4 m/min average robots speed and if welding with filler metal, wire speed), shielding gas and the way the gas is conveyed have a great impact on the welding result.

The laser power must be regulated according to the thickness of the work pieces to be welded. The thicker the sheets, the more laser power is required. The welding speed influences the welding depth and the geometrical form of the welding seam. A faster speed reduces the welding depth and causes a narrow seam. Furthermore, the speed can also affect the cooling of the melt and hence influence its structure in a positive way.

The attainable focus diameter and depth of field depend on the quality of the beam. The beam quality refers to the focusability of the laser beam. “Good beam quality” means that the laser beam can be focused onto a small focal spot with great depth of field. The ideal focus diameter is 0.6 mm. This is determined by the length of the focusing optics. The smaller the focal length of the focusing optics, the smaller the focus diameter and the depth of field will be. On the one hand, it is desirable to use a small focus diameter in order to achieve a high energy density and a welding speed as fast as possible. On the other hand, the depth of field must be adapted to the welding depth. If the focal length is short (in the case of “X” 3 mm) and the focus is small, the highest speeds will be reached at low welding depths. Deep welding seams allow the fastest welding speeds with a long focal length, a large focus diameter and large depth of field.

When laser welding with a linear polarized light, the deepest welding depth can be obtained if polarization is parallel to the feed direction. The polarization is controlled by two lenses, called focalization and collimation lenses. They have a protection crystal which has to be changed every eight hours.

Shield gas has the task of protecting upper and lower beads of the welding seam from reacting with the air as the melt cools. The shielding gas used in this process is argon.

The laser welding parameters are listed in a welding process specification register. Central planning provides the initial parameters and it is the responsibility of the production area to update them. Quality endorses these parameters by performing some destructive tests on the welded sheet metal parts in order to ensure that the specifications given add up to a high quality product.

5.3.4 TT Process.

When renovating a product in the market or in other words; re-designing the product; a technical description of the product is developed, for example its motorization, its body and the consortium goals in what technology refers. For “X”, laser welding is a marketing strategy. They saw other commercial advantages of the laser for welding too, such as:

- Reduction of the car weight, which improves the efficiency of the motor.
- Hermetic joint, which save the application of adhesives.
- High speed.
- Narrow fusion zone, which is aesthetically pleasing, etc.
- Tremendous amount of flexibility inherent to the equipment (cutting, welding, etc.)

In general, the product is designed to be laser welded.

So, once they decided that the joining method of some sheet metal parts of the car body is going to be laser welded, the company started to look for a supplier for the equipment they need. In the case of “X”, they selected the firm TRUMPF for developing the laser generator and firms like HIGHYAG, SCANSONIC and PRECITEC for the welding and cutting heads or optics. All these firms have a German origin. With these firms, “X” signed a contract of exclusivity and confidentiality and developed the equipment they needed together, in a very good example of technology cooperation.

The TRUMPF Group is one of the world's leading companies in production technology. Innovations from TRUMPF are setting new trends - from machine tools for sheet metal and material processing, to laser technology, electronics and medical technology. They are establishing new technical standards and opening up new and more productive possibilities for users. TRUMPF is distinctive for its development of new procedures and powerful machines, quick translation of technical concepts into user-oriented innovations, high standards of quality and reliable customer service.

HIGHYAG has ten years of experience in the laser technology field. Their product range goes from processing heads, through laser light cables and focus heads, to ancillaries for laser materials processing.

SCANSONIC develops and produces system technologies for laser welding in automated manufacturing processes. When welding and soldering with filler metal, they offer the effective and most reliable solutions.

PRECITEC is a global company providing precise mechanical, optical and electronic components and systems, designed for material processing using lasers, as well as process control. Its range of products includes robust distance control and positioning systems, including the relevant software and axle drives, as well as beam guide components for laser cutting and welding. Special mention should be given to our laser cutting heads with their integrated, non-contact, distance sensing mechanism.

In Mexico, “X” is still on the implementation stage of laser welding, while in Germany, the laser welding process is already working efficiently. For the implementation process, the planning, production and maintenance areas prepared a specification catalog, which they give to the technology provider, for example TRUMPF. TRUMPF made the process engineering and installed the equipment. The specification catalog is like a preceding manual. It is a consortium standard and contains all the information there is to know about the product, the processes and the installations.

The people who operate the equipment aren’t a cadre of scientist and optical engineers, but people were trained to run the equipment. The strategy followed in order to have a good acceptance of the new technology transferred, was to make them “feel that they own the system”. A more detailed content about the training will be described in the next chapter, but some of the courses offered to the workers are:

- Robotics.
- Automation.
- Laser principles.
- Programming.

- Machine operation.
- Advanced applications.
- Several levels of machine maintenance.

5.3.5 Problems and success encountered.

Some of the disadvantages observed during this implementation stage are that the laser generating process is very inefficient. The laser is a relatively inefficient converter of electrical energy into output light, with the best lasers achieving only 2 to 15 percent energy conversion, depending upon the type of laser being used. In order to produce 4 kW of output light with an Nd: YAG laser, 110 kW of electrical energy is needed. This is a less than a 4% efficiency of the system.

The low product (position) tolerances needed to make laser welding successful (approximately 0.2 mm and less) lead to high requirements on preliminary operations, product parts and product clamping. Actually, 80% of the issues are because parts aren’t produced in a capable process (stamping and cutting process) and because of the tolerance stack; these parts have to be repaired. The most common defects are: porous welds and undercuts (see section 5.1.4.1 for example figures). There is an idea for the solution of this problem, which consists of using a cell that takes an optical measurement of the auto body to determine the dimensions, and then the laser cuts the sheet metal to the required length before welding the plates in places.

It is important to mention that the product quality goals are difficult ones to achieve, but the Mexican plant managed to reach these goals faster than the German plant. They learned from the experience and errors made in Germany during the implementation of this new technology, since almost half of the project planning staff came from Germany to apply the TT.

There is the high maintenance cost (two times more than with the previously used process) and the high investment costs of the laser equipment, too. But there is an anticipated ROI of four years, and not only are they multiplying the number of laser throughout the whole consortium - there are now more than 450, which put the company well ahead of any other vehicle manufacturer – but "X" is looking forward to the next generation of lasers. Such things as a 6 kW unit that has a resonator efficiency of 20%, a beam quality of 6mm/mrad, flexible distribution of the beam through a cable to 100 m long, an uptime of 99.9%, and a maximum repair of 30 minutes.

5.4 Example of Laser Welding Application within the Autoparts Industry.

Company "Y" is a subsidiary of a German firm, too. It produces stainless steel tubes for automotive exhaust pipes. "Y" is a supplier for firms like Volkswagen (tier 1), Ford, Chrysler, Nissan and General Motors (tier 2). They produce tubes in a large variety of diameters (15 mm – 3") and thicknesses (0.8 mm – 3 mm) using a 6 kW laser generator provided by TRUMPF. They obtained the license to the laser technology through their German headquarters and sent the operators of the equipment for training to Germany.

Tube manufacturing involves a chain of processing steps (roll forming, welding, calibration, cutting, heat treatment when needed etc.), that influence the mechanical properties of the tube. Through selective, localized heat application in laser welding, the thermal stress on the component is reduced to a minimum. Thermal distortion is minimized and the welded manifolds meet the very tight mechanical tolerances. Filler wire is not used and the shielding gas is Argon. A steel strip is continuously roll formed into a tube shape and the longitudinal gap is continuously welded by applying a laser welding process. The following sizing leads to exact tolerances of the tube for the hydroforming process. The external bead of the welded area is always removed, and the internal only when it is necessary

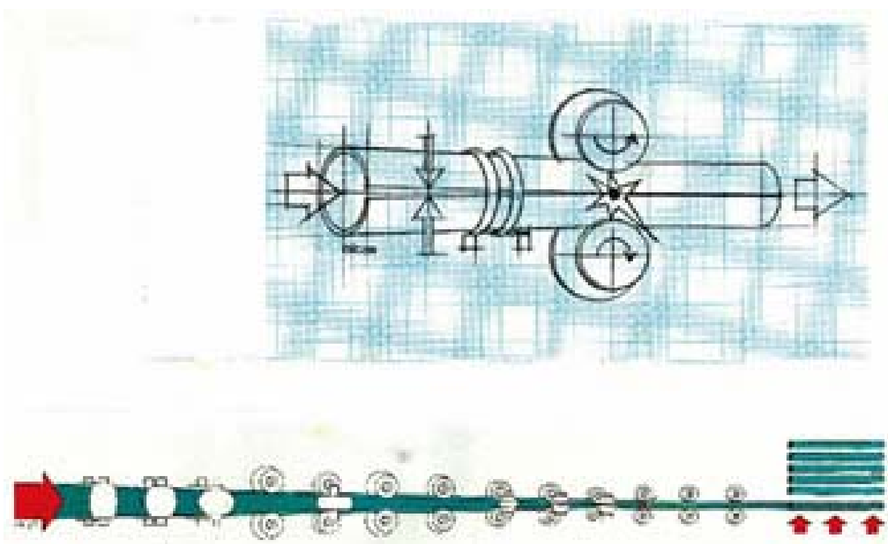

Figure 5.17 Example of a Continuous Roll-forming Process. (Source: V.W. Werke Vincencz Widerholt GmbH)

The second process is the use of laser welding for joining. Laser-welding eliminates the bead formation.

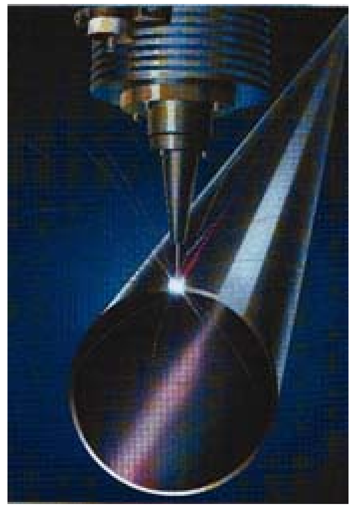

Figure 5.18 Tube Laser Welding. (Source: W.F. Oppermann Rohrwerkstechnik)

“Y” has been applying laser welding efficiently since 1998 and before they used TIG welding. In general, laser welding has the following advantages, compared with TIG welding:

- Higher welding rate for the same supplied power gives lower heat input (per unit length) and consequently less heat damage.
- The focused laser beam is only a few tenths of a mm in diameter, which makes it possible to weld with greater precision.
- A high power laser also has a number of good properties, which makes it particularly suitable for process controlled production systems, which are: High power density, which gives high weld-rate and reduced thermal effects. High flexibility and availability. The laser beam can easily be reflected to inaccessible locations by the use of mirrors, or to several different workstations.
- Good controllability and repeatability of power and power density.

- Non-contact manufacture, which means that you do not have to consider tool wear.

The main advantages of laser welding reported by “Y” are the high welding speed (up to 18 m/min) for pipes/tubes compared to the TIG welding used before (up to 2 m/min); the resistance and the aesthetics of the welded joint. In general, “Y” is very satisfied with their process and is a very good example of successful technology transfer.