POLITECNICO DI TORINO

MASTERS' DEGREE IN AUTOMOTIVE ENGINEERING

FINAL PROJECT

Laser welding for automotive components

Author: Riccardo CAMPANELLA

Tutor: Prof. Franco LOMBARDI

Co-tutor: Ing. Luca CALCIO GAUDINO (Sacel Srl)

Academic Year 2018/2019

Contents

1. Abstract ... 3

2. Introduction to welding ... 4

3. Types of welding ... 6

3.1 Arc welding ... 6

3.1.1 Electrodes ... 6

2.1.2 Arc shielding ... 7

2.1.3 Power source ... 7

2.1.3 Types of arc-welding with consumable electrodes ... 8

2.1.4 Types of arc welding with non-consumable electrodes ... 9

2.2 Resistance welding ... 11

2.2.1 Resistance spot welding ... 11

2.2.2 Resistance seam welding ... 12

2.3 Solid-sate welding ... 13

4. Weld quality and defects ... 14

3.1 Residual stress and distortion ... 14

3.2 Weld defects ... 15

3.2.1 Inspection methods ... 16

5. Laser beam welding ... 17

5.1 Laser beam types and technologies ... 17

5.2 Laser beam welding defects ... 18

5.3 Keyhole mode and conduction mode ... 22

6. Design for manufacturability ... 25

7. Machine setup influence ... 27

8. Control methods for welded components ... 31

8.1 Tools and production process description ... 31

8.2 Forming ... 33

8.3 Washing ... 34

8.4 Welding ... 35

8.4.1 Stage 1 welding ... 35

8.4.2 Stage 1 welding mask and welding operation ... 37

8.4.3 Stage 2 welding ... 40

8.4.4 Stage 2 welding mask and welding operation ... 41

8.5 Quality controls 44
9. Conclusions 49
10. Aknowledgements 50
11. References 51

1. Abstract

The dissertation starts with an overview of the various welding techniques currently used in the industry. More time is spent on the description of laser welding, and the description of the differences between the various subcategories of this particular welding technique.

After that, the dissertation looks at three real cases of laser welding, applied on automotive components, performed for different companies (Katcon, Magna PWT and Valeo). Sacel Srl has made these real case studies possible. Here the candidate had an internship aimed at the development of this dissertation and the design of progressive dies for the production of components implemented in the automotive industry, from the point of view of a second-tier supplier.

Each of the components serves as a demonstration of the different aspects that must be considered when laser welding is performed, from design choices that should help the industrialization process, to machine setups, to control methods to ensure the key features to be within tolerance limits.

The first example involves a rotor welded to a steel shaft; here we can see how design changes might be needed to comply with the production process chosen, and how a variety of factors can influence the performance of the welding.

The second case is of a steel shaft welded to a ball bearing, where machine setup has been the main control method for the welding performance. These tests show how different setups can bring different sources of errors to the final product.

For the latter case, two products, both implemented into the muffler, show how important it is to choose the correct features to be controlled, and the difficulties deriving from measurements on welded components.

2. Introduction to welding

Welding is one of the most widespread joining technologies and has many different implementations in every industrial field because of several advantages, including low cost, design flexibility, efficiency and better utilization of the materials. This operation is carried out in various ways, we may have [4]:

a) **Arc welding**: an electric arc is maniatined between an electrode and the workpiece
b) **Resistance welding**: an electric current pass through two pieces of metal under pressure (spot and seam welding are an example)
c) **Plasma welding**: a particular version of arc welding, where gas is heated at extremely high temperatures and becomes ionized, thus electrically conductive
d) **Solid-state welding**: the join is carried out by pressure mainly, with metal parts kept below their melting temperature
e) **Beam welding**: a concentrated beam of electrons (electron beam welding) or high-energy light beam (laser beam) heats up the pieces to be joined

Whatever the method carried out, the general functioning behind welding is to heat up the two parts to be joined at the melting point, also, support material can be used for this purpose. Once the pieces are solidified, the bond is created, and the two parts are finally joined.

The kind of joints that can be made using this technology are various and can be collected in five main types, as depicted in Figure 1:

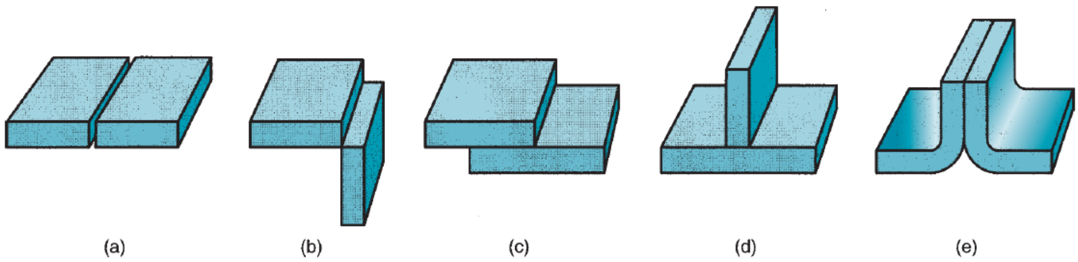


Figure 1: The five basic type of joints: (a) butt, (b) corner, (c) lap, (d) tee and (e) edge [4]

The main drawbacks of welding include risks for the operators, due to the exposure to very high temperatures, and the metallurgic transformations of the material undergoing the welding operation. The first of this problem is easily dealt with by means of automation or protection devices given to the operator; the latter depends on the behaviour of the metals in the different zones affected by the welding. We have, respectively, four zones, as depicted in Figure 2:

- Fusion zone
- Weld interface
- Heat-affected zone (HAZ)
- Unaffected base metal zone

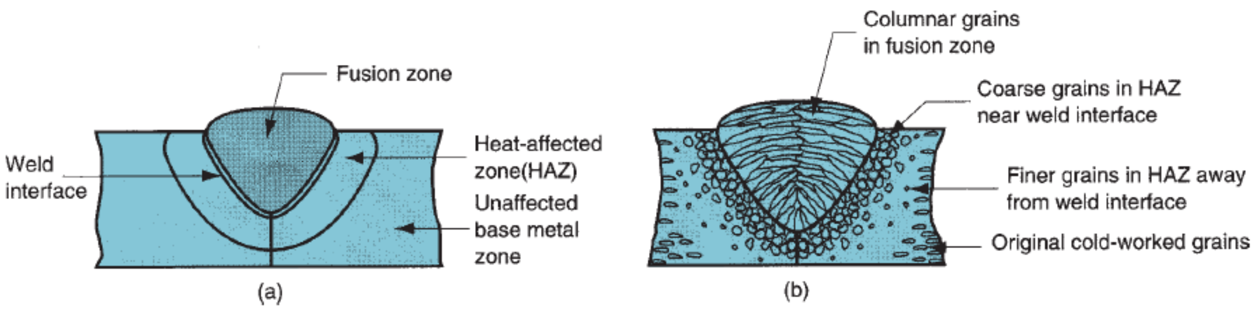


Figure 2: Cross section of typical welded joint: (a) principal zones of the welding and (b) respective grain structure [4]

Fusion zone is the mixture of base metal and filler material (if present) that completely melted during the welding, here the omogenity of the component metals causes the molten mass to solidify by epitaxial grain growth, which causes the grains to be in a columnar disposition, with orientation perpendicular to the welding walls' interface.

Weld interface is a narrow boundary separating the fusion zone from the heat-affected zone, consisting of base metal either melted or partially melted, which has solidified almost immediately, determining no changes in the chemical structure of the base metal involved.

Heat-affeted zone (HAZ) is where the metal was at a temperature below its melting point, but high enough to determine changes in the metal structure. The changes depend on a variety of factors, including heat input, peak temperatures, distance from the fusion zone, welding and cooling time and thermal characteristics of the metal welded. The changes in the material structure are considered usually negative, especially from a structural point of view, since the majority of welding failures happen in this zone.

Unaffected base metal zone sees no changes in the metal structure, but residual stresses may be present because of the shrinkage in the fusion zone.

3. Types of welding

In the following, a brief description of the main welding technologies will be presented, with the exeption of laser welding, which will have its own chapter. After that, specific cases of laser welding joints will be discussed, following real case scenarios for the automotive industry.

3.1 Arc welding

Arc welding is one of the oldest technologies, it's quite simple, too; here the electrode provides the filler material (most of the times), and the heat is generated by an electric arc between the electrode and the workpiece. In Figure 3 a generic arc welding process is depicted:

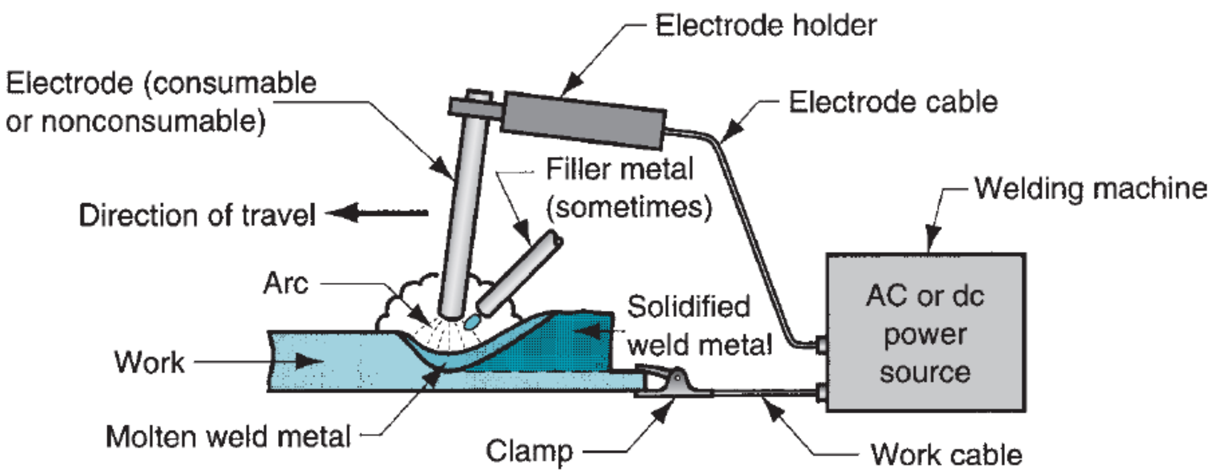


Figure 3: Basic configuration of the arc welding process [4]

The electric arc is provided by the discharge of the electric current in the circuit, and reaches temperatures up to 5500°C, this causes the metal to melt; the following movement of the arc determines the metal to solidify again and to create the joint. Filler metal may be added to strengthen the welding. The movement of the arc can be performed either manually or automatically.

The foundamental elements needed to perform arc welding are the following:

- Electrodes
- Arc shielding
- Power source

3.1.1 Electrodes

Electrodes can be either consumable or non-consumable, the first type provide the filler material and are generally produced in rods or wires; this kind of electrodes must be replaced periodically, thus reducing the uptime of the welding machine (of the operator). On the other hand, consumable electrodes, when used in long wires, can produce a continuous weld line, not depending by the length of the rods. In both cases, the electrode is added into the weld joint as filler material.

Non-consumable electrodes are made of tungsten, which resist the welding and allows the electrode to resist much longer than its consumable counterpart. However, the electrode is gradually depleted with usage (mainly by vaporization), as happens with cutting tools in machining. Any filler material must be fed by means of an appropriate and separated feeding system.

2.1.2 Arc shielding

Arc shielding is necessary because of the high temperatures generated during the melting phase of the materials involved, which causes the metals to be chemically reactive to oxygen, nitrogen and hydrogen present in the air. These chemical reactions can have a huge negative impact on the welding quality, thus, shielding of the arc from the atmospheric agents listed above is necessary and implemented in almost all arc weldings.

Shielding is achieved by covering the electrode tip, arc and molten weld pool with some gas, usually argon, helium or a combination of the two, which prevents the chemical reactions to take place. In some processes, oxygen and carbon dioxide can be used as well, depending on the material to be welded. Arc shielding by means of gas also has additional functions, such as stabilizing the arc and prevent/reduce spattering of the welding.

2.1.3 Power source

Both direct and alternate current are used in arc welding, each solution presents its advantages and shortcomings: alternate current allows to lower operative and purchasing costs but is not suitable for the welding of non-ferrous materials. Also, alternate current generally translates in a slightly worse arc control.

The power delivered must consider the losses in heat transfer, including convection, conduction, radiation and spatter; all these factors reduce the amount of usable heat provided by the power source, and are merged into a Heat Transfer Factor f_1; their influence varies depending on the type of arc welding performed, as depicted in Table 1:

Heat transfer factors for different arc-welding technologies

Arc welding process	Typical Heat Transfer Factor f_1
Shielded metal arc welding	0,9
Gas metal arc welding	0,9
Flux-cored arc welding	0,9
Submerged arc welding	0,95
Gas tungsten are welding	0,7

Table 1: Heat transfer factors for different arc-welding technologies [4]

Arc welding processes using consumable electrodes usually have a higher heat transfer factor, because of the extra energy used to melt the electrode, then transferred to the workpiece as molten metal.

2.1.3 Types of arc-welding with consumable electrodes

Arc-welding has a variety of methods and specific processes, below a summary of the most important with consumable electrodes:

1) **Shielded metal arc welding (SMAW):** consists of a filler material rod, covered with chemicals doing the arc shielding function. The filler material must be compatible with the metal to be welded, and the rod can be manipulated by a human operator, if an insulant handle is present. The equipment is particularly cheap and portable, compared to other methods, making this one of the most versatile arc-welding methodologies

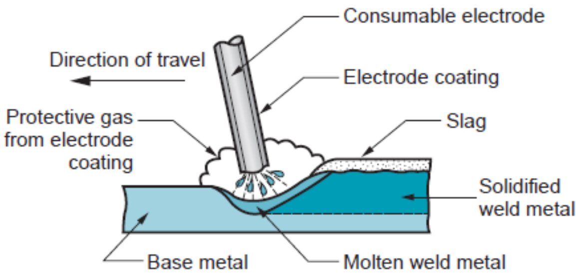


Figure 4: Shielded metal arc welding representation [4]

2) **Gas metal arc welding (GMAW):** here the electrode is made of pure metal, while shielding is accomplished by flooding the arc with gas. Gas selection depends on the material to be welded and other factors. The presence of external gas and metal rods avoids slag formations along the welding cord, reducing or eliminating the need for manual grinding and cleaning of the welding cord after the process.

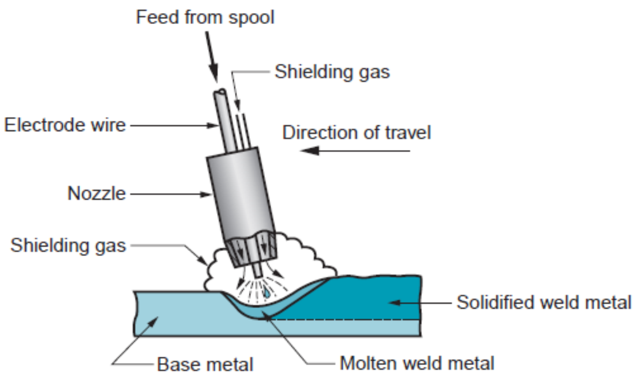


Figure 5: Gas metal arc welding representation [4]

3) **Flux-cored arc welding (FCAW):** this is an improvement of shielded metal arc welding, where the electrode is a continuous tubing containing the the flux and the wire itself, which is flexible, allowing for continuous feeding from a coil. This kind of arc welding can be either self-shielded or gas-shielded.

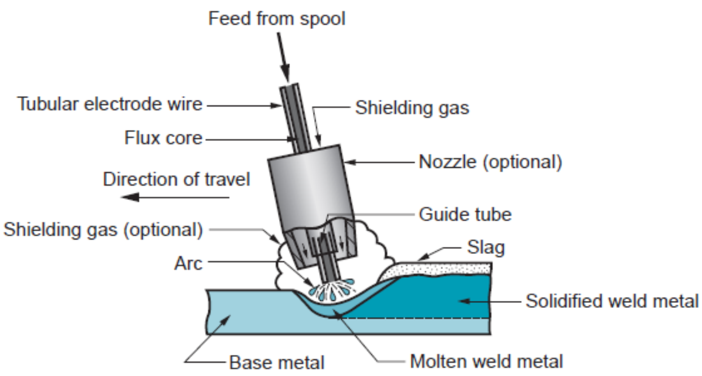


Figure 6: Flux-cored arc welding representation [4]

4) **Submerged arc welding (SAW):** it consists of a continuous bare electrode covered by a coat of granular flux providing the shielding; in this method, the flux completely covers the welding, preventing the dispersion of any hazard, allowing the operator to do the welding without any facial protection. Unfused flux can also be recovered and used for future operations

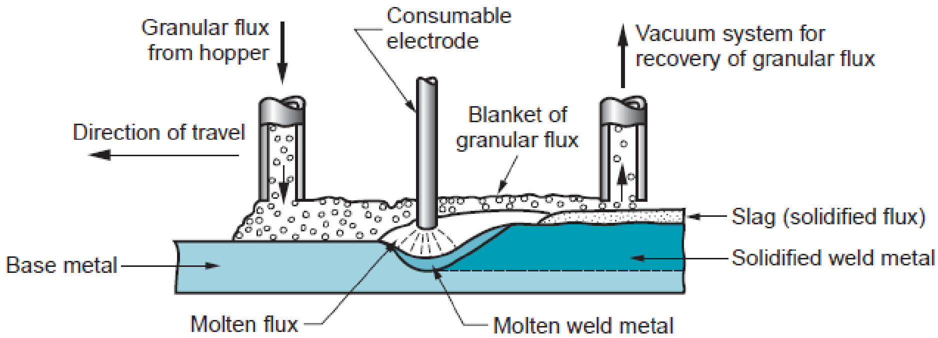


Figure 7: Submerged arc welding representation [4]

2.1.4 Types of arc welding with non-consumable electrodes

Here we refer to arc welding processes using non-consumable electrodes, in particular:

1) **Gas tungsten arc welding:** the electrode is made of tungsten and the shielding is made by inert gas; this process is also known as **TIG** (Tungsten inert gas welding) welding. This welding process can be carried out eother with or without filler material; if used, it is fed by a separate rod or wire.

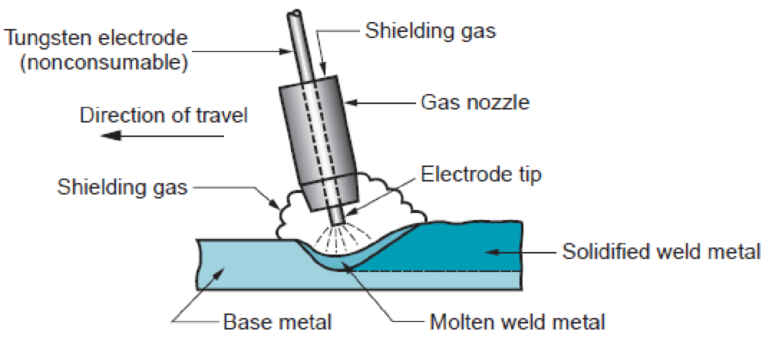


Figure 8: Gas tungsten arc welding representation [4]

2) **Plasma arc welding:** this is a variation of gas tungsten are welding, where the tungsten electrode is contained in a specific nozzle that ensures high-velocity stream of shielding gas. Temperatures can reach much higher levels than other arc welding techniques; also, penetration control is superior, together with welding speed and welding quality. The drawback is the high cost and limitations in narrow spaces.

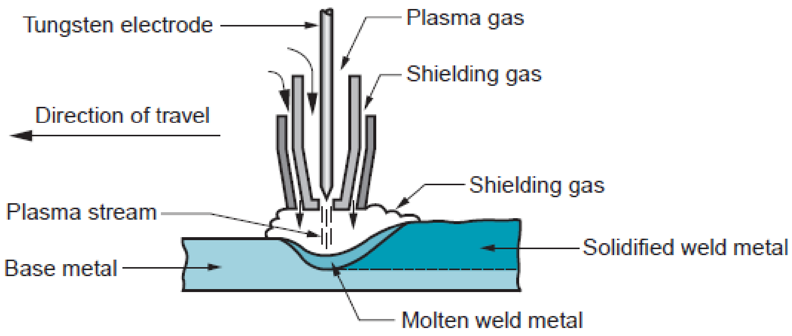


Figure 9: Plasma arc welding representation [4]

2.2 Resistance welding

In resistance welding, a combination of pressure and heat is used to perform the welding operation; heat is generated by electrical resistance to the current passing at the joint to be welded. The most widespread technology for resistance welding is spot welding, which is depicted in Figure 10.

In spot welding, and in resistance welding in general, neither gas shielding or filler metal are needed, and the electrodes, which also apply the pressure, are non-consumable. These factors allow resistance welding to be particurarly suited for mass production with high production rates, especially if automation is considered. Other advantages include reliability and high reproducibility of the weld. Drawback are the higher costs compared to arc welding, and fewer types of joints weldable using this technology.

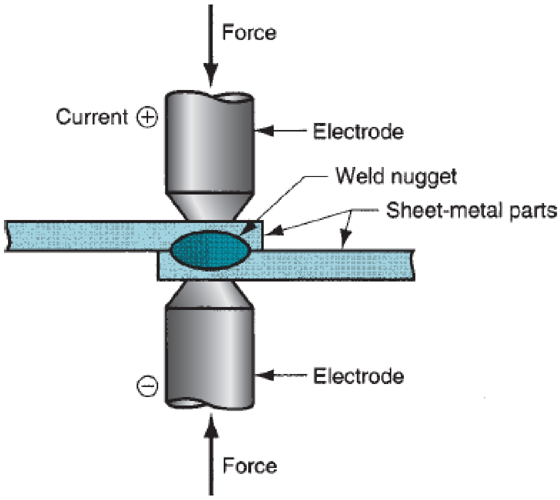


Figure 10: Typical arrangement for resistance spot welding [4]

2.2.1 Resistance spot welding

Resistance spot welding is the most important and most used resistance welding technology, especially when the welding involves metal sheets, this makes spot welding ideal for car body assembly, where individual bodies can have up to 10,000 individual spot welds. Also, if performed in a proper way, the strength of the joint resulting from spot welding is comparable to the strength of the base metals, this makes spot welding the go to technology when it comes to sheet metal joints [6].

For the outcome of the welding, the correct combination of pressure and current is needed, a typical cycle can be seen in Figure 11, where the main steps of a spot welding cycle are highlighted:

1) Insertion of the parts between the electrodes
2) Closing of the electrodes and application of the clamping force
3) Actual welding time with current flowing thru the electrodes
4) Switching off of the current and maintaining of the pressure, depending on the specific cases the force can be also increased, and current might be applied to achieve some stress relief in the weld region
5) Opening of the electrodes and removing of the assembly

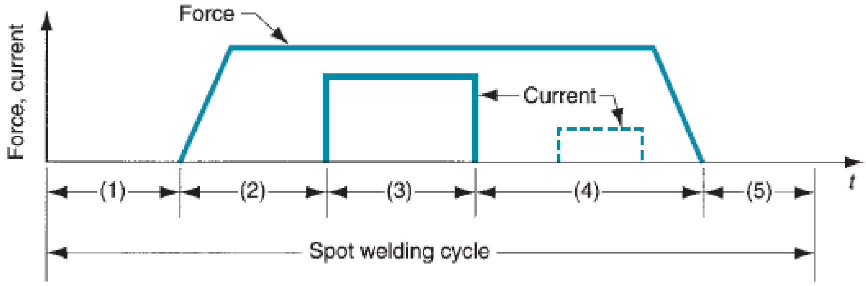


Figure 11: Typical evolution of pressure and current during a spot-welding cycle [4]

2.2.2 Resistance seam welding

Resistance seam welding may be seen as a variation of spot welding, where the stick-shaped electrodes are replaced by rotating wheels, as depicted in Figure 12; the working principle is the same as spot welding, but now the welding is repeated so that a series of overlapping spots can be made, this allows to get also continuous weld lines or individual weld nuggets along the same line.

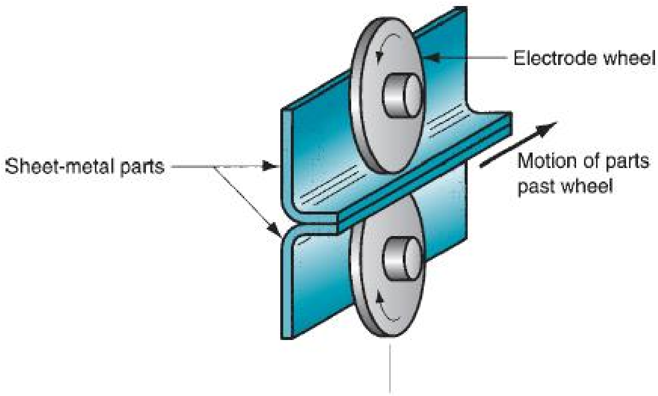


Figure 12: Typical scheme for resistance seam welding [4]

2.3 Solid-sate welding

In solid-state welding, the joint can be achieved with a combination of heat and pressure (as in resistance welding) or with pressure alone, consider that, if both heat and pressure are used, the heat generated is not enough to melt the metal involved; this makes pressure a key component to generate a localized melting around the interested surfaces. For these reasons, time must be taken into consideration, too for this kind of process.

The absence of melting between the metal parts means that the interested surfaces must be completely free from gases, lubricant or chemical films that might compromise the welding success. Consider that this problem is present in the other welding mechanisms, too, but high temperatures usually burn or dissolve any chemical film or gas that might compromise the welding quality. This means that in solid-state welding, careful cleaning of the surfaces is necessary for the achievement of satisfactory quality.

Despite the risks related to surface cleaning, solid-state welding presents some advantages respect to the other technologies of welding, the main one being the absence of melting, thus the absence of Heat Affected Zones, this allows the metal to retain its original characteristics, even after the welding has been performed, avoiding problems related to mechanical characteristics of the base metal to be changed/worsened during the welding operation.

Many solid-state welding processes have been developed; the main ones are listed below:

- **Forge welding**: the metal is heated to high temperatures and then joined by means of a hammer or similar tools.
- **Cold welding**: the parts are subjected to high pressure, this requires exceptional cleaning of the surfaces, and at least one of the parts must be of ductile material, no heat is provided.
- **Roll welding**: a variation of either forge and cold welding, where the pressure is applied with the parts passing thru two rolls, heat can be applied or not, depending on the specific applications.
- **Diffusion welding**: the parts are subjected to a combination of heat and pressure (the heat usually being well below the melting point of the metals involved), solid-state diffusion takes place, creating the bond; time is relevant in this technology, and diffusion can require even more than an hour.
- **Explosion welding**: the energy of detonated explosives is used to generate the pressure necessary to create the bond, no external heat is provided.
- **Friction welding**: quite widely used process, the friction is generated by rubbing of the two surfaces (usually by rotation of one of the two parts), once enough heat is generated, pressure is applied to create the bond. Further machining (turning) is usually required to get rid of the flesh created during the process and create a smooth surface in the welding region.
- **Friction stir welding**: a rotative tool is brought along the joint line between the two parts to be bonded, the stirring of the external tool provides the material to generate the weld seam.
- **Ultrasonic welding**: here the bond is created by the oscillatory shear stress of ultrasonic frequency applied to the surfaces.

4. Weld quality and defects

Weld quality is foundamental to assure the physical integrity of the joint, which defects can translate in joint integrity, with potential failure of the whole assembly. The following discussion relates to arc welding, mainly, but it is applicable to the other welding technologies we have seen so far.

3.1 Residual stress and distortion

Rapid heating (followed by melting) and successive cooling cause the material to face thermal expansions and contractions, which finally cause the material to get residual stresses, which can potentially cause distortion in the welding zone; this problem is emphasized by the restricted area of the welding.

We might consider a butt-welding operation as an example to look at the possible stresses and deformations undergone by the interested parts in the weld zone:

At the weld cord, the metal melts and solidifies quite rapidly, the solidification of the molten pool translates in shrinkage at the borders of the weld cord. This means that residual tension is left at the weld interface, which causes reactionary compression to occur further away from the weld cord. Also, longitudinal stress is generated, due to the difference in temperature (and hence in residual stress) experienced by the base parts during the welding operation [2]. A representation of stresses induced by welding operations is depicted in Figure 13:

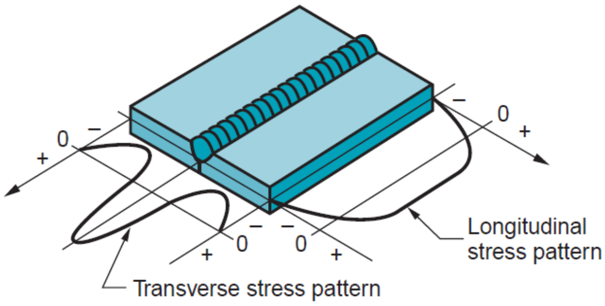


Figure 13: Longitudinal and transverse stress pattern after a butt-welding operation [4]

These stresses caused by thermal expansions/contractions might develop in potential distortions and warps in correspondence of the welding zone, and can potentially affect the whole assembly, as shown in Figure 14:

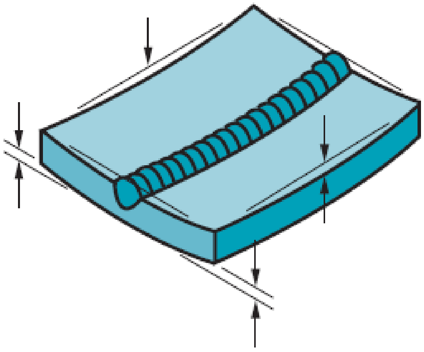


Figure 14: Warping and deformation after a butt-welding operation [4]

These two problems are addressed in almost every welding process involving melting of base metal, and are dealt in different ways [2]:

- Welding fixtures can be used to physically restrain the base parts during the welding operation
- Heat sinks can be used to help dissipate the thermal energy from the welding cord and reduce thermal induced stresses/distortion
- Tack welding can be adopted prior to the actual welding, this allows to create a rigid structure pre-existing to the welding, helping the base parts to better sustain the thermal induced stresses
- Better selection of welding parameters (speed, amount of filler material used, depth of the welding etc.)
- Heating treatments of the parts can help reducing the thermal gradient between the welding cord and the other zones of the base parts, thus reducing thermal induced stresses, this can be done either before the welding operation (preheating) or afterwards (stress relief)
- Proper design of the welding operation

3.2 Weld defects

Thermal induced stresses/distortions are not the only problems that can be encountered with welding operations, the main ones being listed below [2]:

- **Cracks:** fractures affecting either the weld or the base metal nearby, they represent a serious defect due to the significant strength reduction caused to the welding.
- **Cavities:** include either porosity defects and shrinkage voids, both consist of small cavities formed by either trapped gases or shrinkage during solidification.
- **Solid inclusions:** non-metallic solid trapped in the welding.
- **Incomplete fusion:** when fusion isn't occurring in the whole cross section of the joint, lack of penetration can be a consequence of this defect.
- **Aesthetic appearance:** oxidation can take place during the welding operation, as well as ultrafine particle deposition on the weld surface; this can lead to change in the color of the base metal, resulting in quality inconformity when the aesthetic appearance of the surface is important.

Every weld defect listed above, but aesthetic ones, can potentially bring structural weaknesses to the welded part, thus resulting in the potential failure of the joint and assembly. It is then foundamental to keep track of the welding operation, in order to assure the highest possible standard for the welding, which must be free from such defects.

Graphical representation of these defects will be shown later on, in the laser welding section, together with the specific laser welding defects that can be encountered.

3.2.1 Inspection methods

Quality of the welding can be verified in a variety of ways, including both destructive and non-destructive methods. Destructive tests include visual inspection, which is still the most widely used inspection technique; mechanical tests, where the mechanical characteristics of the welding are tested (tensile and shear tests), and metallurgical tests, where metallic structure, defects and condition of the heat affected zone are investigated; some of the latter methods are used further on in this dissertation to investigate the weld quality of the real parts studied, in particular, specimens have been cut at the welding interface and the welding cord section has been observed at the microscope, searching for cracks on the welded material.

Non-destructive tests, instead, are made to keep the specimen intact, some examples are dye-penetrant and fluorescent-penetrant tests, along with magnetic particle testing and ultrasonic testing; radiographic testing is available, too [4].

5. Laser beam welding

Laser beam welding is the last welding technology to be developed, in fact it is quite recent compared to the technologies seen before. Also, compared to the previous technologies, lser welding presents a series of advantages [3]:

- Small spot size
- High velocity and precision of the welding
- Reduced heat affected zone size

These, along with many others, make laser beam welding ideal for very precise operations, allowing to control the energy input into the welding, thus the welding penetration and the resulting strength of the joint. However, this precision is requested in the parts preparation, too, this means that parts must be positioned and machined with very high precision, to get the maximum out of laser welding.

5.1 Laser beam types and technologies

Several types of laser beams are used in laser welding operations, the main ones being listed in Table 2, while in Figure 15 it is possible to see the power spectrum for each laser welding typology:

Type of laser	Laser characteristics
CO_2	• Wavelength: 10.6 µm; far-infrared ray • Laser media: CO_2-N_2-He mixed gas (gas) • Average power (CW): 50 kW (Max); 1-15 kW (normal)
Lamp-pumped YAG	• Wavelength: 1.06 µm; near-infrared ray • Laser media: Nd^{3+}: $Y_3Al_5O_{12}$ garnet (solid) • Average power (CW): 10 kW (cascade-type max and fiber-coupling max); 50 W-7 kW (normal); efficiency: 1-4%
Laser diode (LD)	• Wavelength: 0.8-1.1 µm; near-infrared ray • Laser media: InGaAsP, etc. (solid) • Average power (CW): 10 kW (stack-type max); 15 kW (fiber-delivery max) • Merits: compact, and high efficiency (20-60%)
LD-pumped solid-state	• Wavelength: about 1 µm; near-infrared ray • Laser media: Nd^{3+}: $Y_3Al_5O_{12}$ garnet (solid), etc. • Average power (CW): 13.5 kW (fiber-coupling max); (PW) 6 kW (slab-type max)
Disk	• Wavelength: 1.03 µm; near-infrared ray • Laser media: Yb^{3+}: YAG or YVO_4 (solid), etc. • Average power (CW): 16 kW (cascade-type max) • Merits: fiber delivery, high brightness, high efficiency (15-25%)
Fiber	• Wavelength: 1.07 µm; near-infrared ray • Laser media: Yb^{3+}: SiO_4 (solid), etc. • Average power (CW): 100 kW (fiber-coupling max) • Merits: fiber delivery, high brightness, high efficiency (20-30%)

Table 2: Main laser typologies and their characteristics [2]

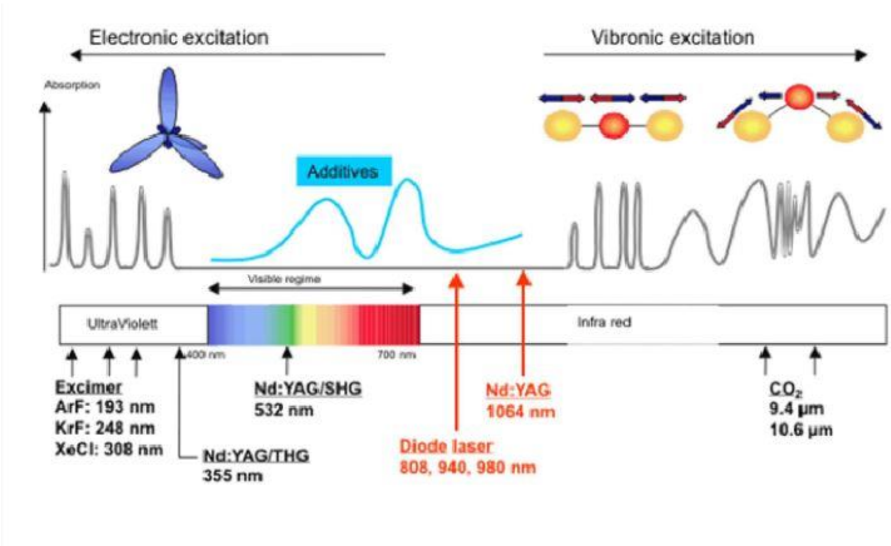


Figure 15: Laser welding technologies' power spectrum [6]

Some considerations for each laser welding technology can be expressed [2]:

- CO_2 laser is easier to achieve a high power, but must face some inconvenients, such as Ar plasma formation reducing the welding depth, if used as shielding gas
- Nd: YAG laser can be operated both in CW or in PW; the latter being used for small parts welding, such as electric components and battery cases, while the first is used for metal sheets and bigger parts. The drawback of this technology is the low electrical efficiency, defined as the ratio between the laser output to electrical input; this makes this technology unsuitable for very high-power applications
- On a scenario of high-power lasers, particular interest has been developed around disk, fiber and LD lasers, because of the higher efficiency that adds to the higher beam quality than lamp and LD-pumped YAG lasers. In particular, though, LD lasers suffer from a poor beam quality, compared to disk and fiber ones

5.2 Laser beam welding defects

For what concerns defetcs, to the ones described for the previous welding technologies, spatter and stray arcing add to the list, which are linked to the vaporization of the material nearby the laser beam, where temperatures reach their maximum [2]. Hence, a full list of possible laser welding defects is depicted in Figure 16.

In particular, spatter refers to the ejection of melt droplets from the welding cord, this might result in further defects such as underfill, undercuts, craters and so on. It is worth to notice that this problem may occur with other welding techniques, too, but laser welding is where this problem becomes more urgent, because of the high precision required. Spatter represents a further problem when the aesthetic appearance of the joint is important, because of the evidence of the defect [5].

Spatter is even more dangerous because the defects deriving from its formation can lead to reduced welding strength and mechanical properties of the joint, for this reason, spatter control is foundamental during the welding operation.

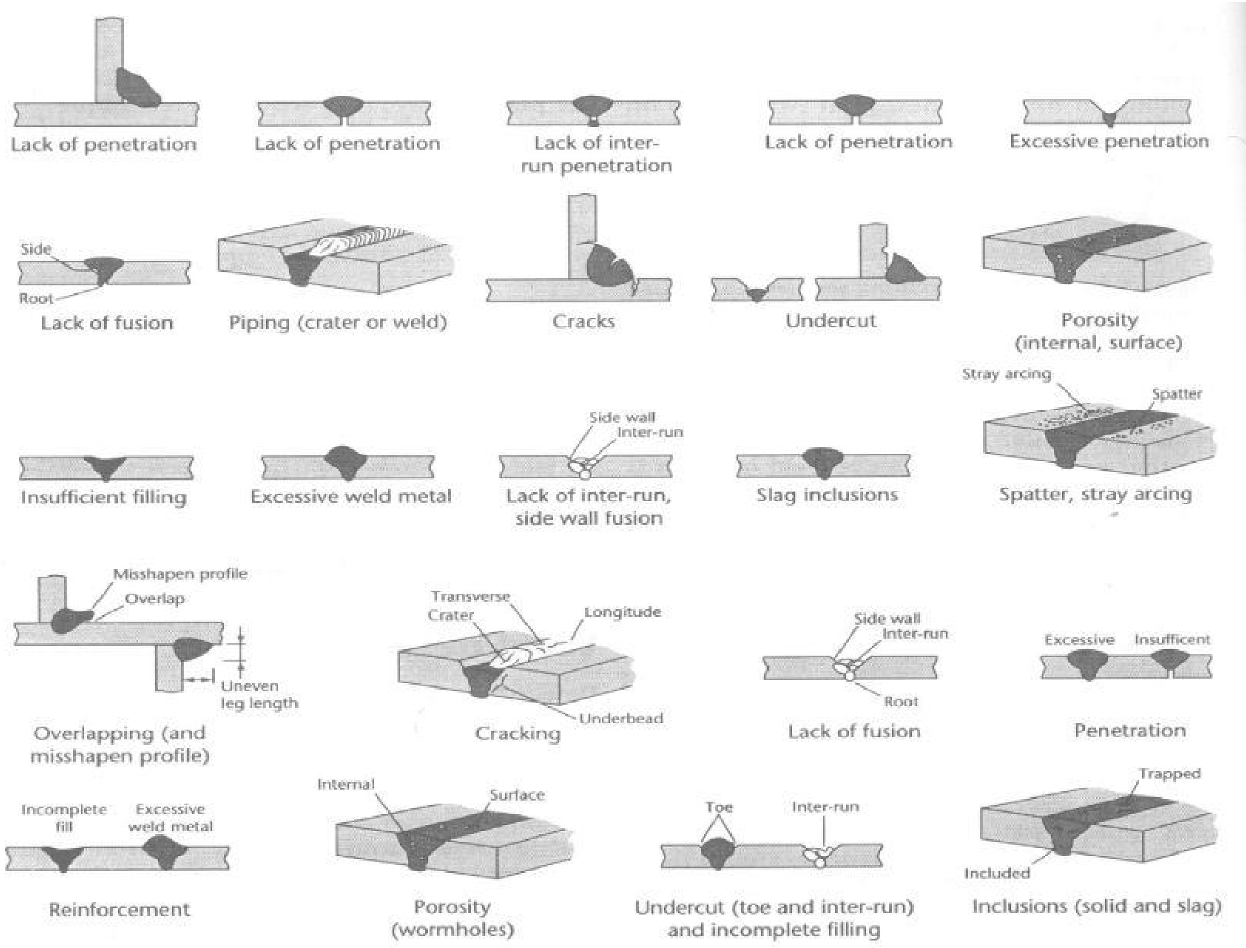


Figure 16: Full list of possible laser welding defects [6]

As mentioned before, spatter involves the ejection of droplets of melt material from the weld pool, caused by high accelerations almost perpendicular to the welding surface; in Figure 17, we can see a high-speed sequence of spatter droplets being ejected from a weld pool:

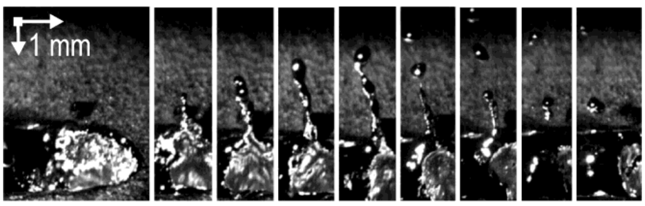


Figure 17: High-speed imagin sequence of droplets being ejected from a weld pool [5]

Spatter formation is mainly generated the keyhole mode, which is one of the two possible regimes for laser welding; both methods will be discussed in further detail in the following, but spatter formation is mainly generated during the keyhole mode, which is the most common case [1].

In Figure 18 we have a schematic representation of keyhole mode: the keyhole is kept open by the recoil pressure, created on its boiling surface. The pressure on the front part of the keyhole wall is greater than the pressure of the rear, this gradient accelerates the melt around the keyhole, finally making the spatter droplets to be ejected from the weld pool [1].

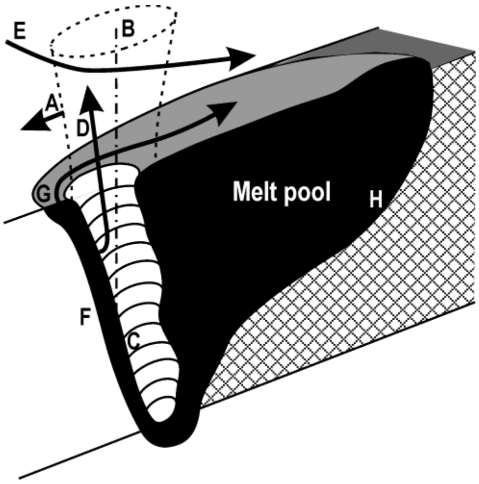


Figure 18: Scheme of keyhole mode (A): welding direction, (B): laser beam, (C): keyhole, (D): vapour jet, (E): shielding gas flow, (F): melting front, (G) melt flow passing around the keyhole, (H): solidification front [1]

If we consider a plane where the weldi direction is horizontal, and the laser one is vertical and directed downwards, we can say that, when the vertical component of the flow close to the top surface exceeds a certain threshold, droplets of spatter can escape the weld pool. This threshold is defined by a combination of surface tension, surface geometry, viscosity and gravity, the surface tension being the most important parameter, which can also be influenced by local temperature and eventual presence of oxidation or impurities [1]. This mechanism is represented in Figure 19:

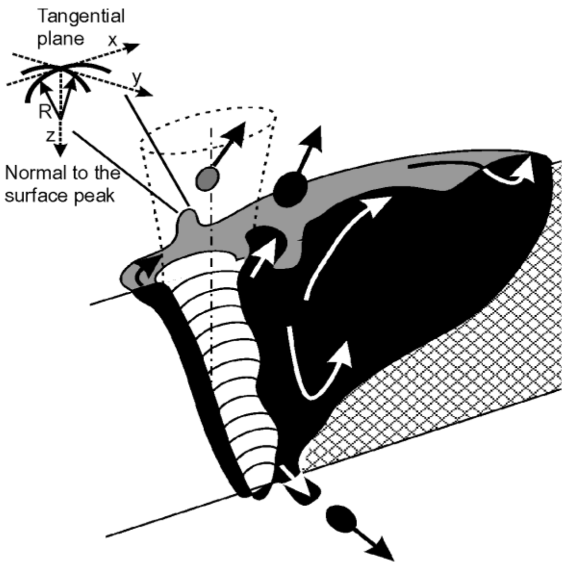


Figure 19: Representation of the momentum redirection from horizontal to vertical, which may overcome surface tension [1]

It is possible to plot the threshold speed at which the droplets will start to escape vs the radius of the surface bump of the melt material, as depicted in Figure 20:

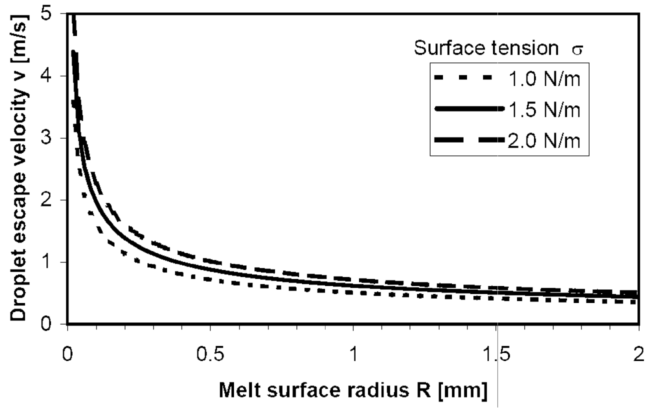


Figure 20: Relationship between the droplet escape velocity and the surface bump radius of the melt material [5]

As we can see, the narrower the radius of the bump, the higher the threshold velocity, this explains why if small volumes of melt emerge as a column, velocities involved become high, as shown previously in Figure 17. On the contrary, relatively smooth surfaces or broad humps make for relatively low escape velocities for droplets [1].

The energy input to the welding is made by the laser only, this leaves with some possible mechanisms which are responsible for the transfer of some laser energy into the vertical thrust exerted on droplets escaping the weld pool; we might have, in fact, one of the following:

- The keyhole and the liquid-solid interface surrounding it have different geometries, this explains the presence of some vertical component in the melt motion, necessary to travel around the keyhole.
- Keyhole's diameter experiences periodically and/or sporadically fluctuations, diameter increase reduce the distance between the keyhole and the liquid-solid interface surrounding it; this narrowing causes an increase in flow acceleration locally in both horizontal and vertical planes. This phenomenon is more evident if pulsed laser welding is performed, since the energy supply to the keyhole is intermittent.
- Undulations or humps on the keyhole wall become preferentially heated, especially on their upper side, which might evaporate during the weld; this evaporation causes some material to be propelled vertically, this phenomenon is particularly evident when fiber laser welding is implemented.
- Localized overheating or low boiling point contaminants (particularly with zinc coated mild steel) may cause the evaporating material from the keyhole, which might drag melt from the upper edge of the keyhole. This phenomenon too is characteristic of fiber laser welding.

5.3 Keyhole mode and conduction mode

As mentioned before, two different regimes are possible in laser welding: keyhole mode and conduction mode, the main difference being the power density used in the two modes and with keyhole mode ultimately getting the lead in industrial applications because of its characteristics.

In particular, keyhole mode takes the lead on conduction mode because of deeper penetration, smaller heat affected zone, and higher productivity achievable. On the other hand, though, keyhole presents some criticalities, such as possibly high levels of porosity, instabilities and spatter, as mentioned in the previous paragraph. These are amongst the reasons why keyhole mode is not suitable for aluminum alloys; in fact, we have possible degradation of the mechanical characteristics of the material if treated with the keyhole mode [2].

In conduction mode it's possible to better control the heat delivered to the workpiece; this, along with the larger beam, which reduces fit-up problems typical of laser welding, and the lower quality needed for the beam itself, makes conduction mode particularly suited in conditions where these characteristics are more valued; even good weld penetration has been shown to be possible with this method.

But conduction mode as disadvantages, too, such as the coupling efficiency of the process, especially when highly reflective materials are involved. It is worth to remember that coupling is defined as the percentage of energy coming from the laser that is absorbed by the material; in laser welding of stainless steel, for example, absorption of the material is around 65% in keyhole mode, while just 15% in conduction mode. Coupling, though, depends on other factors, too, like wavelength of the laser, surface finishing, material and its thickness; steel is generally between 20% and 90%, while aluminum is usually in the range 10-80%.

In Table 3 we can see the main differences between these two modes and their respective advantages and drawbacks:

Process	Advantages	Disadvantages
Keyhole mode	• Low heat input, hence low distortion • Deep penetration with a big aspect ratio • High productivity	• Unstable process • High levels of porosity • Big amount of spatter • Loss of alloy elements • Degradation of mechanical properties • Good beam quality required
Conduction mode	• No vaporization, thus no porosity, cracks or undercut on the welds • No spatter • Stable process and control of heat input • Good gap bridging capability due to the large beams used • Relatively low-quality beam is sufficient	• Low coupling efficiency • Slow process • High heat input causing distortion

Table 3: Keyhole mode Vs Conduction mode characteristics [2]

As mentioned before, the main difference between the two modes is the power density implemented: in keyhole mode, the power density is higher than the level required to cause boiling of the material, while in conduction mode this value is not reached. However, the boundaries between the two modes are not well defined, and usually the power density threshold considered is about 10^6 W/cm^2, but also lasers below 1 kW may be considered to operate in conduction mode. In the end, conduction mode is defined as the mode where vaporization of the material is negligible, or where power density is not enough to cause boiling. It is worth to notice that neither of these definitions consider other welding parameters such as welding speed, beam diameter and material, which influence the transition phase for each specific welding operation.

In pusled laser welding, a third regime has been detected, named mixed mode; this mode has characteristics in common with both the previous modes. This regime has been identified using the drilling model, and its characteristics can be seen in Figure 21:

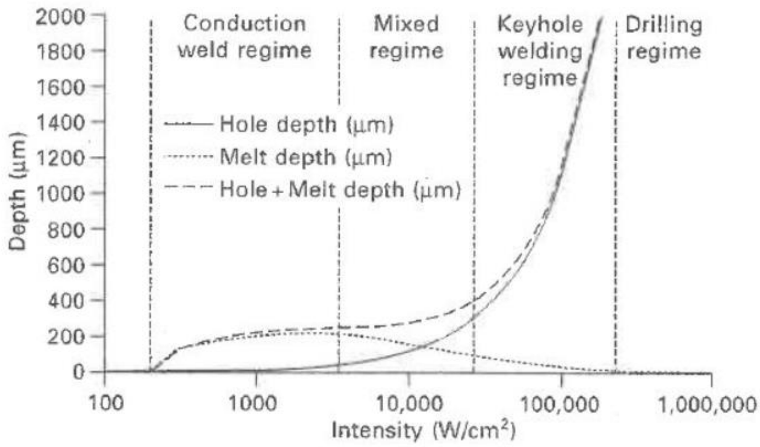


Figure 21: Identification of the three welding modes in pulsed laser welding [2]

When conduction laser welding is used, an optimum beam diameter can be found, depending on the power delivered and the weld speed, which grants the highest weld depth. This mechanism is explained by Figure 22 in the specific case of aluminum conduction welding, where we can see that, increasing the beam size, the surface temperature remains at the boiling point of the material; this is true untila certain threshold, where a further increase in beam radius causes the surface temperature to be lower because of a spot size which becomes too large. This finally affects weld depth in a negative way and sets the optimal beam size to achieve the maximum possible depth [2].

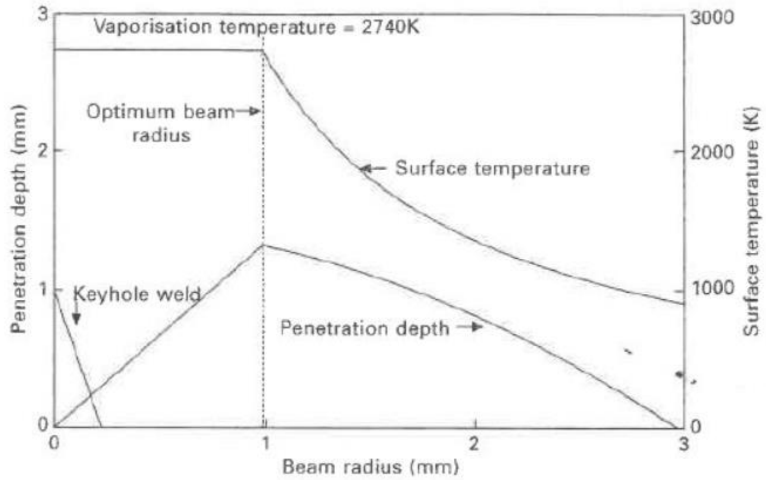


Figure 22: Penetration depth and surface temperature as a function of beam radius for aluminum [2]

6. Design for manufacturability

In this section, the most important factors influencing laser welding performance are considered, which sometimes are not even fully controllable. That is because of original components' errors, both from previous machinery operation, if the part is fully produced within the company, or external suppliers, if the parts to be welded are coming from an external company. Also, internal factors within the welding operation itself, or depending on the control methods adopted, could influence the overall quality of the final product; such factors are investigated more deeply in the following chapters.

Thus, we can summarize these main factors to into the following points:

- Type of junction
- Geometry of the parts
- Materials involved
- Overall quality of the starting components and of their production process
- Parameters used for controls and control methods
- Costs

To show how the design can be changed according to these factors, a real-world scenario is described, showing the modifications adopted on a welding, performed to join a rotor to a steel shaft. The 3D model of these components are depicted in Figure 23:

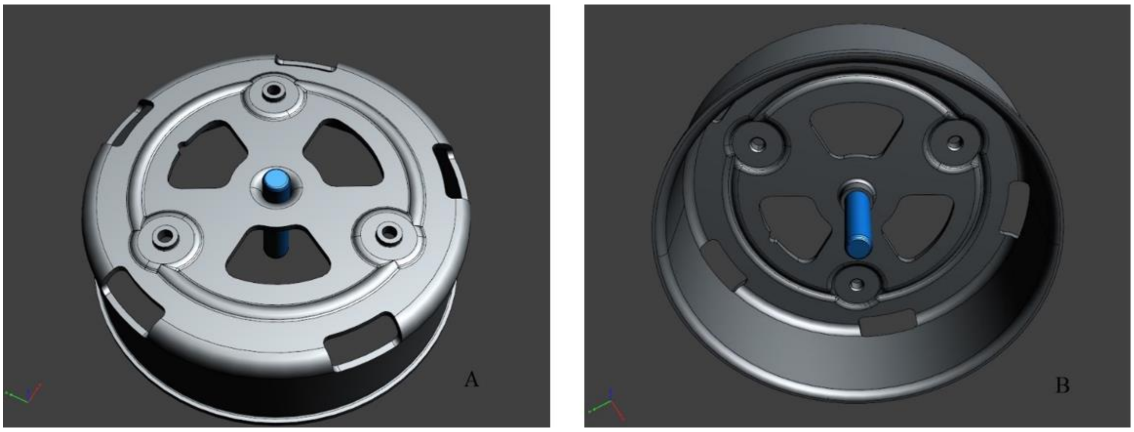


Figure 23: Rotor and shaft assembly: (A) top view, (B) bottom view [7]

Sacel produces both the rotor by sheet metal forming, and the shaft by turning, then, proceeds to the welding operation, also done within the company.

Three generations of the rotor have been discussed, with changes done both because of welding feasibility, and because of internal decisions within the customer's company. The current generation should start production in 2020, expecting an end of production in 2028. Two versions are present, with a peak of the annual production over 900.000 units. Table 5 depicts the production volumes expected for each year:

Year of production	300W Version	425W Version
2020	27.790	-
2021	963.925	127.746
2022	863.629	271.294
2023	828.086	275.310
2024	776.154	258.942
2025	733.564	251.773
2026	619.866	229.122
2027	213.498	139.230
2028	133.756	111.556
Total	**5.160.268**	**1.664.974**

Table 4: Annual production expected [7]

As mentioned before, some changes were applied to increase the feasibility of the welding; in particular, the welding operation itself saw a change in design from the original version. The client first proposed the welding operation to be performed by a single beam, which should have passed thru the formed rotor to reach the shaft.

Subsequent tests revealed that this solution did not meet the quality standards required, because of deformations and subsequent misalignment between the rotor and the shaft, probably caused by the long time required to complete the welding.

These problems lead to a new solution, resulting in a setup where the beam would come from above, providing a better penetration and quality of the welding; also, the beam was split into two branches, each taking half of the revolution around the weld interface, with a slight overlap between the two cords. In this way, the time required for the welding was reduced drastically, thus the deformations within the components that were leading to scrap production.

This final aspect resulted of high importance to maintain the tolerances between the limits, in particular, the one related to the concentricity of the axes, foundamental to maintain the balance of the rotary parts of the assembly. In Figure 24, you can see the schematization of the two solutions:

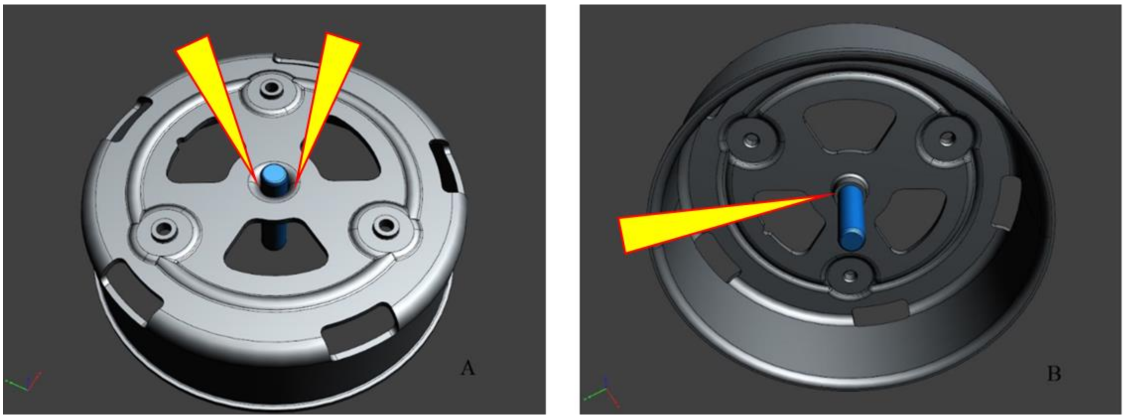


Figure 23: Welding setups: (A) final configuration proposed by Sacel, (B) original configuration proposed by the customer [7]

At the time of writing, though, the company opted for another solution for the shaft/rotor joining, which consists in an interference joining between the shaft and the rotor. This allows to reduce the costs related to laser welding, thus the overall cost for the client.

7. Machine setup influence

As mentioned before, machine setup is another big topic, when it comes to factors influencing the welding performance. Once again, an example taken from a real-world scenario will serve as a proof of this correlation. This welding involves a steel shaft, which material is C45, and a ball bearing, of the type 608Z, both depicted in Figure 25, which are part of a rotor for an automotive front wiper motor. Sacel Srl and Trumpf Sarl, using different parameters and laser types, summarized in Table 4, have made the welding tests. Trumpf has performed tests from number 1 to number 4, while Sacel has carried out test 5.

The critical aspetcs of this welding are the material of the shaft, which has a high percentage of carbon (0.45%), potentially translating in brittleness after the welding, with subsequent risk of cracks, leading to fatigue fractures and finally failure of the welding itself. Another key parameter is the misalignement between the bearing and shaft axes after the welding. Large values of misalignment may cause noise and reduce bearing service life; the maximum misalignment should stay in the range of ±1 or 2 minutes of arc, according to ball bearing manufacturer SKF [8]. This value has proven to be of difficult revelation, thus, neither Sacel nor Trumpf present quantitative results in that sense.

Trumpf reports mention the presence of longitudinal cracks on the weld surface, visible with an optical microscope; further tweaking of testing parameters 1, though, achieved the eliminations of said cracks. Concerns are also present over the depth and width of the weld, which are believed to be possibly not adequate for the task required. It is worth to mention that Sacel carried out some preliminary tests on the weld strength, with the outcome of satisfactory results.

Cycle times presented a great influence by the type of laser used, as shown in Table 5: continuous wave lasers, in fact, have cycle times up to 10 times faster than their impulse counterparts, making for a strong contender for the final choice of the parameters. it is worth to remember that cycle time here refers to the time necessary to perform the welding, only, without the time requested by the operator to setup the welding phase and remove the complete assembly after that (machine setup time). Cycle time might also influence the presence of errors within the final product, especially from the misalignment point of view. A longer cycle time, in fact, would more easily lead to thermal deformation of the sourrounding material, leading to failures in meeting the tolerances requirements for this feature.

Sacel’s specimens report the presence of some sort of spatter, which might be caused by the presence of lubricant inside the ball bearing. However, this problem did not seem to affect welding strength, and the droplets remaining at the side of the bearing wall can be easily washed away with the help of a metal brush. This suggests the aesthetic-only nature of this issue [7].

The need for a shielding gas has also been investigated by Trumpf, making a test without any gas, which resulted in crack on the weld bead, thus incompatible with the requests of the customer; no noticeable differences have been registered by using Argon instead of Nitrogen as shielding gas.

Finally, it is worth to mention that the microscope images of Sacel’s welding depth show two different values, most likely due to the impulse nature of the laser used for the welding. Thus, the tabelled value for Sacel’s test has been registered as the average of the two values reported in the images.

Process parameters	1	2	3	4	5
Machine and type of laser					
Machine	TruLaser Station 5005	TruLaser Station 5005	TruLaser Station 5005	TruLaser Station 5005	Rofin SW 500
Laser device	TruDiode 903	TruPulse 203	TruPulse 203	TruDiode 903	YAG
Setup					
Optics setup	BEO D70	D35	D35	BEO D70	D45/100
LLK Ø [µm]	300	300	300	300	600
Focal length [mm]	150	200	200	150	110
Collimation [mm]	200			200	NA
Magnification ratio	1:0.75			1:0.75	1:1
Focus Ø [mm]	0.225			0.225	0.6
Welding parameters					
Impulse duration [ms]	-	9	9	-	4
Frequency [Hz]	-	11	12.5	-	12
Impulse numbers	-	98	98	-	105
Source voltage [V]	-	-	-	-	280
Energy [J]	-	-	-	-	5
Power a.W.	700	3000	2600	800	-
Feed rate [m/min]	3.5	-	-	3.5	-
Focus position [mm]	+1.5	-	-	+1.5	-
Start ramp [W/°]	280/41.5	-	-	10%-100% in 50ms	-
End ramp [W/°]	140/41.5	-	-	100%-10% in 50ms	-
Angle of setup (respect to shaft axis) [°]	45	40	40	45	40
Offset [mm]	0.2	0.15	0.15	0.1	0
Shielding gas					
Gas type [type, l/min]	Nitrogen, 30	-	Nitrogen, 15	Nitrogen, 30	Argon, 15
Nozzle type	Conical	-	Conical	Conical	Conical, Ø8mm
Nozzle arrangement	Dragging	-	Fixed to laser's assembly	Dragging	Fixed to laser's assembly
Welding results					
Penetration [mm]	0.54	0.5	0.4	0.60	0.45
Intersect. Width [mm]	0.69	1.1	1.15	0.70	0.31
Cycle time [s]	0.7	8.2	7.9	0.7	8

Table 5: Summary of the various parameters tested, and results obtained [7]

Below, some pictures of the tests carried out and of the results obtained are shown; in particular, test setups and cross sections of the welding results are present:

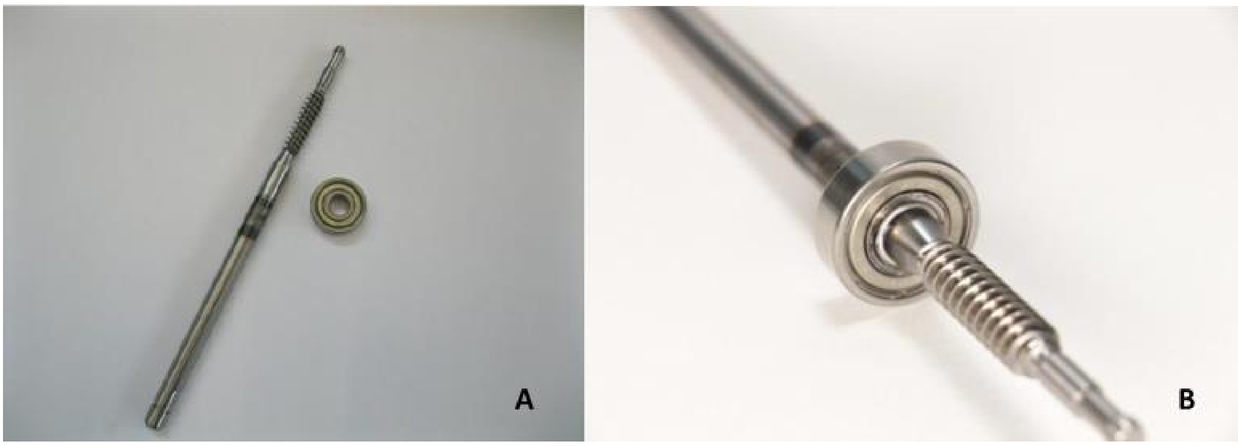
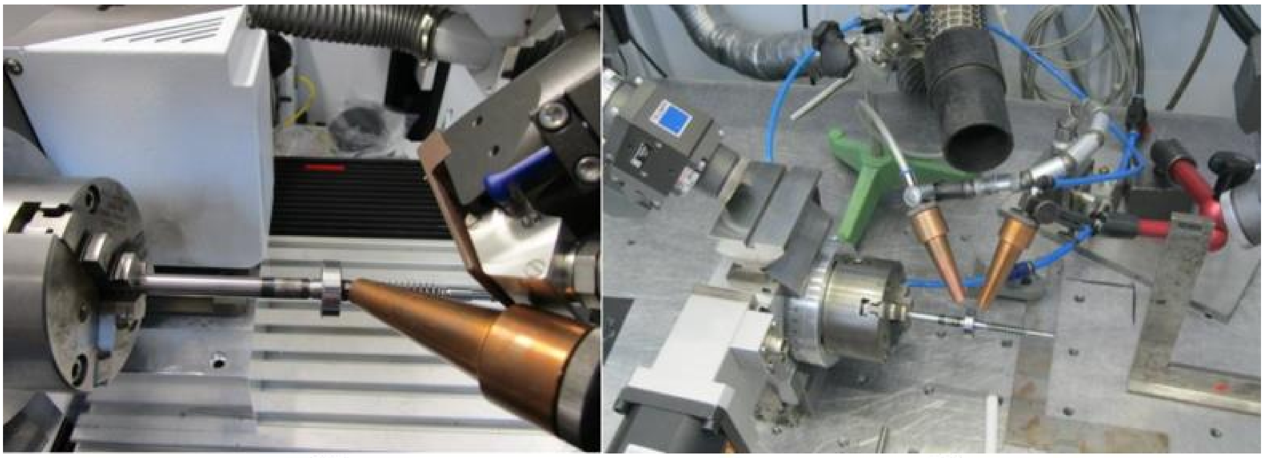


Figure 25: Ball bearing on shaft welding: (A) pieces to be welded together, (B) final welded assembly [7]



(A) (B)

Figure 26: Welding setup and clamping situation, (A) parameter 1 and 4, (B) parameter 2 and 3 [7]

(A) (B) (C)

Figure 27: Welding cord details: surface free of cracks, (A) parameter 1, (B) parameter 2, (C) longitudinal crack on the weld surface, parameter 4 [7]

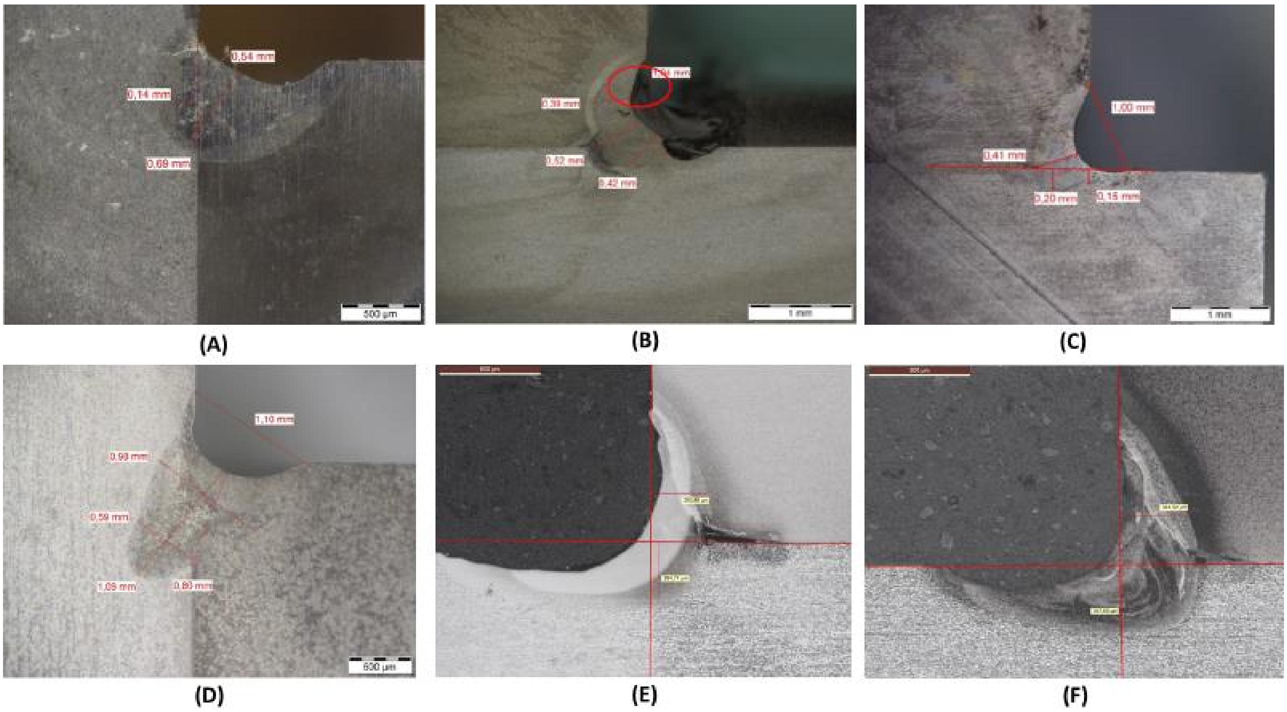


Figure 28: Cross-section of the welded joint with different parameters: (A) parameter 1, (B) parameter 2, (C) parameter 3, (D) parameter 4, (E) parameter 5, side 1, (F) parameter 5, side 2 [7]

At the moment of writing, the company responsible for the project is deciding wether to continue sperimentation or not because of budget problems, confirming the cost as one of the most deciding factors for welding feasibility.

8. Control methods for welded components

Control methods represent the last of the major factors discussed in this dissertation. In fact, it is foundamental to decide both the features to be controlled and the methods by which such features are controlled. Again, this is convalidated by an example of on-field experience from the internship experience of the candidate.

This project is a consolidated one, and it is in production phase, already, with an annual production about 100k units after the first-year ramp-up. It consists of two separated assemblies (named stage one and stage two, respectively); both are finally mounted into the muffler, being part of the system directing the exhaust gases flow inside. The two complete parts are present in Figure 29:

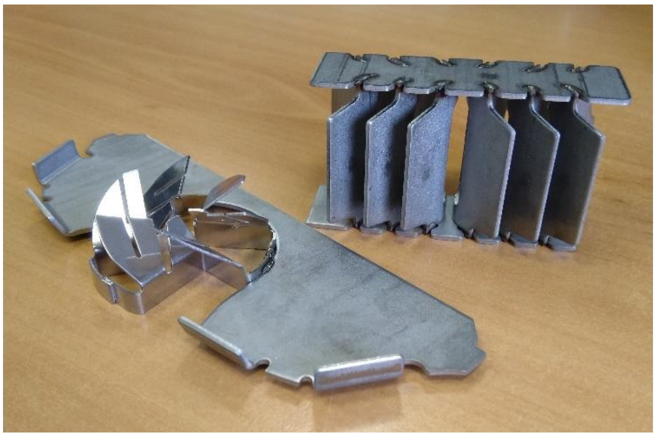


Figure 24: The two components for the silencer assembly: Stage 1 on the left and Stage 2 on the right [7]

Sacel is responsible for the whole process, starting from the raw material, thus, this project can also be a great example to look at the management of a complete product, highlighting the interactions between the various stages of the production process, and the relationship with the customer needed to achieve satisfactory results for both parts, too.

Particular interest resides in the welding masks required to perform the welding, which are foundamental to keep the single pieces in position during the welding phase and have a huge impact on the tolerances we are able to keep after the welding. A poorly designed mask, in fact, can lead to big variations between the pieces' position, resulting in scraps generation in the last phase of the production process, which represents a very high cost due to the previous production steps already completed. This was particurarly true for Stage 2, which had the most heavily modified design during the quotation phase.

To this extent, welding masks must ensure the correct positioning of the parts, regardless of the external factors that could potentially influence the welding performance, within the tolerance limits agreed with the customer.

8.1 Tools and production process description

The preliminary phase of the production process involves the feasibility analysis of the product, as designed in the first place by the customer, where Sacel gives suggestions on design chances that could improve the feasibility of the particulars without modifying the functionality of the assembly. In Figure 30 and Figure 31, the first revision drawings of the assemblies are depicted.

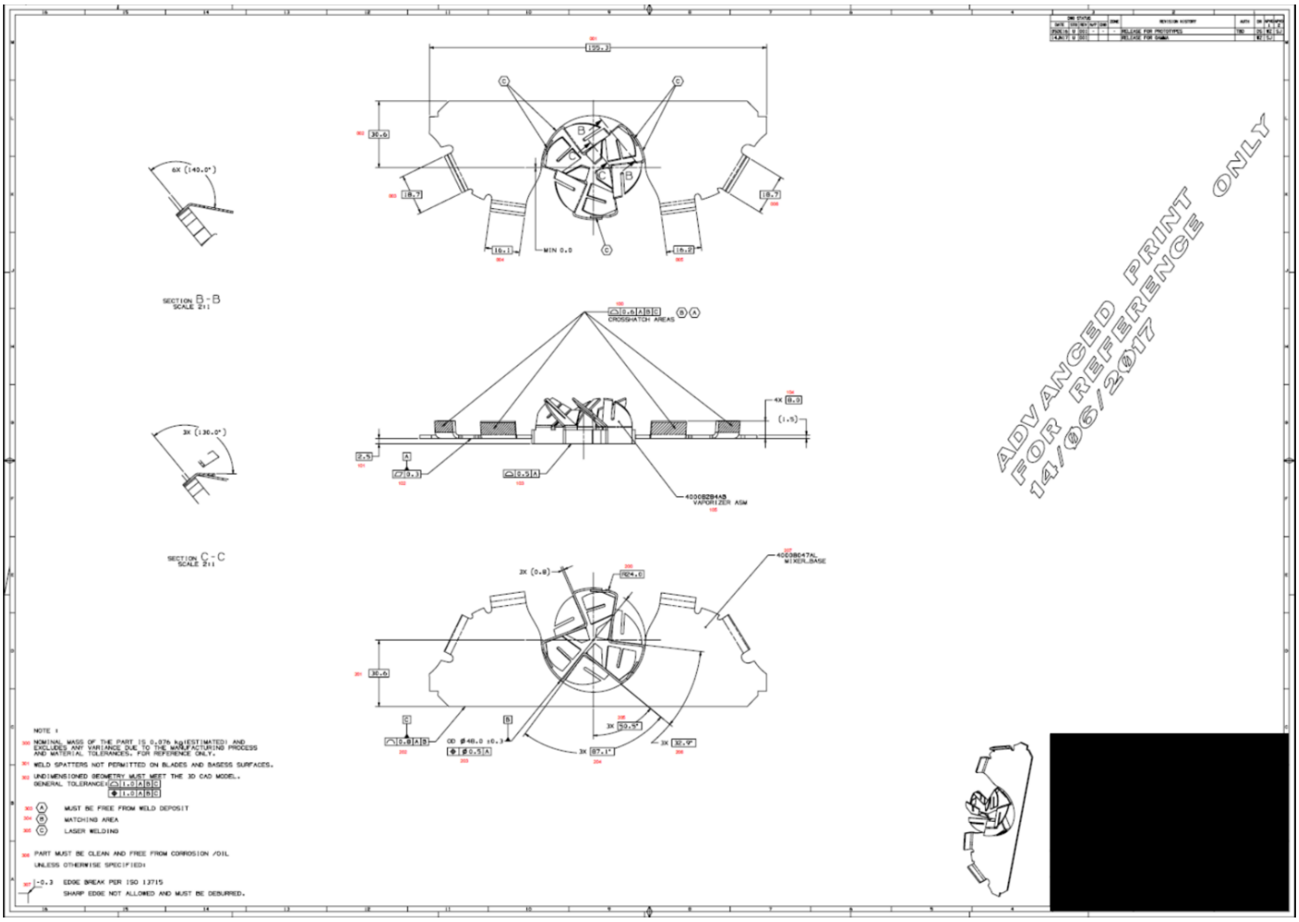


Figure 25: Stage 1 technical drawing, revision 01 [7]

The customer, who might accept or reject the suggestions given in the feasibility analysis, evaluates the changes proposed by Sacel. Of course, trade-off between customer requirements and Sacel's capability is needed; once boh parts are satisfied with the results, the final revisions of the drawing are released, and the actual production starts. As previously mentioned, Stage 2 is the one which was modified the most during this phase, because of too tight tolerances which couldn't be satisfied.

For both assemblies, the entire process is designed from raw material, and can be summarized in the following steps:

- Forming of the single components
- Washing of the components
- Welding of the components to create the final assembly
- Quality check and dimensional reports (both for single components and final assembly)

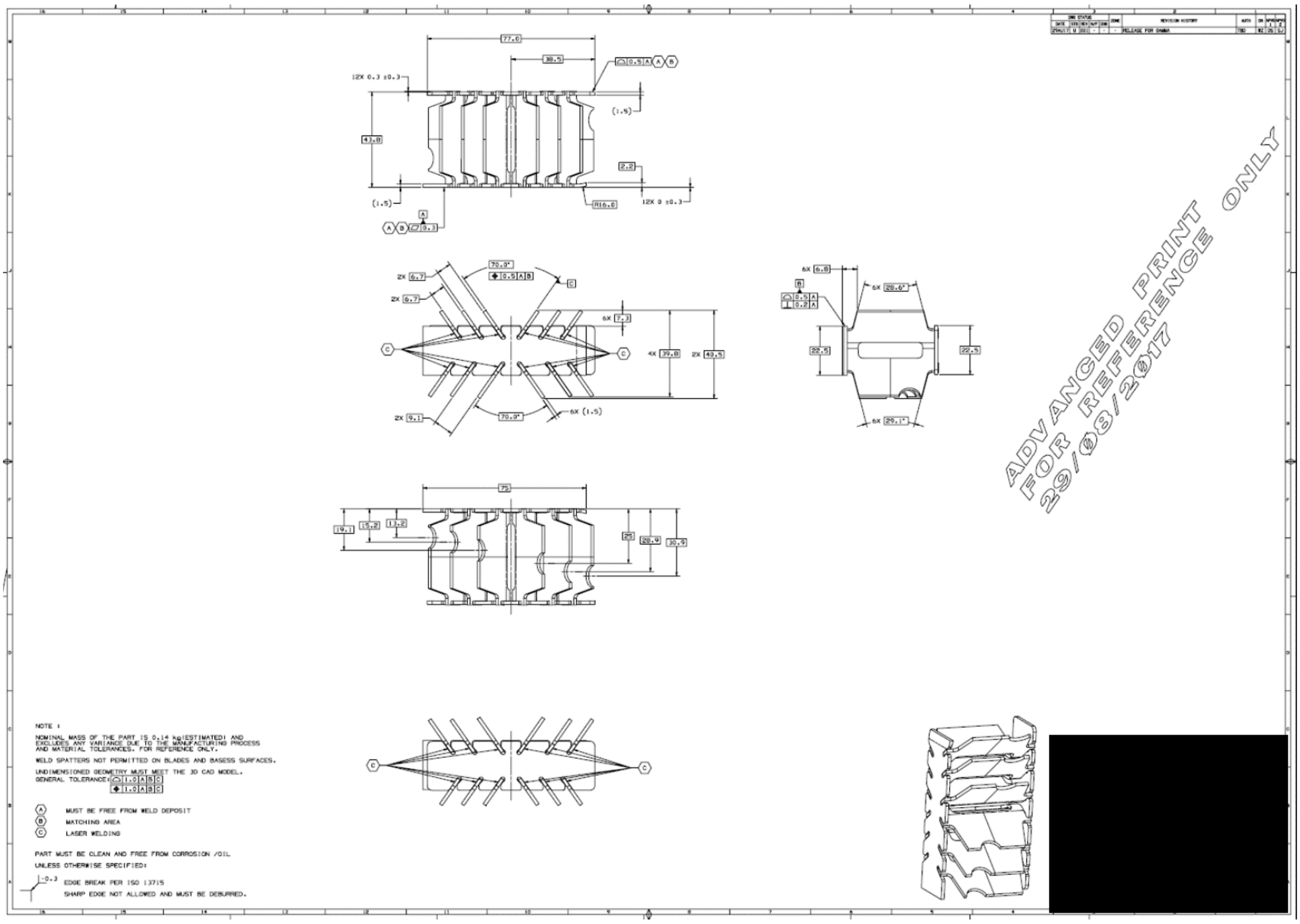


Figure 26: Stage 2 technical drawing, revision 01 [7]

8.2 Forming

The forming process is obtained for the most part with the use of progressive dies, except for the Mixer Base Upper and Mixer Base Lower (two components for the Stage 2), which are obtained through a simple cutting die. An example of the progressive dies used for the production of the single components for Stage 1 and Stage 2 is depicted in Figure 32.

As Figure 32 shows, a metal sheet enters the die, which can be divided into three different sections:

- Shearing zone
- Bending zone
- Detachment zone

Inside the shearing zone, the metal sheet is cut, practically defining the geometry of the final component, except for the attachment zone, wich is necessary to be kept because it's necessary to keep the components moving through the die. The number of steps required depends on the complexity of the geometry involved; in this example, the operation is carried out in just three steps.

In the bending zone, the bendings of the components are performed; depending on the kind of bending which has to be performed, two steps may be necessary to achieve a single bending, the second one being an adjustement, most of the times. In this specific case, just one step is required.

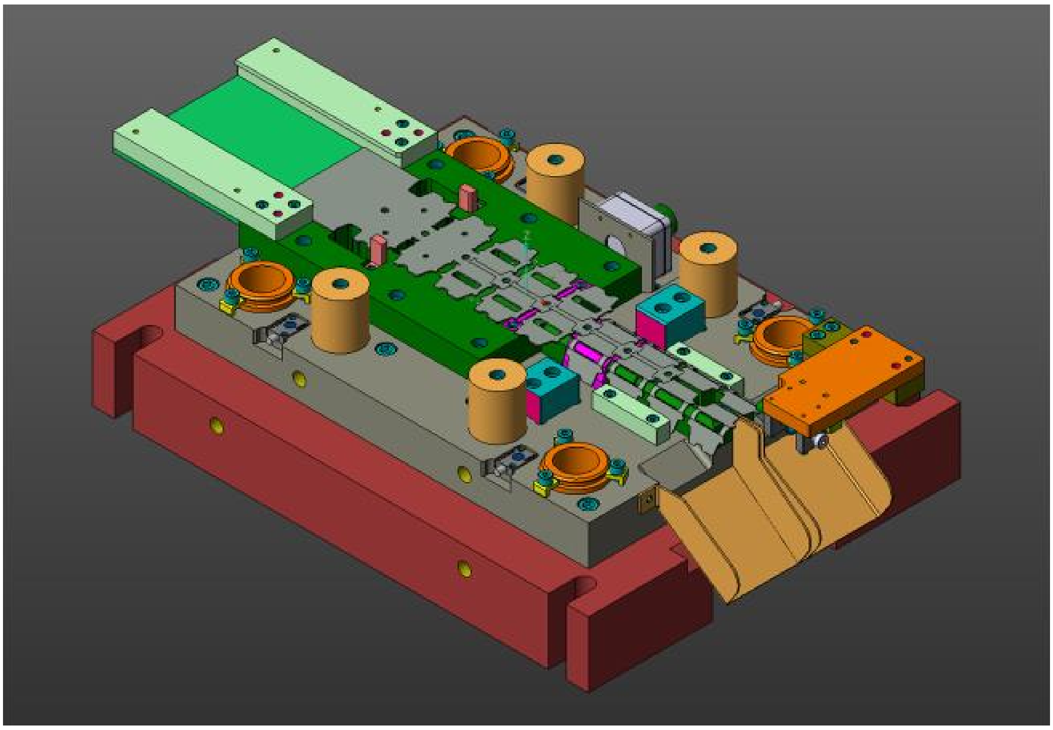


Figure 27: 3D model of the progressive die used for the production of a component for Stage 2 assembly (lower part) [7]

Finally, the detachment zone makes the final cut, detaching the single pieces from what remains of the original metal sheet; in this case, separation of the two pieces produced is performed. This is necessary in case one shearing punch fails, causing scraps production from one of the two sides; the adoption of separated slides allows to save one half of the production when the defects are noticed, reducing waste and increasing production efficiency.

8.3 Washing

The washing step is needed after the forming phase, because of the lubricant oil used inside the progressive dies, which may cause impurities to enter the welding region, thus causing potential failures to the assembly, once completed.

Given the flammable nature of the lubricant, too, the lack of this step may cause, in extreme cases, fires, due to the very high local temperatures experienced during laser welding. This production step is performed in industrial washing machines.

The characteristics of the components allow to not use specific washing racks for each component, in fact, the pieces are stiff enough to withstand the stresses deriving from stacking of the components on the metal bucket used in the washing machine.

8.4 Welding

Finally, the welding step is performed by means of a laser welding machine; in particular, a YAG machine operating at 500W is used for the welding of Stage 1, mounted on an anthropomorphic arm from ABB (model IRB 2400). For the welding of Stage 2 assembly, instead, it is used a CO_2 laser machine operating at 2kW, moved by a cartesian robot. Both weldings are performed on a rotating platform, to increase productivity by reducing the downtime required to place the single components on the welding masks, operation done manually by a human operator.

For both Stages, specific welding masks have been designed, aimed at mantaining the correct position between the components, resulting in finished assembly respecting customer specifications. For both welding masks, a more detailed description follows.

8.4.1 Stage 1 welding

This assembly has five welding points in total, as indicated in the technical drawing; for sake of clarity, the detail of the drawing representing the welding points is depicted in Figure 33.

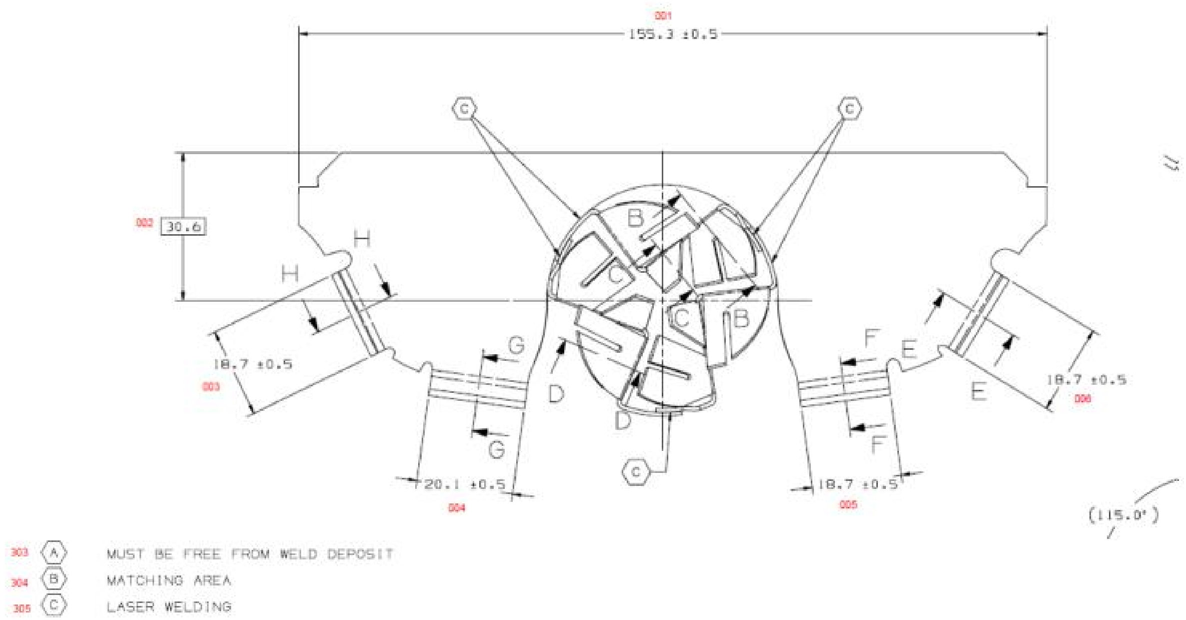


Figure 28: Stage 1 technical drawing, detail of welding points [7]

Three of this welding points are performed vertically, and weld together the three blades, the other two are performed horizontally, and joint the blades with the base, completing the assembly.

A scheme of the welding points with the length of the welding cords (expressed in angles of rotation of the anthropomorphic arm) is depicted in Figure 34. We can clearly see that the horizontal points do not overlap with the vertical ones. It is worth to mention that the positioning of such welding points follows an attempt of trade-off from Sacel in the early phases of production design. The proposal was to make an alternative design, aimed at making the welding easier. Such proposal, though, saw a negative response from the customer, who decided to keep the original layout.

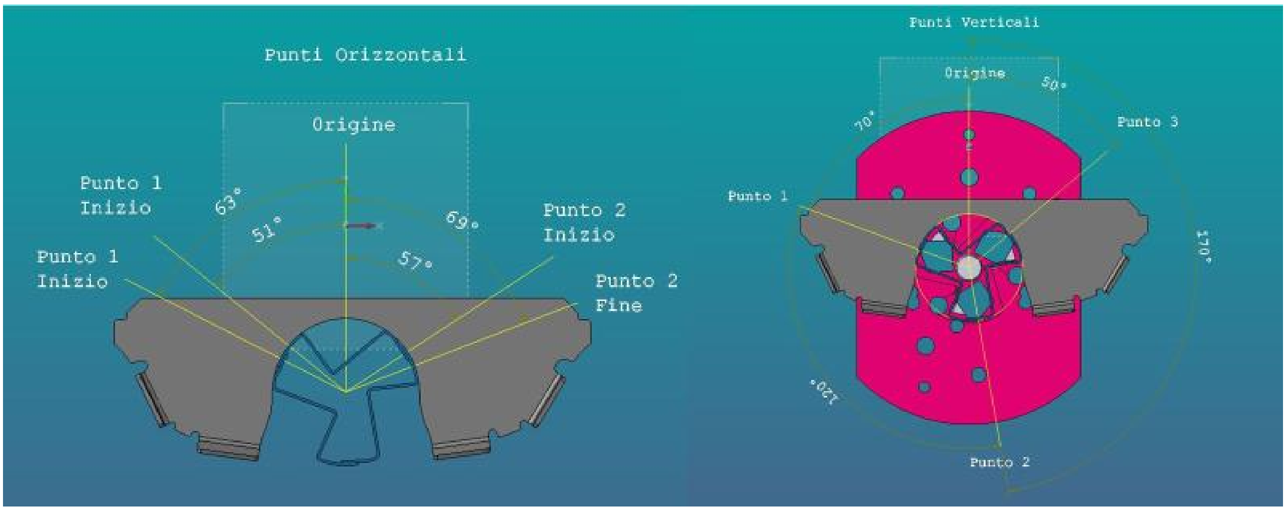


Figure 29: Schematization of the welding points for Stage 1: on the left, the horizontal points, on the right, the vertical ones [7]

The problem highlighted by Sacel was about the vertical points and the shape of the blade junction interface, if the blades would have experienced deformations. In fact, because the radius of the base and the one of the blades needed to match, such deformations would have interfered with the correct positioning between the blades and the base, creating a gap and making impossible the weld junction between them.

Sacel's proposal was to either simplify the matching or modify the geometry of the blades, changing the contact interface between the blades and the base, thus avoiding the need to match the radius of the blades with the base's one. Such solutions are represented in Figure 35 and Figure 36.

The customer, who opted for a matching simplification, increasing the radius of the blades' bending in the overlap zone, eventually rejected Sacel's proposal. In this way, though, the matching of the radius was made easier, and the problems related were greatly reduced, granting satisfaction for both parts.

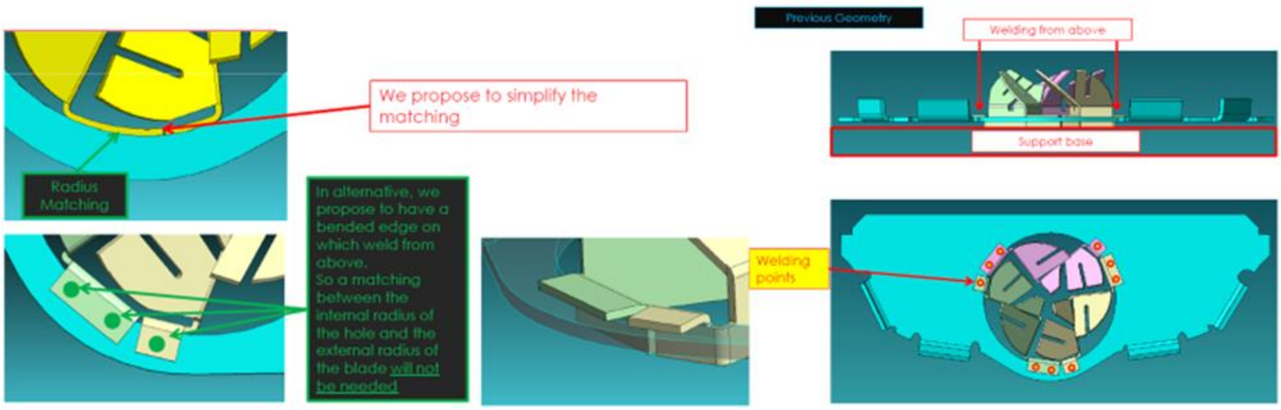


Figure 30: Sacel's proposals of design change on Stage 1, 1 of 2 [7]

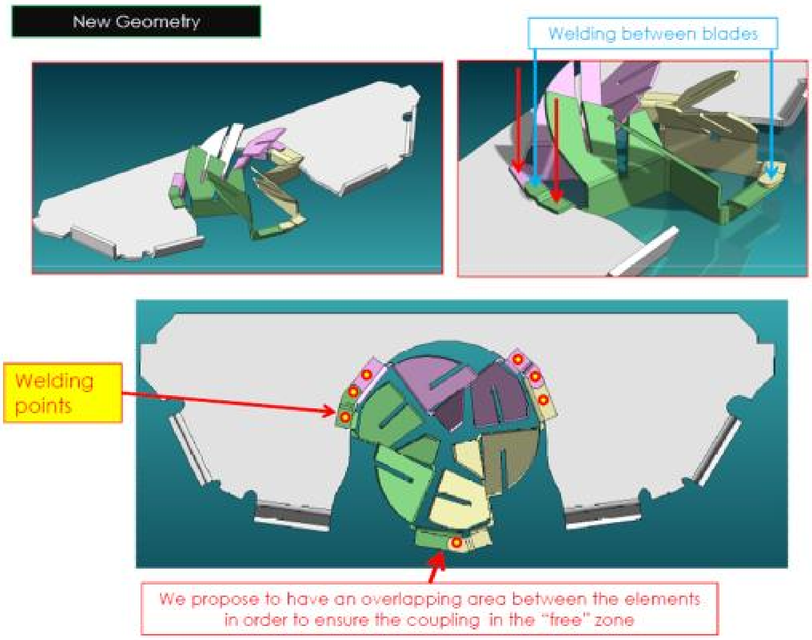


Figure 31: Sacel's proposals of design change on Stage 1, 2 of 2 [7]

8.4.2 Stage 1 welding mask and welding operation

As previously mentioned, we need the single components to be hold in position during the welding phase, to avoid errors that could produce scraps which are somewhat dangerous from an economical point of view.

Introducing errors in this step of production, in fact, represents an economical loss for Sacel which is very high. The reason is that each production step represents a cost for the manufacturer, from the raw material, to the tools' utilization, to the energy required to run such production tools, and, of course, the time required for production. To these aspects we must add the quality checks already performed after each previous production step.

All these operations contribute to the build up of the eventual economic loss in case a defect is generated in the last steps; for these reasons, the further the step is performed, the higher quality requirements need to be taken to avoid scraps. It is worth to mention that these considerations apply for shipping and transportation of the final assembly to the final customer, too, but these aspects lay beyond the purpose of this dissertation.

Now that we made clear the importance of the accuracy needed for this final step, we can look at the iterations that led to the final mask design for this product. For this case, the first iteration was mostly oriented to make the customer understand the need for new and specific equipment for this welding. It was presented to the customer in the initial stages of the quotation phase. Figure 37 shows the 3D model of this equipment on its first iteration, with the laser beams from the machine highlighted in green.

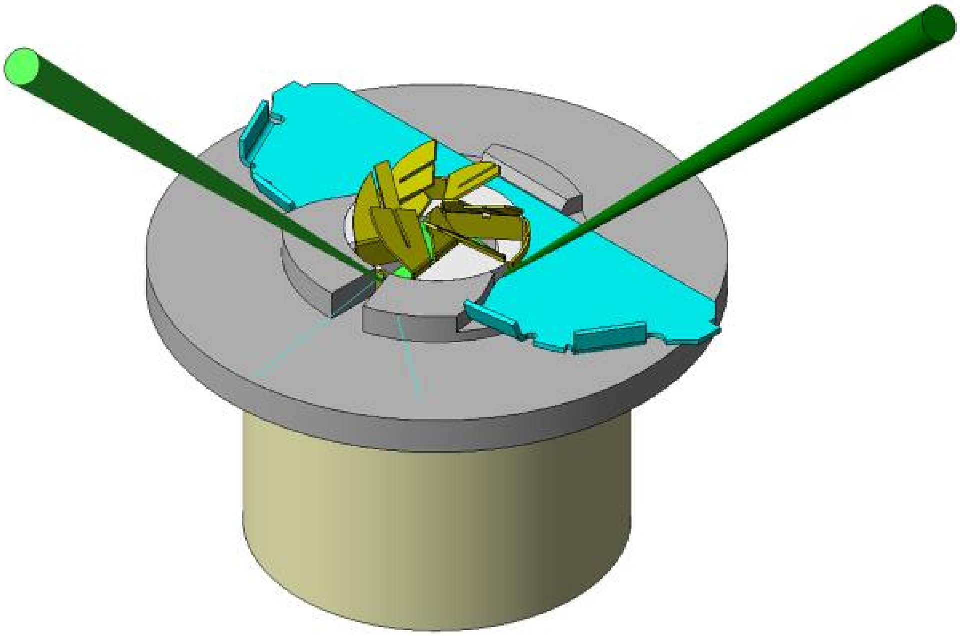


Figure 32: Welding mask for Stage 1, first concept. In green the laser beams from the welding machine [7]

Further on, the design was developed to achieve the final revision of this equipment, depicted in Figure 38 as the actual tool mounted on the laser welding machine. As the figure shows, the mask is mounted on a rotating platform, this increases productivity by reducing the overall time required for the welding operation. The operator, in fact, is able to load the components of the new welding while the first one is undergoing the welding program on the other side of the rotating platform. The opening and closing of the mask are performed by a pneumatic clamp which assures the necessary closing strength to be applied to the components.

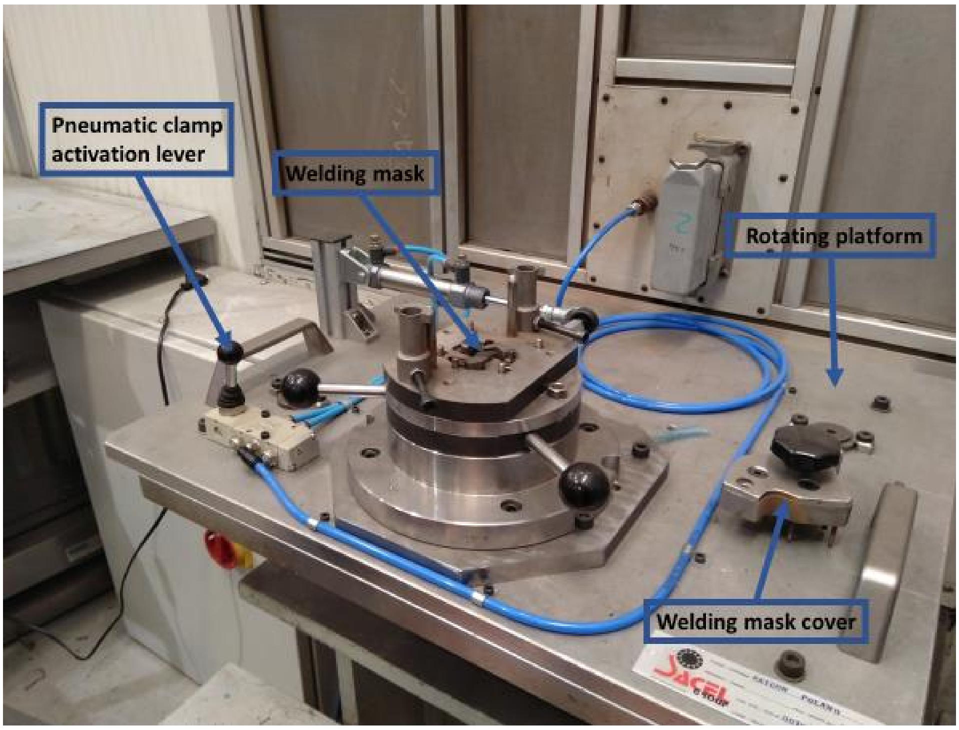


Figure 33: Stage 1 welding mask, final version, as mounted on the welding machine, with the main components highlighted [7]

The steps required by the operator to perform the welding are illustrated in Figure 39 and include:

- Opening of the pneumatic clamp
- Insertion of the base and the blades
- Closing of the pneumatic clamp
- Placing of the cover on the closed mask
- Launching of the welding program (the rotating platform switches places)
- Removal of the cover, opening of the clamp of the removal of the complete assembly from previous cycle on the other mask

In Figure 39 we can see the sequence required to perform the welding: first o all, the mask assembly without the final piece (Figure 39(A)), with the pneumatic clamp in the open state, as well as the teeth that will be clamping the components to assure the welding to be effective. With the clamp open, the operator places the base, as shown in Figure 39 (B); then the blades (Figure 39 (C)), and the clamp is then closed (Figure 39 (D)); finally, the cover is placed, and the welding program is started (Figure 39 (E)).

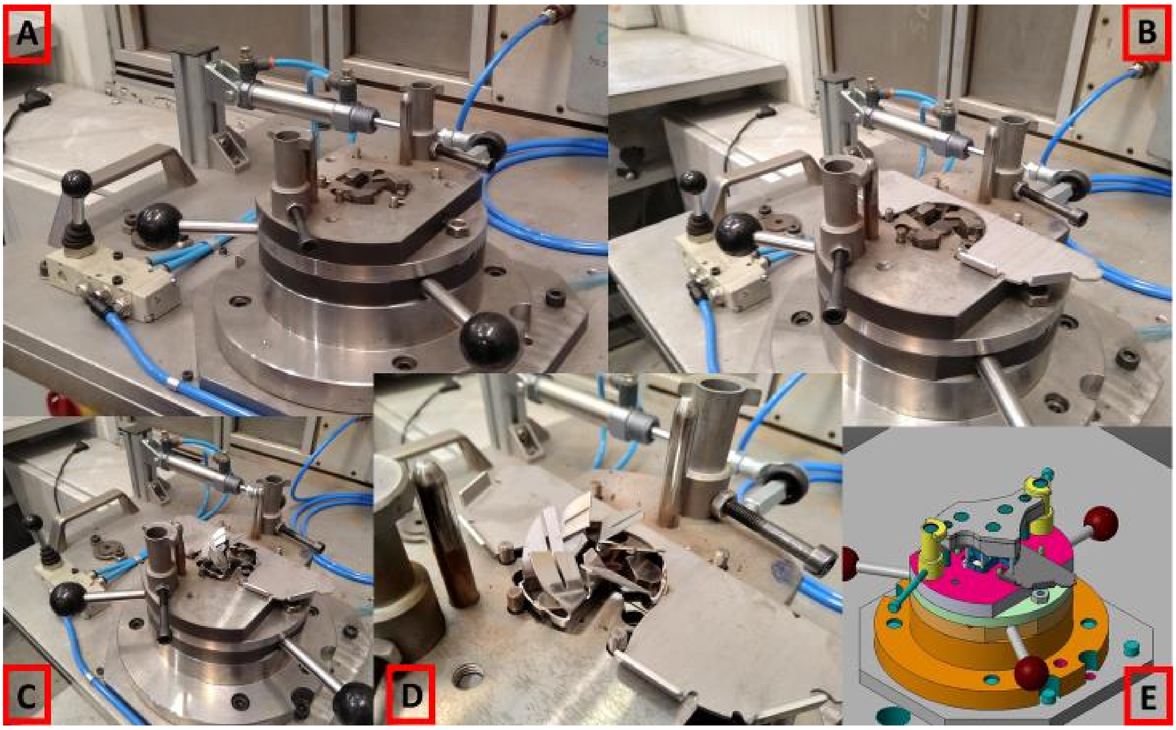


Figure 34: Sequence of operations required for welding of Stage 1: (A) opening of the clamp, (B) positioning of the base, (C) positioning of the blades, (D) closing of the clamp, (E) positioning of the cover and launch of the welding program [7]

When the welding program starts, the platform rotates, and the previously mounted assembly can be taken off after the clamp opening, allowing for a new cycle to be started. By the time the operator has prepared the next cycle, the welding cycle for the previous one is ready for removal, and a new cycle can begin.

8.4.3 Stage 2 welding

This welding presents 24 welding points, half on the upper part and the other half on the bottom, as shown in Figure 40; again, a detail of the technical drawing is given for sake of clarity. This assembly has undergone more changes during the quotation phase, due to design requests that were impossible to satisfy reliably way during production.

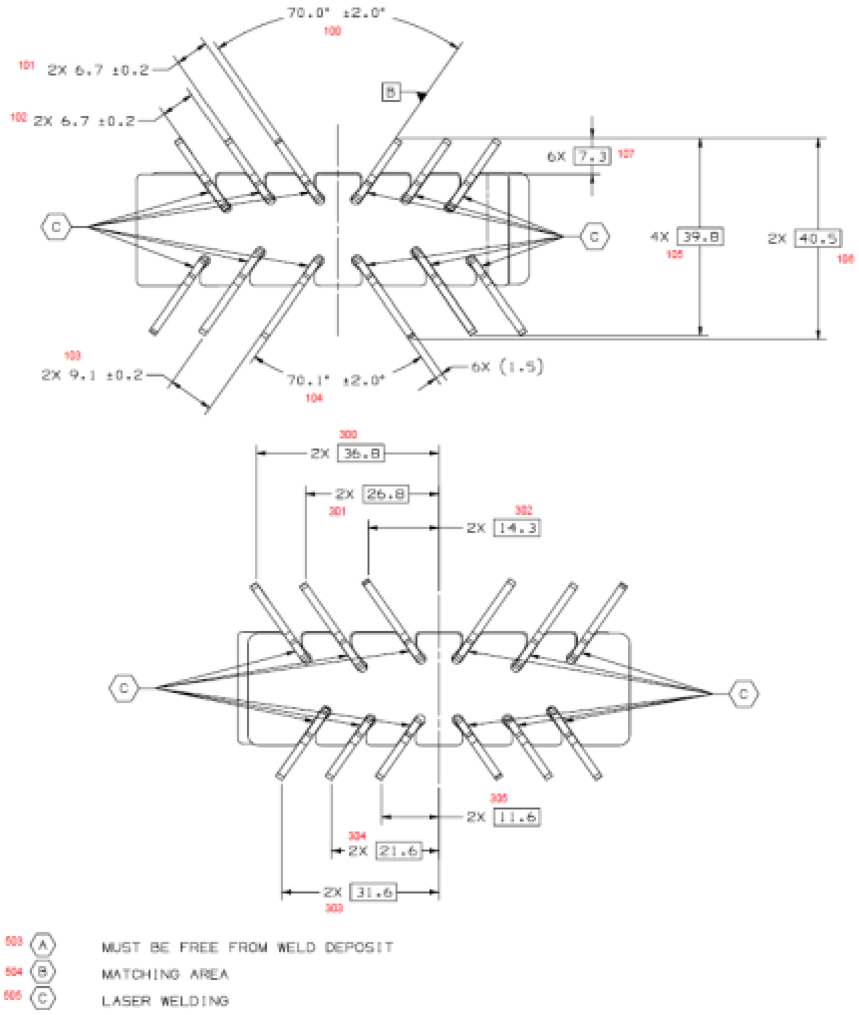


Figure 35: Stage 2 technical drawing, detail of welding points [7]

The final revision of the technical drawing presents a table resuming all the changes agreed by both parts, for each change, the drawing coordinates of the quotation that has been modified is indicated, together with values of such quotations both prior and after the changes. This table is shown in Figure 41; the general trend has been the increase of tolerances limits, especially for features that are of difficult measure.

As above mentioned, this welding is performed with a Cartesian robot arm, this means that the assembly needs to be rotated during the welding operation to allow the welding of the bottom part of the assembly. This is carried out by a pneumatic circuit activating the mask supports, allowing the rotation and exposure to the laser of the bottom face of the assembly.

DWG STATUS					ZONE	REVISION HISTORY	AUTH	DR	APVD 1	APVD 2
DATE	STG	REV	N/P	CHG						
	U	001	-	-	-	BASED ON 40008285AD_001		EA	WZ	SJ
27JL18	R	001				RELEASE FOR PRODUCTION		EA	WZ	SJ
09AU18	R	002				3D MODEL UPDATED		EA	WZ	SJ
09AU18	R	002				RELEASE FOR PRODUCTION		EA	WZ	SJ
24JA19	R	003		A	K8	$12X0.1^{+0.3}_{-0}$ REMOVED				
				B	M12	$12X0.2^{+0.3}_{-0}$ REMOVED				
				C	J10	70.0° ±2.0° WAS 70.0° ±0.5°				
				D	G10	70.1° ±2.0° WAS 70.1° ±0.5°				
				E	H9	6X 7.3 WAS 6X7.3±0.2				
				F	H8	4X 39.8 WAS 4X39.8±0.3				
				G	H8	2X 40.5 WAS 2X40.5±0.3				
				H	J6	6X6.8±0.6 WAS 6X6.8±0.2				
				J	F13	19.4±0.6 WAS 19.4±0.2				
				K	F12	15.5±0.6 WAS 15.5±0.2				
				L	F12	13.5±0.6 WAS 13.5±0.2				
				M	F9	25±0.6 WAS 25±0.2				
				N	E8	28.9±0.6 WAS 28.9±0.2				
				O	F8	30.9±0.6 WAS 30.9±0.2				
				P	D11	2X 36.8 WAS 2X36.8±0.2				
				R	D11	2X 26.8 WAS 2X26.8±0.2				
				S	C10	2X 14.3 WAS 2X14.3±0.2				
				T	B10	2X 11.6 WAS 2X11.6±0.2				
				U	B10	2X 21.6 WAS 2X21.6±0.2				
				V	A11	2X 31.6 WAS 2X31.6±0.2		EA	WZ	SJ

Figure 36: Table of design changes' history for Stage 2 assembly [7]

8.4.4 Stage 2 welding mask and welding operation

As for Stage 1, Stage 2 has seen a couple of iteration for the welding mask design, the first being presented to the customer in the early stages of the quotation stage, and then developed to achieve the final revision actually in use; the 3D model of the first revision is depicted in Figure 42. The same considerations about the importace of the mask quality discussed for Stage 1 apply for this case.

The final version of this mask follows the same idea of the one used on Stage 1, from a productivity point of view. In fact, the mask is doubled and mounted on a rotating platform, allowing the operator to load the single components of the next cycle while the first one is being welded on the other side of the platform.

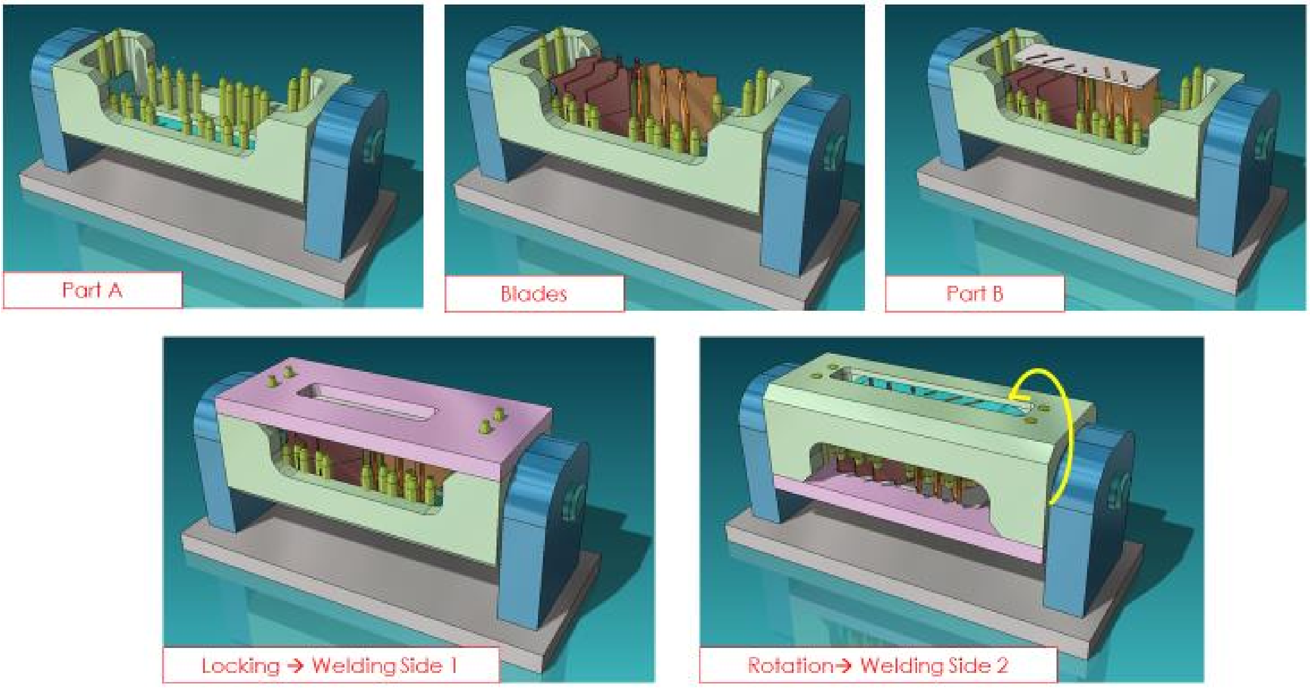


Figure 37: Stage 2 welding mask, revision 01 [7]

The 3D model of the actual tool and the welding sequence are shown in Figure 43 and 44, respectively; the red cone in Figure 43 represents the laser beam. It is worth to notice that, being the tool rotated upside down during the welding, the cover needs to be secured at the tool, and this is achieved by two horizontal clamps.

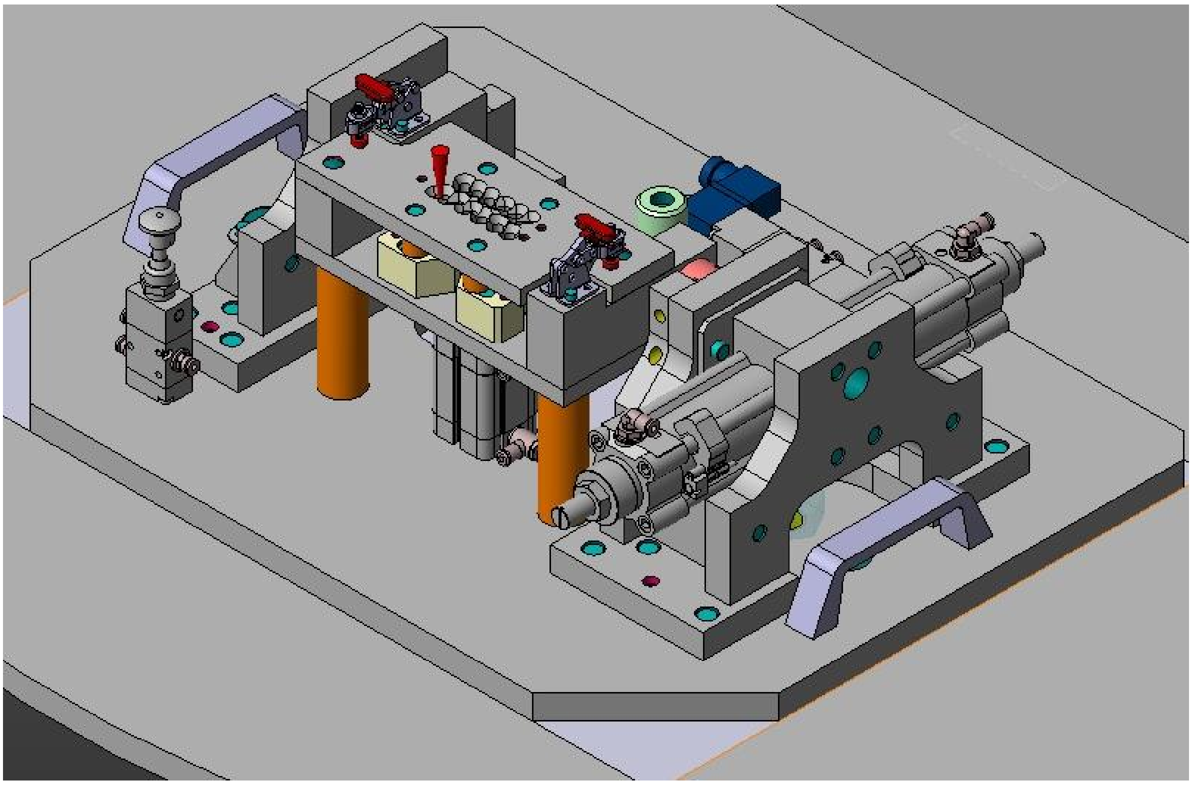


Figure 38: Stage 2 welding mask, final revision [7]

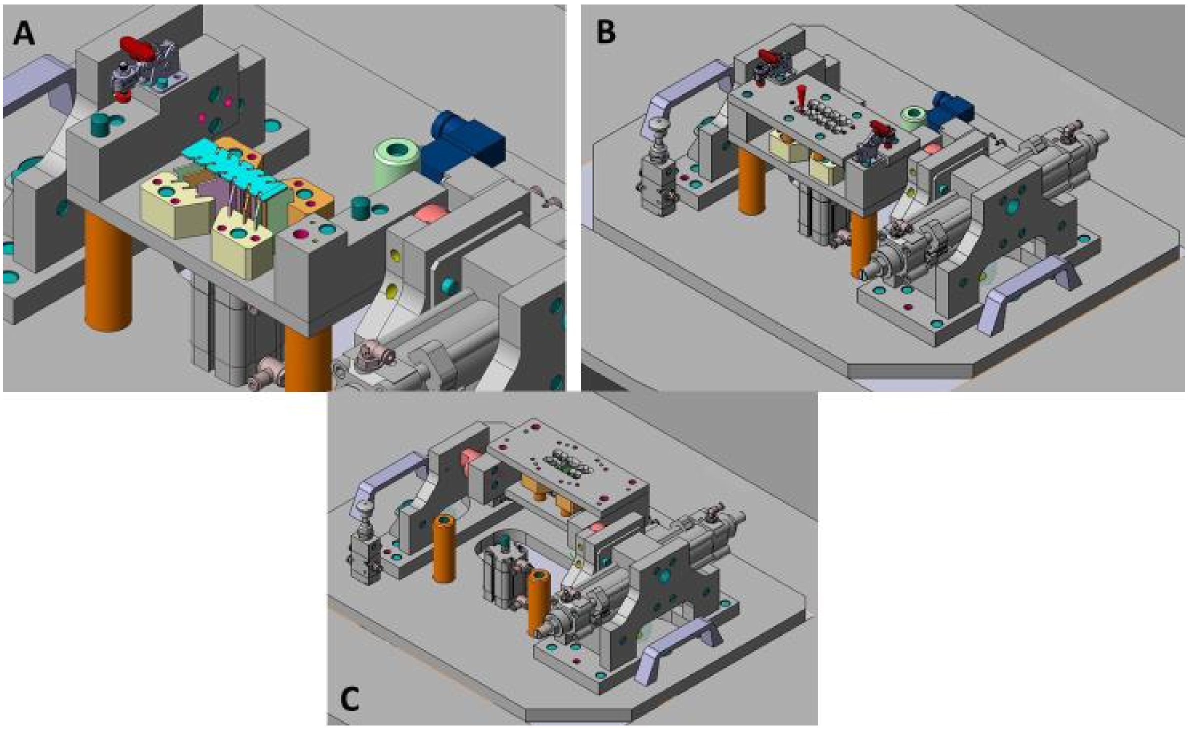


Figure 39: Sequence of operations required for welding of Stage 2: (A) positioning of the single components, (B) closing of the mask with the cover and securing with the clamps, (C) rotation of the mask (automatically done inside the welding zone) [7]

As shown in Figure 44, the following sequence is required to the operator to perform the welding, this includes:

- Positioning of the bottom plate, blades and top plate (Figure 44 (A))
- Positioning of the cover and closing of the clamps (Figure 44 (B))
- Launching of the welding program
- Unloading of the finished product coming from the previous cycle

In Figure 44, we can also see the mask when the rotation is performed, this operation is automatically done inside the welding zone by means of the pneumatic cylinder at the mask side. After the welding, the mask rotates back to its original configuration, so that the operator is able to open the clamps and unload the finished assembly. The functioning of the rotating platform is regulated in the same way as for Stage 1: the rotation of the platform allows the operator to load/unload the single components and the final product, respectively, while the welding program takes place for the other half of the rotating platform, resulting in increased productivity and reduced cycle time.

8.5 Quality controls

Quality controls represent a key feature to assure the achievement of design specifications, as described by the customer, in a continuous and reliable way. For these reasons, quality controls are implemented after each phase of the production process, from raw material to the finished product.

Figure 40: DEA Hexagon measuring machine, of the type used to gather the data inserted in the dimensional reports [7]

Controls and measurements type and accuracy range extensively, and vary greatly depending on the phase of production, in fact, we have different steps from process definition to full operating production, these include:

FOT (First of Tool): in this phase, the entire production process is defined, from production sequence (forming, washing, welding etc.), to tools definition (die, washing machine and welding machine used for the production, specifying if different machines are used); finally, tools' working parameters are defined. Everything is submitted to the customer through a dimensional report, that will be eventually approved, being the products satisfactory for the customer.

In this phase, the measurements for quality controls are done based on the technical drawings, verifying all the measurements indicated in the peening. Measurement machines such as the DEA (illustrated in Figure 45), able to measure precisely up to a thousandth of millimeter, are the ones gathering the measurements. An example of dimensional report, instead, is shown in Figure 46, and it is relative to Stage 1 finished product.

CENTER OF MEASURE	PPAP N°	Date

Sacel s.r.l Strada del Paschetto, 19 S.Giorgio Canavese (TO) 10090 - ITALY	Quality Assurance Manager [redacted] Quality Manager [redacted] PPAP Manager & Metrology [redacted]

Dimensional Report (ISIR)

LEGEND TOOL				DRAWING INFORMATION		
				Customer [redacted]		
C	Caliper	P	Profilometer	Part Number [redacted]		Rev. Num 001
M	Micrometer	BPP	Gauge Block			
T	Comparator	MT	Traction M.	Part Name MIXER ASM.		Rev. Date 25/07/18
CMM	3d Machine	SP	Gauge Diam			
OM	Optical Mach	G	Glossmeter	Date 10/12/18	Operator Fardin M.	
R	Roughness	D	Durometer			

FIGURA / CAVITY					F2P1	F2P2		F1P1	F1P2	Results	Tool	NOTE	SPC	COMMENTS NOTES
Num.	Symbol	Nominal	Min.	Max	Dim.	Dim.	Dim.	Dim.	Dim.					
N°001		155,300	-0,500	0,500	155,322	155,326		155,334	155,321	OK	CMM			
N°002		30,600			REF	REF		REF	REF	\	CMM			
N°100-1		0,000	-0,300	0,300	0,072	0,071		0,068	0,070	OK	CMM			
N°100-2		0,000	-0,300	0,300	0,147	0,152		0,190	0,153	OK	CMM			
N°100-3		0,000	-0,300	0,300	0,151	0,152		0,157	0,159	OK	CMM			
N°100-4		0,000	-0,300	0,300	0,124	0,140		0,110	0,136	OK	CMM			
N°101		2,500			REF	REF		REF	REF	\	T			
P146		0,000	-0,500	0,500	-0,293	-0,516		-0,422	-0,267	NC	CMM			
P147		0,000	-0,500	0,500	-0,214	-0,407		-0,310	-0,177	OK	CMM			

Comments and Notes	
#1	Measured on Points P130–>P147

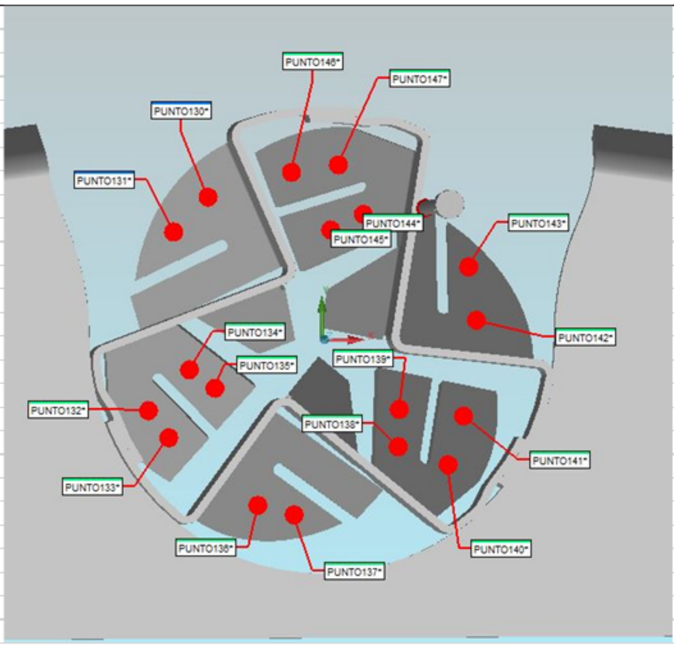


Figure 41: Part of the dimensional report for the FOT of Stage 1 [7]

PPAP (Production Part Approval Process): this is a milestone for the production process, after this phase, the production process is frozen, and no changes are allowed without customer's permission.

Full production: the products should respect customer's specifications and controls are performed periodically to check for variations, which may come from a variety of factors (tools' wearing out, operators' mistakes, improperly done maintenance etc.). All of these factors are taken into account in the **FMEA** (Failure Modes and Effect Analysis) analysis, where all the possible istances that could lead to scrap production are investigated and listed, together with the occurrence and severity of each factor.

From the FMEA, the control detail document is produced: this document summarizes every quality control to be done during production phase, both during machine and/or tool setup and full-scale production, by means of a table, to be filled by both the quality control employee and the operator present at the time of production. A new table has to be filled whenever the tool is mounted on the die (in case of components obtained by means of progressive dies) or a certain threshold of machine downtime is exceeded (weekends, for example). An example of this document is shown in Table 6, representing the control detail document for Stage 1 final product.

Phase	Cont.	Characteristic	T	Instrument	C/C	R.P.	Tech. documentation	N.C.	Freq.	Val.	V. cont.
670	SET	Machine parameters verification	A	Visual	0	A	Sheet of parameters	1	1		
680	SET	Correct welding	A	Visual	0	A	Specimen	2	1		
700	SET	Specimen conformity	A	Visual	0	B	Specimen	2	1		
705	SET	Presence of all components	A	Visual	0	A	Specimen	2	1		
710	SET	Dimension 2.50 +/-0.40 (Dim.101)	V	Caliber	0	B	Customer drawing	2	1		
720	SET	Diameter Ø48.00 +/-0.30 (Dim.207)	V	CMM OGP	0	A	Customer drawing	2	1		
730	SET	Absence of errors and deformation	A	Visual	0	C	Specimen	2	1		
800	PRO	Correct packaging	A	Visual	0	A	Sheet of packaging	2	1		
805	PRO	Correct welding	A	Visual	0	A	Specimen	2	124		
810	PRO	Specimen conformity	A	Visual	0	A	Specimen	2	124		
820	PRO	Presence of all components	A	Visual	0	B	Specimen	2	124		
830	PRO	Dimension 2.50 +/-0.40 (Dim.101)	V	Caliber	0	A	Customer drawing	2	124		
840	PRO	Diameter Ø48.00 +/-0.30 (Dim.207)	V	CMM OGP	0	A	Customer drawing	2	124		
850	PRO	Absence of errors and deformation	A	Visual	0	C	Specimen	2	124		

Table 4: Example of control detail document for Stage 1 finished product [7]

As the table shows, two different macro-phases take place, highlighted by the Control (Contr.) column: setup and production. The first one is followed by the quality control employee, with the goal of restoring the machine parameters to the values indicated in the PPAP document and verify the conformity of the product; in this phase, the controls are carried out on every single product coming out from the machine, as the frequency column in the table shows. The number of final products to be controlled, instead, is reported in the Number of Controls (N.C.) column.

The production macro-phase reflects the controls already performed in the setup phase, but the operator is responsible for these ones, and the frequency of controls is varied, for this specific case, controls must be performed once every 124 pieces produced.

Column "T" indicates the type of controls to be performed, which may be one of the following:

- **V**: the control is carried out by variables; this means the control/measure gives a value that must be checked with the reference ones and must fall within tolerance range. The reference measure is indicated and refers to the technical drawing peening, and the measures are subjected to Cp and Cpk studies to keep variability under control. Different measurement tools might be used for such controls, such as calibers, comparator gauges and, as used for Stage 1 case, a CMM OGP machine. This last instrument, an example of which is shown in Figure 47, is a measurement tool based on image acquisition, which is then compared to a model loaded on the machine. One of the best pros deriving by the use of this machine is that the measurement is independent from the orientation of the controlled part, translating in a more reliable measure. The main drawback is the additional time required for the measure to be carried out, potentially slowing down production if the control frequency was too high.

Figure 42: An example of a CMM OGP measurement machine, such as the one used for Stage 1 production controls [7]

- **A**: the control is carried out by attributes; this means controls that are either visual (as the ones performed for this specific case) or made by means of gauges using the go-nogo approach, such gauges are a fast and relatively easy way to determine wether or not a feature is within tolerance range or not. The easiest example that could be made about this kind of gauges is the control of a hole: for this feature, a double-diameter shaft, with the smaller one that is able to enter the hole in case of minimum dimension, represents the gauge. The bigger one, instead, should not pass through the hole when the maximum dimension of the hole is obtained; thus, the hole will successfully pass the control if the smaller diameter only passes through the hole, the control will be failed if the gauge either does not enter into the hole at all or enters completely.

It is worth to notice that some controls might be made using the variables type during setup, while attributes controls are used for production, even though this is not the case for Stage 1 final product.

The last two variables of the control detail document that sre still to be explained are the Class Characteristics (C/C), and the Reaction Plan (R.P.) columns. The first one represents the importance of each control featured in the control detail document, based on the following coding:

- **0:** significative for Sacel
- **C:** critical for the customer
- **I:** important for the customer
- **S:** secondary importance for the customer

The Reaction Plan column, instead, resumes the operation neede by the quality control employee or the operator, if the control should give a negative result. Again, the action to be performed are referred to a code where each letter represents the action required, with the meaning of each letter listed below; we have:

- **A:** regulation of the tool/machine
- **B:** dismounting of the tool/machine
- **C:** cleaning of the tool/machine
- **D:** quality intervention

Of all the actions listed above, quality intervention is not present for the final product of Stage 1, that's because this action is generally reserved if the raw material shall have problems, which may range from visual defects on the surface to wrong dimensioning or out-of-tolerance measures. In these cases, the supplier is notified of the problem met, and solutions are taken accordingly.

It is finally worth to mention that no requirements from the strength-of-the-welding point of view were declared by the customer, this being the reason why no data have been gathered regarding welding strength and no specific testing other than empirical ones have been performed to assure the necessary strength of the welding.

9. Conclusions

Laser welding has proved to be an extremely viable and versatile joining method for the metalmechanical industry, and the ongoing trend of increasing laser power will allow these characteristics to be developed even further in the future. However, many challenges are still to be faced, mostly related to the weldability of different materials within the same joint [2]. On this topic, empirical results show that some weldings of this kind are achievable, with satisfying results, too, as the ball bearing on a steel shaft case demonstrated.

In this case, in fact, we have seen how the welding of a ball bearing to a steel shaft of C45 steel is achievable, with good results, too, in terms of welding strength and weld quality, from both a mechanical and an aesthetical point of view. As discussed before, the mechanical strength of this welding could not be evaluated with specific tests, but the images obtained by microscope are a good indication of a result, which is probably good enough for the tasks requested by this joint.

Technology improvements, though, helped to achieve already important goals, especially in terms of beam precision and depth. Nevertheless, complex products requirements show how welding machinery accuracy and precision must be coadiuvated by a robust production of the initial components [7], which must respect the weldability requirements that, especially in laser welding, are particularly severe.

Many factors, though, can change the outcome of the welding, resulting in scrap prosuction. We have seen how careful design of both the parts and the production process is the key to reduce to a minimum the chance of out-of-tolerance products. With these factors in mind, we cannot forget about the economic considerations regarding laser welding, which, despite being an extremely effective joining process, might be too expensive for certain applications, to the point that other joining processes (such as interference joining) are preferred over laser welding, as the second case we talked about showed.

Once the design and the machine parameters are set, it is foundamental to define the control methods to ensure the parts are produced by specifications. In this scenario, both the features to measure and the measurement machines/methods are key aspects of the control methods as a whole. Once again, economic considerations lead to more strict controls as the production process approaches the final product, necessary to minimize the economic losses coming from scrap production. In this state of mind, the key factors result to be the ones that are most likely to cause errors within the production process, the choice of which is greatly influenced by experience, too.

To this extent, good communication both between companies and suppliers, and within the company itself, is always advisable, and should be aimed at achieving the best trade-off between design requirements and process capability. To achieve this goal, design requirements should always take into consideration the production process' strengths and weaknesses, making design choices accordingly.

Unfortunately, from the experience matured during my internship at Sacel, I personally saw how this awareness of the production process is lacking in most situations, especially in big companies where design and production are different realities. Here, different people with little to no communication between them or the key roles are involved in these different phases of a project.

10. Aknowledgements

In this section, I want to thank everyone who helped me in both this final project and in the entire degree course.

First of all, I want to thank my parents and my sister, who supported me in every tough moment of this course, making me find the extra motivation I needed when things were not going well, both from here and abroad (I love you, sister). Thanks to Erika, who made this last year very special to me, together with her family.

Thanks to everyone I had the fortune to meet during this degree course, both to the ones I shared just a module with, the ones who have been with me since the first year (Luca and Riccardo), and the ones I met outside of Politecnico (Matteo).

Thanks to the brothers I met on the rugby field of VII Rugby Torino, and to the awesome friendships born around that field (Rebecca, Gaia, Christian, Daniele, Luca, Beppe, and everyone else).

Thanks to Sacel Srl, which gave me the opportunity to write this final project and get a glimpse on the job world; the experience I got there will surely be of great impact for my future. Also, thanks to all the awesome people I met there, both from the technical office and the other sections of the company.

Finally, thanks to my tutors, Prof. Lombardi and Prof.ssa De Maddis, for the support necessary to make this project possible and finished in time.

To all of you, my deepest gratitude, you have been part of this experience and you made it special, everyone in his/her very own way. I probably wouldn’t have made it without you, thank you very much.

11. References

[1] Svenungsson J., Choquet I., Kaplan A. F. H., (2015) "*Laser welding process - a review of keyhole welding modelling*", Physics Procedia 78 (2015) 182 – 191.

[2] Katayama S., (2013) "*Handbook o flaser welding technologies*", Woodhead Publishing series in electronic and optical materials.

[3] Daurelio G., Cento L., Esposito C., (1982) "*Saldatura a laser CO2 da 2 kW di acciai al carbonio e inossidabili*", S.l.

[4] Groover M. P., (2010) “*Foundamentals of modern manufacturing*”, John Wiley & Sons, Inc.

[5] Kaplan A. F. H., Powell J., (2012) “*Spatter in laser welding*”, Luleå University of Technology

[6] Foundamentals of Manufacturing and Assembly technologies course material

[7] Sacel S.r.l. internal archives

[8] SKF.com