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LASER JOINING IN AVIATION: MAKING THE BATTERY PACKS OF THE ELECTRIC DRIVETRAIN

This review provides a detailed overview on bonding techniques used for the assembly of battery packs of modern hybrid and full electric vehicles that are appearing in aviation with special attention towards the more modern laser techniques. We introduce conventional and modern welding and brazing procedures and compare them thoroughly. Among the available alternatives laser based techniques seem to be exceptionally promising due to their reliability, reproducibility and ease of automation, which we will also corroborate in this review. Our work is being supported by the EFOP-3.6.1-16-2016-00014 project, entitled "Research and development of disruptive technologies in the area of e-mobility and their integration into the engineering education".

Keywords: *Electric and hybrid aircraft, Lithium-ion battery cells, Battery assembly, Laser joining, Laser welding*

INTRODUCTION

Nowadays, environmental friendly solutions are gaining more and more attention in every field of technology and research. Engineers and scientists are looking for new types of energy sources, mainly due to the dwindling supplies of fossil fuels and posing a smaller strain on nature. As a result, modern vehicles have alternative power sources, instead of conventional combustion engines, the most common of these constructions are hybrid or full electric drive systems. As of today we already see these trends in the car industry (Tesla Motors, Nissan, BMW, etc.) with the appearance of full electric automobiles even in the premium sector. This beginning trend is inevitably expanding and soon full or partially electric (hybrid) vehicles will take over the entire market. This change is present in aviation too, but the process is considerably slower, mainly due to the limited performance of energy storage units (accumulators) and the more critical importance of safety issues. Therefore currently hybrid drive systems are more common in the aviation sector with the full electric versions lagging behind. Hybrid vehicles usually have a conventional (combustion) drive system with an auxiliary low power electric motor, which works the same way as the full electric drive system. A simplified schematic electric drive scheme of a currently existing and operational full electric airplane (VUT 051 RAY) can be seen in Figure 1 [1]. Due to the above reasons these machines have a very limited flight time (typically less than an hour) and weight carrying capacity (around few hundred kilograms), but they fulfill 2 seater models perfectly, e.g. for the educational purposes of pilots [2].

Regarding the power source of the electric motor, the best engineering practice dictates to create the large capacity battery pack of several small capacity cells connected in parallel and/or in series instead of using one single large capacity unit. Using this method we gain a cost effective (the large scale production of small cells provides reduced costs), highly customizable (custom voltage and amperage values based on construction) and modular system which is exceptionally important given the fact that battery life of individual cells can be very different. These large capacity battery assemblies are produced using the multi-level production scheme presented in Figure 2 [3].

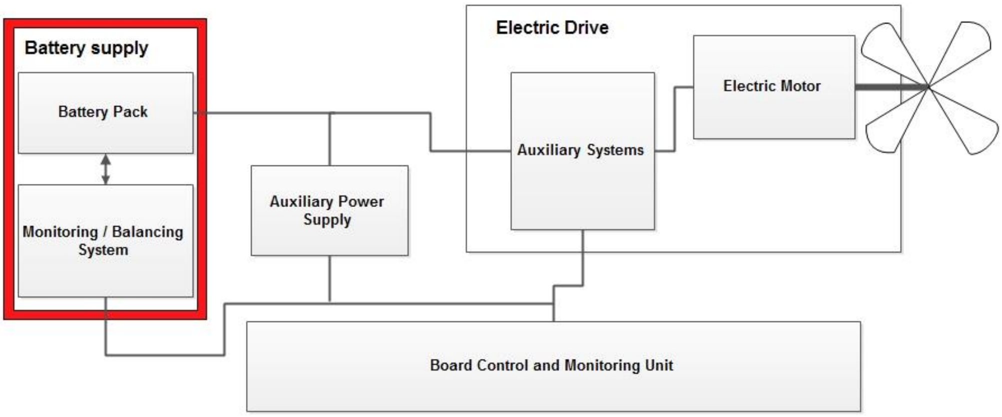


Figure 1 Full electric plane drive sceme [1]

At different levels of the manufacturing process, different joining techniques are used and these cannot be universal, as battery pack specifications are usually unique for the given engineering problem. In general, it can be said that mechanical joining (screw, riveting, etc.) is used at the pack and module levels of the assembling process to preserve modularity, while some form of permanent and much more refined bonding method (i.e. welding or brazing) is used at the unit and cell levels to reduce overall weight, electrical resistance and to achieve improved mechanical properties of the joint [3]. In this paper, we aim to review these latter joining techniques, more specifically, laser welding and laser brazing for the production of battery packs used in the aviation industry.

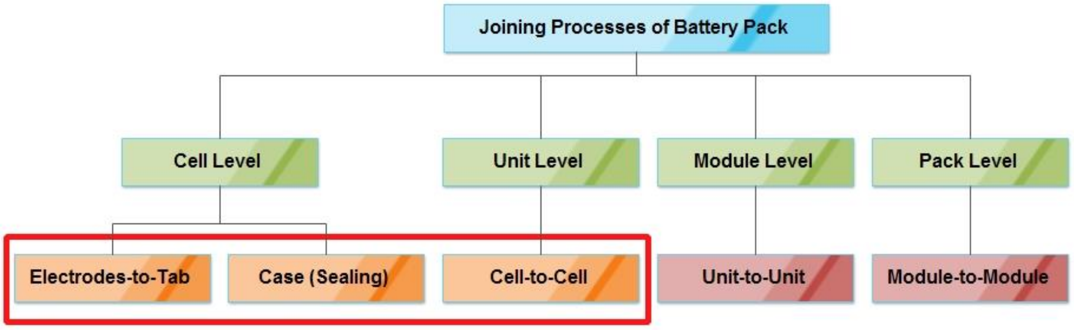


Figure 2 The hierarchy of battery pack manufacturing [3]

WELDING AND BRAZING TECNIQUES

Welding is a technique for joining materials (typically metals or certain plastics) by fusing the materials to be joined. Welding is therefore distinct from other joining processes such as brazing or soldering where the base material does not melt. For enhancing the mechanical, electrical, and chemical (e.g. corrosion resistance) properties of the joint, filler materials may be added to the weld pool, when the process is called braze welding. Using this latter method a bond that is mechanically stronger then the base metal can even be formed. The welding process usually requires a shielding atmosphere in the form of some kind of inert gas (or a mixture of gases) that protect the weld pool from contamination and chemical degradation (most importantly oxidization or nitridation). For this purpose the use of noble gases (e.g. helium, or argon) is typical [4][5].

Brazing and soldering are material joining methods where two or more metallic pieces are bonded together via the wetting and resolidification of a filler metal. Brazing and soldering is different from welding in that the melting of the pieces to be joined do not occur in these processes, which is why the soldered/brazed joint is said to be mechanical, instead of metallurgical. The main difference between soldering and brazing is the temperature that is needed for the formation of the joint. The liquidus temperature of the filler is below and above 450 °C for soldering and brazing, respectively. The molten filler make intimate contact with the parts to be joined due to capillary action, i.e. wets the surfaces to be joined. During soldering and brazing a flux is usually used to assist in wetting at the process temperature and also to protect the molten filler material from contamination and oxidization [4][5].

The main characteristics of these joining processes are summarized and compared in Table 1 below.

Parameter	Process		
	Soldering	Brazing	Welding
Joint formed	Mechnanical	Metallurgical	Metallurgical
Filler metal melt temperature (°C)	<450	>450	>450
Base metal	Does not melt	Does not melt	Depends on subtype
Fluxes to protect and to assist in wetting of base metal surfaces	Required	Optional	Optional
Typical heat sources	Soldering iron, Ultrasonics, Resistance, Oven, Laser	Furnace, Chemical reaction, Induction, Torch, Infrated, Laser	Plasma, Electron beam, Tungsten and submerged arc, Resistance, Laser
Tendency to warp or burn	Atypical	Atipical	Potential distortion and warpage of base-metal likely
Residual stress	Atypical	Atypical	Likely around weld area

Table 1 Comparison of the major characteristics of welding, brazing and soldering [5]

In general, sheet materials are best suited for welding techniques, but other geometries (tubes for example [6]) are also possible. In Table 2 we show some sheet material joint geometry configurations that are commonly used in engineering practice with special attention to geometries used for battery joining (these geometries are typeset in red).

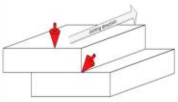
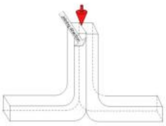
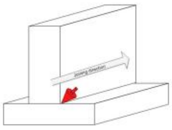
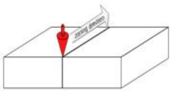
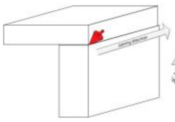
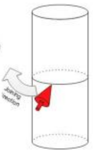
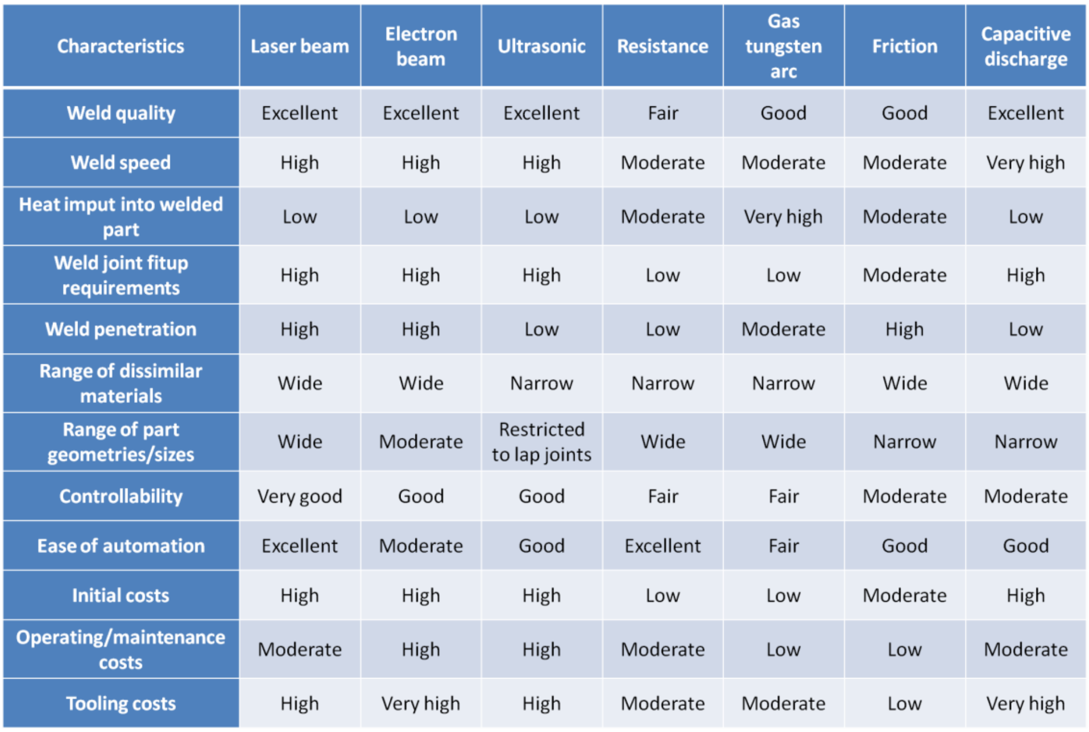
Joint Type	Lap joint	Edge joint	T-joint	Butt joint	Corner joint	Circular axial joint
Applicability	The most common configuration for all materials.	Usualy applied for thin sheet material joining where the joint's width is in the order of the thickness of both members.	Limited joinng angles possible, but a full penertration joint can be formed with sufficient power.	Very commonly used for joining ferrotious or other high viscosity alloys.	Similar to T-joints, difficult to realize for very thin sheet materials.	Used for joining tubular shaped matals.
Illustration						

Table 2 Typical joint designs for metal bonding [4]

The most widespread lithium-ion battery cell geometries are the cylindrical and pouch configurations [7]. Thus, the most common joint designs used for battery joining technologies are the lap and edge geometries. Lap geometry can be used for both cylindrical and pouch type cells and has several advantages over other joint types. Lap configurations are highly tolerant for welding beam and weld seam misalignment, thin-on-top and thick-on-bottom welds are easily achievable (thick-on-top and thin-on-bottom joints are less desirable) and weld width (multiple passes) can improve weld strength. The edge joint is slightly less common due to lack of applicability for cylindrical cell joining, but is still among the most popular geometries for battery module-to-module bonding. The biggest advantage of this edge configuration is the wide array of joining angles possible with the appropriate forming of edges. The mechanical strength of the edge joint is primarily dependent on the depth of the weld seam between the sheets (heat/energy absorption and transfer effects are critical in this case) [4][8].

Welding can be achieved by many heat sources and usually each heat source represents a different welding technique. A detailed description of some of the most common and most widely used welding methods are shown and compared in Table 3.



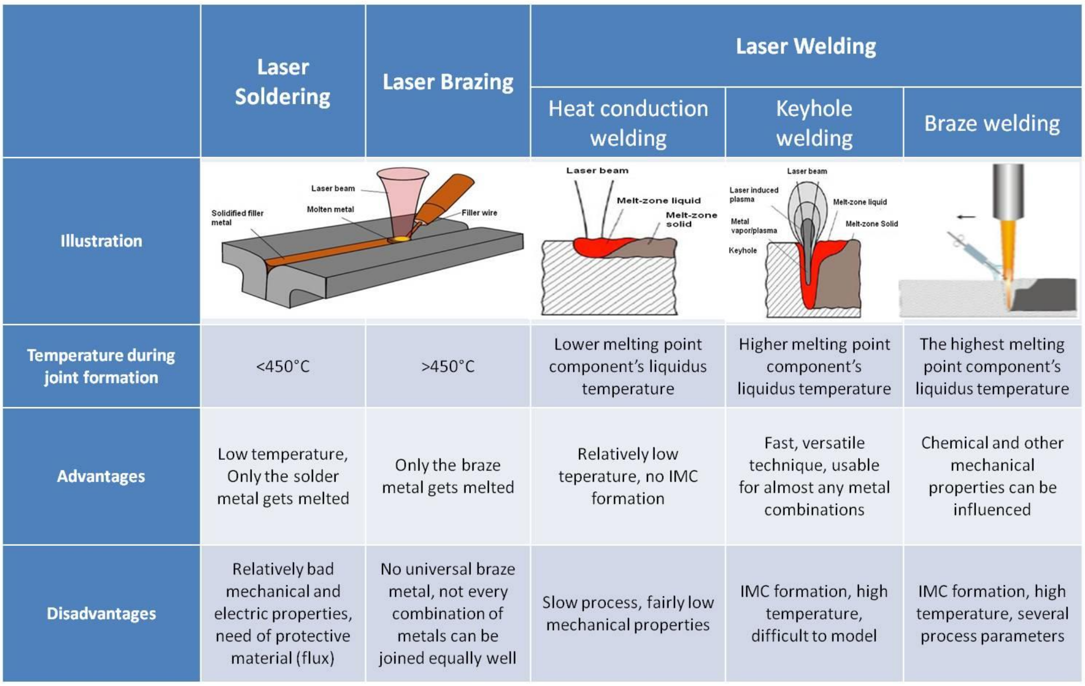
Characteristics	Laser beam	Electron beam	Ultrasonic	Resistance	Gas tungsten arc	Friction	Capacitive discharge
Weld quality	Excellent	Excellent	Excellent	Fair	Good	Good	Excellent
Weld speed	High	High	High	Moderate	Moderate	Moderate	Very high
Heat imput into welded part	Low	Low	Low	Moderate	Very high	Moderate	Low
Weld joint fitup requirements	High	High	High	Low	Low	Moderate	High
Weld penetration	High	High	Low	Low	Moderate	High	Low
Range of dissimilar materials	Wide	Wide	Narrow	Narrow	Narrow	Wide	Wide
Range of part geometries/sizes	Wide	Moderate	Restricted to lap joints	Wide	Wide	Narrow	Narrow
Controllability	Very good	Good	Good	Fair	Fair	Moderate	Moderate
Ease of automation	Excellent	Moderate	Good	Excellent	Fair	Good	Good
Initial costs	High	High	High	Low	Low	Moderate	High
Operating/maintenance costs	Moderate	High	High	Moderate	Low	Low	Moderate
Tooling costs	High	Very high	High	Moderate	Moderate	Low	Very high

Table 3 Conventional and modern welding processes [4]

According to the above reasons laser welding is well suited for battery joining problems, but it requires a delicate system design and precise calculations as well as professional operation skills [4].

LASER WELDING AND LASER SOLDERING/BRAZING

According to the previous section laser welding and laser brazing techniques are versatile and provide an excellent quality joint with exceptional mechanical, electrical properties for a large variety of materials. The only cons of the laser based joining techniques are the relatively high investment costs and the fact that the system has to be tailor made for every joining problem. Despite these disadvantages nowadays laser joining techniques are coming more and more into view and these processes are heavily assisted by the rapid development of high power diode and continuous wave fiber lasers that have excellent beam properties and focusability. With the use of these modern lasers it is possible to build a highly automatable laser joining system that operates at high speed, precision, and exceptional reproducibility. Among others, the most important advantage of the laser joining techniques is the small heat affected zone (HAZ), that prevents metal distortion (internal strain after welding) and also partly responsible for the very high process speeds that ensures that only a minimal amount of intermetallic compounds (IMCs) are formed (that are brittle and have a high porosity), if any. To achieve perfect conditions a thorough investigation and adjustment is required in advance because of the fact that there are plenty laser and other process parameters that come into play during the laser bonding procedures (e.g. laser power, wavelength, scanning speed, etc.). In summary, laser welding and laser brazing has a great potential for battery joining, but it has to be examined and designed with great care. All three of these joining methods have several subtypes. In Table 4 we summarize and compare the most commonly used subdivisions of laser joining [4][5][8][9].



	Laser Soldering	Laser Brazing	Laser Welding		
			Heat conduction welding	Keyhole welding	Braze welding
Illustration					
Temperature during joint formation	<450°C	>450°C	Lower melting point component's liquidus temperature	Higher melting point component's liquidus temperature	The highest melting point component's liquidus temperature
Advantages	Low temperature, Only the solder metal gets melted	Only the braze metal gets melted	Relatively low teperature, no IMC formation	Fast, versatile technique, usable for almost any metal combinations	Chemical and other mechanical properties can be influenced
Disadvantages	Relatively bad mechanical and electric properties, need of protective material (flux)	No universal braze metal, not every combination of metals can be joined equally well	Slow process, fairly low mechanical properties	IMC formation, high temperature, difficult to model	IMC formation, high temperature, several process parameters

Table 4 Major types of laser joining techniques [5][8]

Laser soldering and laser brazing

Laser soldering and laser brazing can be achieved with a relatively low beam power and not so demanding laser setup because they take place at a fairly low temperature and a low melt point filler material is used. The solder material can be added to the system in multiple ways, a common solution is the pre-applied solder paste or a powder injection at the joint area. Another frequently used method is the addition of solder/braze material in form of a cold (in some cases heated) wire. In the latter case a very precise adjustment of wire feeding unit is needed because if the wire is fed into the soldering/brazing spot too quickly or too slow the joining area might get damaged, the joint that is formed can be faulty or might not even form, at all [4][5].

The main difference between the two types of these laser joining technologies is the temperature where joint formation takes place. Laser soldering and brazing happens at temperatures below and above 450 °C, respectively and as a general rule of thumb the latter results in a stronger joint and with a lower electrical contact resistance. A slight inconvenience of these techniques is that the solder and braze materials are not universal, but have to be chosen individually for each contact metal combination and not every combination of metals can be joined equally well using these methods. Moreover, the potential joining geometries are also limited. In summary, laser soldering and laser brazing are less demanding on the technical aspects than laser welding, but may still result in a joint of high enough quality that might be sufficient for battery joining, especially when laser brazing is realized [5].

Laser welding

Laser welding requires a higher power laser system (in order to melt both metals) with great precision as welding in general is an autogenous joining process which means that no additional filler metals are added to the weld. For reducing the role of fit up errors, that results in faulty joints, a clamping system is commonly used. If light absorption of the metal is sufficiently high at the wavelength of the welding laser (in most cases in the vicinity of 1 µm or at 10.6 µm) a low power laser might be applicable. Despite these strict conditions laser welding is widely used for joining similar metals, and can also be used for joining dissimilar materials (i.e. for heterogeneous joining) for most metal combinations. The reason for that is that laser welding, in general, results in joints of excellent mechanical and electrical properties. Laser welding has a large variety of possible weld geometries as we have shown before in Table 2. The difference between the three major types of laser welding, schematically shown in Figure 3, resides mainly in the differences *i)* in the geometry of the formed weld pool and *ii)* the thermal processes that dominate during the formation of the weld [4][8].

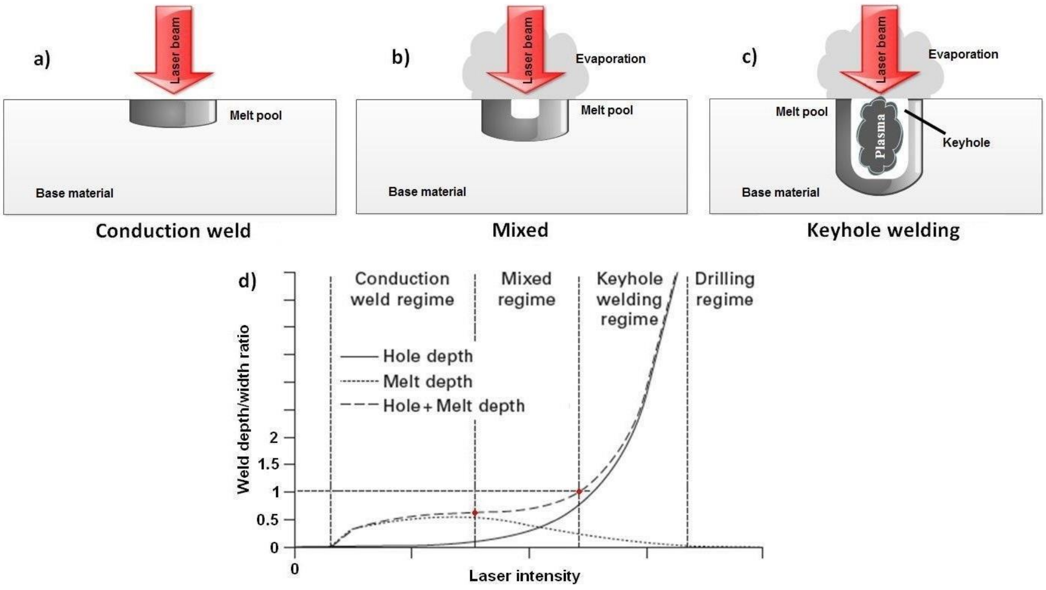


Figure 3 Laser conduction (a), mixed (b) and keyhole (c) mode welding and (d) the change of weld pool geometry as a function of laser intensity [8]

Conduction welding occurs, if the depth of the weld pool is less than half of its width (i.e. the weld width) and no boiling or intensive evaporation of the metals to be joined occurs. If the depth is equal to or greater than the width and a so called "keyhole" is formed (where evaporation, plasma formation and boiling are jointly present) we speak of *deep penetration or keyhole welding* (in some rare cases a mixed regime is also stably formed) [8].

This *conduction mode laser welding* is usually achieved by using a low power, usually defocused laser beam. During the formation of the joint most of the base material is not directly heated by the laser light, but instead via heat conduction from the upper metal layer that is melted by the beam. This process is much slower (in general half the speed) than that of keyhole mode laser welding and results in a lesser quality joint (both in terms of mechanical and electrical properties). However, a huge advantage of this welding mode is its shallow penetration and very limited volume of metal melting, that practically denies any formation of IMCs, thus making this technique a feasible alternative for dissimilar metal joining where keyhole mode welding is limited by light absorption, or results in an IMC rich (brittle) welding seam. Conduction mode laser welding can also be used if we can't achieve a perfect fit between the metal parts to be joined, as it uses a larger beam spot size (defocused beam) in comparison to deep penetration laser welding [8].

During *deep penetration* or *keyhole mode laser welding*, typically proceeding at much larger energy densities than conduction welding, both the base and upper metal layers melt and a keyhole is formed between them. In the keyhole a mixture of the two metals is present in multiple phases (solid, liquid, vapor and even plasma) and the various chemical and physical processes taking place are far more complex. The detailed discussion of these processes is very challenging and difficult to model. The energy coupling in this mode is excellent since the energy of the laser beam is absorbed by multiple reflections happening along the keyhole's walls, thus making the process energy efficient and fast if a powerful enough laser source is used. Keyhole mode welding requires a very precise material fit up and delicate parameter tuning, but provides a versatile, very fast solution for joining almost every metal combination (low solubility metal combinations result in IMC rich, brittle joints) [4][8].

The third frequently used laser welding type is called *laser braze welding* or *laser welding with filler metal*. The name already reflects that this laser joining technique is the combination of keyhole mode laser welding and laser brazing. In this joining method additional metal or metals (usually in form of a wire) are added to the weld pool during welding. This metal additive provides several benefits like eliminating certain weld defects (for example undercutting) or resulting in better chemical, mechanical or electrical properties via forming an alloy with the other metals. In certain cases, it even allows the welding of imperfectly fit up parts in special joint geometries. In terms of geometries laser braze welding is possible in every case where standard laser welding is applicable, however the precise adjustment of filler metal wire alignment and feed rate is essential. When metal combinations with low solubility and very different melting points are to be welded/bonded (e.g. aluminum and iron) the use of a filler metal is unavoidable during keyhole mode welding, i.e. actually laser braze welding is realized [8][10].

The role of protective gases in laser welding

As mentioned above laser keyhole mode welding requires a large enough energy density to melt both metal components. The required magnitude of energy density usually ionizes the gas above the metal target and a plasma plume is formed resulting in a substantial energy loss. To reduce the energy loss in the gas and to protect the molten metal pool from undesirable chemical reactions a shielding gas atmosphere is usually applied. The gas or mixture of gasses needs to have a high enough ionization energy to prevent plasma formation and the gas cannot form a compound with the given metals in order to protect them from contamination and oxidization. Because of these reasons noble gases (or combinations of them) are used for this purpose. The effect of the presence of different shielding gases on the weld of a steel plate (6 mm thick) produced with a continuous wave CO_2 laser (5 kW power) is shown in Figure 4 [8].

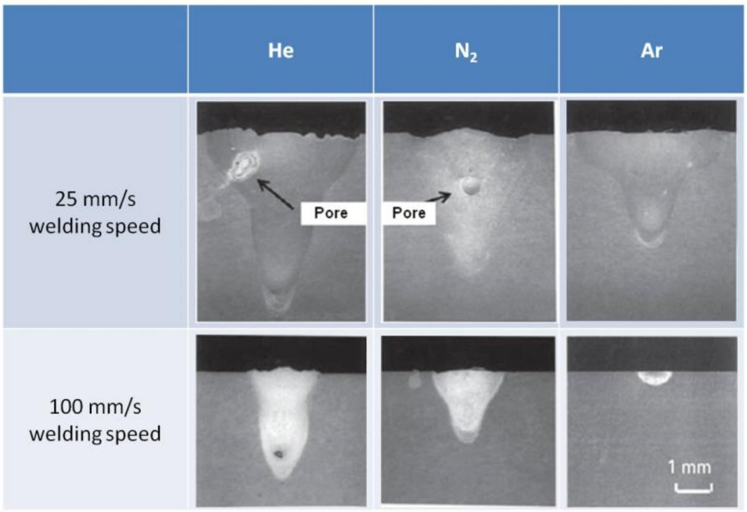


Figure 4 The effect of shielding gas on the weld quality [8]

It can be seen that the presence and material of the shielding gas atmosphere can have radical effects on the weld quality.

LASER BRAZING AND LASER WELDING FOR BATTERY JOINING

Based on the previously discussed properties, advantages and disadvantages it is clear that laser keyhole welding and laser brazing are the two best candidate laser bonding techniques for battery pack assembly. Laser keyhole welding in particular shows great potential and is a widely studied method. In this section we will show how laser keyhole mode welding is applied for cylindrical type lithium-ion battery cell joining and we will present a few results that can further improve the already good qualities of this technique in order to make the process more consistent which improves reproducibility (that is a key prerequisite for the application in aviation).

Spot welding and seam welding

Battery cell laser welding can be achieved with both laser mode types namely: pulse and continuous wave mode lasers. In engineering practice according to the weld there are two types of battery laser welding methods: spot welding and seam welding. Spot welding is the simplest form of laser welding (both conduction and deep penetration mode is possible) and is performed by a single, high energy laser impulse (sometimes a series of pulses) focused onto a specific area on the target surface. Spot welding is less desirable and is rarely realized with continuous wave mode lasers as it provides a small contact area and thus it usually results in a joint with weak mechanical properties [4][7].

In the field of batteries, another, more common type of laser welding scheme is applied, the so called seam welding. In laser seam welding the parts to be welded are rotated or moved under the laser focus head allowing a continuous (or overlapping spot) weld bead to form. In general it results in an all-around better joint and can also be used both for conduction and deep penetration mode welding. Seam welding can be achieved by both pulsed and continuous wave mode lasers. Using a continuous wave is self explanatory and pulsed mode can also tend towards seam formation at high pulse repetition frequency and a large overlap factor [7][11].

The effect of temporal and spatial modulation in seam welding

According to various research groups seam welding of battery cells can be made more stable by certain special alterations during the welding process.

Spatial power modulation

One of these special modifications is called spatial modulation of the laser beam. Spatial power modulation is the process when the relative position of the continuous wave mode welding laser beam and the metal targets to be welded is changed. This can easily be achieved by a laser welding setup equipped with a three dimensional galvanometric scanner head. The patterns in which this method can be realized is limitless, but engineering practice shows that a spiral pattern is by far the most efficient [12][13].

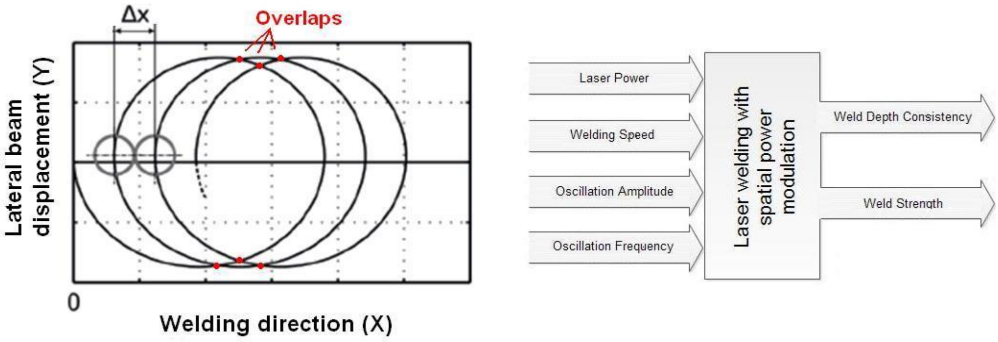


Figure 5 Spatial laser power modulation and its parameters [12]

As shown in Figure 5 spatial power modulation has four basic process parameters that can influence the properties of the formed weld. Two of these, namely the oscillation frequency and amplitude are specific for this particular kind of alteration of the regular seam welding technique. In the following we will discuss the effects of these modulation parameters on the formed joint's properties.

On one hand the oscillation amplitude has an effect on process reproducibility by influencing the consistency of the weld depth. Consistency of the weld depth is defined as a quotient of the maximum and minimum value of the penetration depth. The effect of the modulation amplitude on the uniformity of the penetration depth can be seen in Figure 6 at three different overlap factors (which is also related to the speed of welding) [12][14].

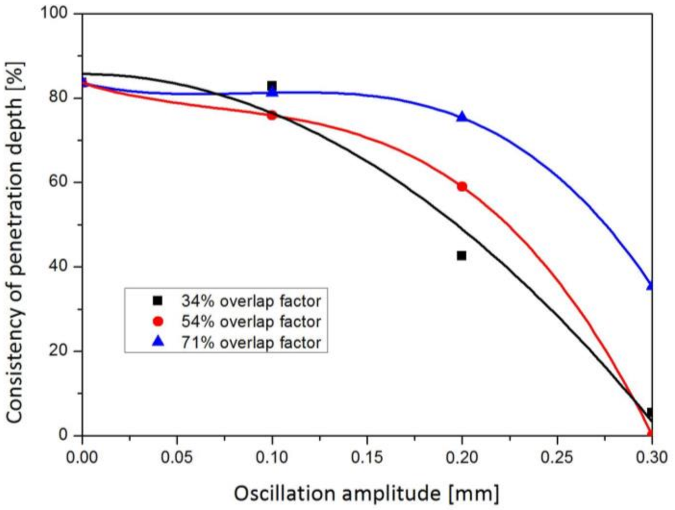


Figure 6 The effect of spatial laser power modulation amplitude on weld depth consistency [14]

In general, a rather small value of the oscillation amplitude is desirable with a large overlap factor (which will reduce the overall weld speed) for achieving the most consistent results.

On the other hand, both the frequency (a) and amplitude (b) of the modulation (when every other parameter are the same) has an effect on weld strength, which are shown in Figure 7 at several different laser power values [13][15].

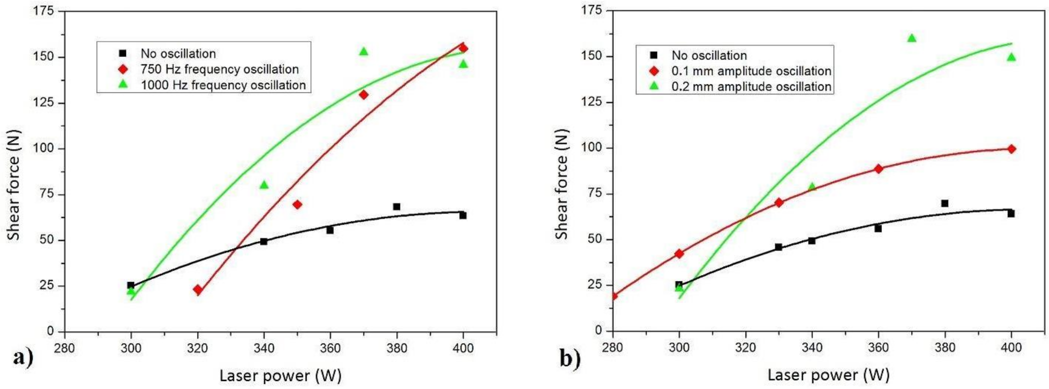


Figure 7 The effect of modulation frequency (a) and modulation amplitude (b) on joint strength [15]

These results clearly indicate that at lower laser power values the effect of the spatial power modulation parameters is minor. However with increasing laser power the span of the achievable joint strengths will be increased. The results show that the higher frequency and larger amplitude oscillation results a stronger bond [15].

As a summary, spatial power modulation (with optimally chosen parameters) results in an increased volume of molten metal and weld width which provides a larger contact area (stronger bond) and improves reproducibility by stabilizing the weld depth.

Temporal power modulation

The other significant modulation technique that is gaining more and more ground in laser welding is temporal power modulation. In this process the power of the continuous wave mode laser is being changed in time during processing. The most common method is to use a sinusoidal temporal power modulation around the deep penetration threshold power value. However, other temporal power waveforms can also assist the welding process. For example applying a low plateau power at the beginning of the process can increase energy coupling via preheating, while slowly increasing the laser power at the start of the welding process can reduce metal spatter formation or slowly decreasing power at the end of the welding process can reduce undercutting effects [13][16].

Here we will only review the effect of the sinusoidal power modulation. The effect of sinusoidal temporal laser power modulation frequency on weld depth can be seen in Figure 8. In these measurements the modulation was performed around the deep penetration threshold of the given metal and the penetration depth (which is related to weld strength) and the number of melt ejections (that is in connection with surface smoothness and keyhole stability) was counted [16].

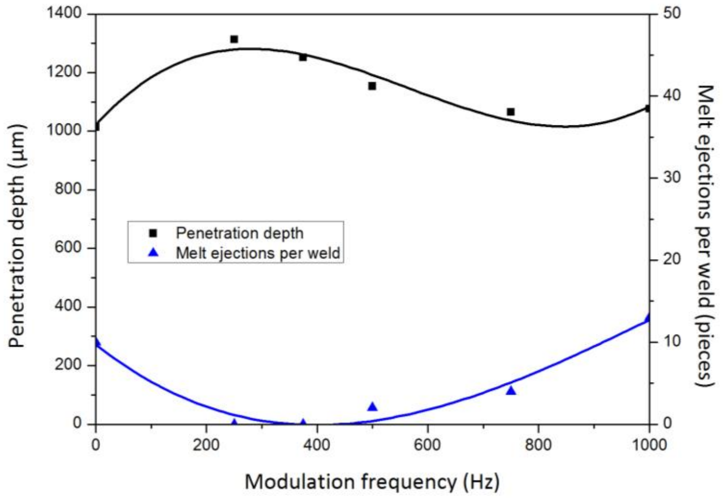


Figure 8 The effect of temporal (sinusoidal) laser power modulation frequency on weld properties [16]

These results show that the power modulation frequency has an optimum value which results in the deepest penetration and the lowest number of melt ejections [16].

In summary, temporal power modulation in itself can reduce the molten metal ejection effect that occur during welding and thus results in a smoother weld bead and can result in a stronger joint via promoting deeper penetration. It is important to note that temporal modulation requires very precise adjustments and calibration to determine the optimum process parameters [13][16].

Both spatial and temporal power modulation can be applied individually or simultaneously in any battery cell seam welding application to improve weld properties, but they have to be adjusted and designed with care. In Figure 9 a schematic sketch of a typical laser setup can be seen in which these methods can be realized for joining the poles of battery cells [13].

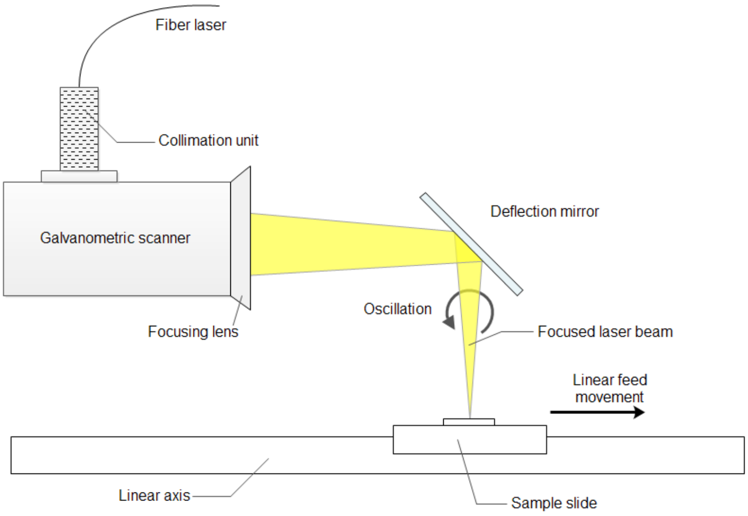


Figure 9 Schematic sketch of a laser welding setup [14]

Comparison of conventional and laser joining techniques

In the previous section we presented the most wide spread realizations and modern perspectives of applied laser welding for metal and battery cell joining. As a final note, we will show that according to currently available research data, laser brazing and laser welding do indeed provide a very good quality (both in terms of mechanical and electrical properties) joint suitable for any industrial sector, including aviation, that requires a fail-safe joining solution.

A comparison of different welding and brazing techniques in terms of electrical resistance (a) and joint strength (b) can be seen in Figure 10 [17][18].

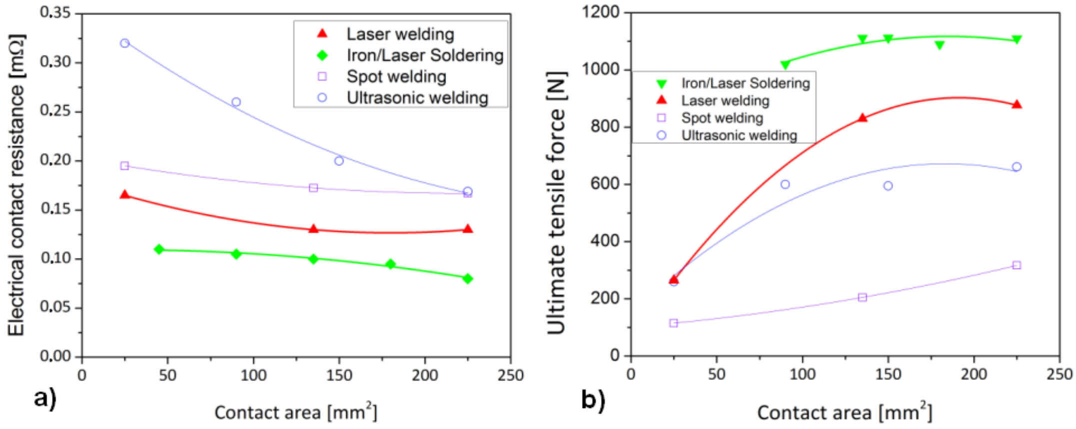


Figure 10 Electrical resistance (a) and mechanical strength (b) of joints produced with different welding and soldering techniques [17][18]

It is obvious that laser welding and laser brazing has superior performance over conventional joining methods. They are the most suitable and versatile joining techniques available as of date for joining battery cells for electrical airplanes as they provide the best mechanical and electrical property joints with good reproducibility among other beneficial properties (e.g. internal stress free, corrosion resistant, etc.).

CONCLUSIONS

In this paper we described how the battery pack of a full or partially electric aircraft is built and introduced various mechanical and metallurgical joining techniques that are potentially applicable at various levels of the battery assembly procedure.

A basic overview of brazing, soldering and welding was presented with special attention to laser assisted methods. The laser joining techniques, alongside with their subdivisions, were thoroughly described. We have shown that the laser bonding procedures, most notably laser welding and laser brazing, indeed result in a joint with superior mechanical and electrical properties as compared to alternative joining methods. Beyond that it was also shown, that laser based techniques are exceptionally promising for their application in aviation due to their reliability, reproducibility and ease of automation.

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A LÉZERES KÖTÉSEK REPÜLŐGÉP-IPARI ALKALMAZÁSA AZ ELEKTROMOS HAJTÁSRENDSZEREK AKKUBANKJAIBAN

Az összefoglaló tanulmányunkban bemutatásra kerülnek a repülőgépiparban megjelenő modern hibrid és elektromos hajtásrendszerű kisrepülőgépek akkubankjának összeállítása során alkalmazott kötési technikák, különös figyelmet fordítva a legkorszerűbb lézeres eljárásokra. A konvencionális és modern hegesztési és forrasztási eljárásokat részletesen bemutatjuk és különféle szempontok alapján összevetjük egymással. A számos szakirodalmi eredmény alapján a lézeres technika automatizálhatósága, megbízhatósága és további számos előnyös tulajdonsága miatt rendkívül ígéretesnek tűnik a fenti célokra, melyet tanulmányunkban alátámasztunk. Munkát az EFOP-3.6.1-16-2016-00014 számú, „Diszruptív technológiák kutatásfejlesztése az e-mobility területén és integrálásuk a mérnökképzésbe” című pályázat támogatja.

Kulcsszavak: *elektromos és hibrid hajtású repülőgép, Lítium-ion cellák, elektromos cella összeállítás, lézeres kötés, Lézeres hegesztés*

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