Nd:YAG Laser Welding of Aluminium Alloys

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Division of Materials Processing

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by

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Preface

This work was carried out at the Division of Materials Processing at the Department of Materials and Manufacturing Engineering at Luleå University of Technology. I would like to thank my friends and colleagues at the division and the department for all their help and I look forward to further co-operation during the next couple of years.

I would like to express my gratitude to Professor Claes Magnusson, Luleå, Dr. John Powell, Nottingham and Dr. Alexander Kaplan, Vienna, for rewarding discussions and guiding during the course of this work. Finally I would like to thank my parents and my sister for your support and Jenny for your love.

Luleå, December 1998

Tomas Forsman
Abstract

This thesis presents the development of laser welding of aluminium and describes what can be performed with modern Nd:YAG lasers in the wide range of commercial aluminium alloys available. Specific process and quality problems during aluminium welding have been approached and studied experimentally. In some cases analytical models have been developed in order to help explain the process and to support the conclusions.

Paper one is a literature review comprising laser welding of low density structural materials, i.e. aluminium alloys, magnesium alloys, titanium alloys and polymers. The paper describes the properties of the different materials and explains how the properties influence the laser welding process and the weld results. For some of the materials laser welding was found to be the only successful fusion welding process.

Paper two investigates Nd:YAG laser lap welding between sheets of two different coated aluminium alloys. Successful welds were produced using a certain gap width between the two sheets, which gave the best weld quality and strength. Pulsed and continuous laser welds were produced and compared with respect to porosity, surface profile, etc.

Paper three investigates the factors affecting the absorptivity of the work-piece during Nd:YAG laser keyhole welding of an aluminium alloy. The influence of surface condition on absorption was shown to be negligible. Experimental absorption measurements by calorimetry were compared to analytical absorption values using a simple model based on Fresnel absorption during multiple reflections in the keyhole.

Paper four solves a problem with initiation defects during experimental tailored blank laser welding. A model based on the line source model was used to show that the weld was overheated during the initial 100 mm. By using a ramped power input the overheating was minimised and the defects disappeared.
Papers


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Introduction

The study of laser welding of aluminium is a fairly new science. So far, laser welding research has focussed on steel because it is by far the most widely used material for structural purposes. In this introduction the process of laser welding of aluminium will in some cases be described in comparison with steel in order to highlight similarities and differences.

1 Properties of aluminium

Aluminium is the most abundant metal in the crust of the earth at 8% by weight compared to 5.8% of steel [1]. It is obtained from bauxite containing around 50% of hydrated alumina (aluminium oxide) as well as iron oxides, silica and titania. Aluminium is produced by extracting pure alumina from bauxite by the Bayer process and then smelting alumina by the Hall-Heroult process. The whole process of producing 1 tonne of aluminium, from mining the bauxite to the final product, demands 70 000 kWh of energy compared to 15 000 kWh for producing 1 tonne of steel.

Since the resources of bauxite are finite and the production of aluminium is so energy demanding, it is important that aluminium is reused as much as possible. Aluminium can easily be remelted and turned into a new product and is therefore ideal for recycling.

The low density of aluminium is the principal reason why it is increasingly gaining interest by the automotive and aerospace industry [2-3]. A beam made in an aluminium alloy can for instance be 8 times as stiff as a steel beam of the same weight. By using aluminium instead of steel where appropriate, the weight of a car can therefore be decreased by as much as 40%. Decreased weight results in decreased fuel consumption, which is important for cars and of crucial significance in the case of aeroplanes.

Even though practically all materials can be laser welded, the properties of steel happen to suit the laser welding process especially well. Compared to steel, aluminium possesses some properties, shown in table 1 [4-5], which make the welding process more sensitive and in effect makes it more difficult to produce welds without defects.

Table 1. Physical and mechanical properties of aluminium and steel [4-5].

<table>
<thead>
<tr>
<th>Property</th>
<th>Pure aluminium</th>
<th>Duralumin (AA2017-T4)</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [kg/m³]</td>
<td>2700</td>
<td>2800</td>
<td>7800</td>
</tr>
<tr>
<td>Melting point [°C]</td>
<td>660</td>
<td>650</td>
<td>1350</td>
</tr>
<tr>
<td>Boiling point [°C]</td>
<td>2490</td>
<td>2400</td>
<td>2750</td>
</tr>
<tr>
<td>Yield strength [MPa]</td>
<td>10</td>
<td>275</td>
<td>800</td>
</tr>
<tr>
<td>Tensile strength [MPa]</td>
<td>45</td>
<td>425</td>
<td>1000</td>
</tr>
<tr>
<td>Elongation [%]</td>
<td>50</td>
<td>22</td>
<td>20</td>
</tr>
<tr>
<td>Thermal conductivity [W/m K]</td>
<td>236</td>
<td>160</td>
<td>45</td>
</tr>
<tr>
<td>Coeff. of thermal expansion [10⁶/K]</td>
<td>23</td>
<td>24</td>
<td>12</td>
</tr>
<tr>
<td>Melt absolute viscosity [10¹³ Ns/m²]</td>
<td>2.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Melt surface tension [10³ N/cm]</td>
<td>8.6</td>
<td>-</td>
<td>18</td>
</tr>
</tbody>
</table>
In addition to the properties shown in table 1 there are two properties that make aluminium very special. First there is the hard aluminium oxide (\(\text{Al}_2\text{O}_3\) or alumina) which automatically builds up to a layer of \(\sim 10-20\) nm (thicker in a humid environment) on the surface of an aluminium sheet. If the layer is removed, for instance by grinding, it will be recreated at once and continue to grow at a decreasing speed. The natural surface oxide efficiently protects the bulk material from corrosion which means that aluminium can withstand humid and salt environments 100 times better than mild steel and 15 times better than zinc coatings [6]. Furthermore the surface oxide has a melting point of 2050°C. Therefore, when the aluminium underneath the oxide melts during welding the oxide will still be solid in the form of oxide fragments. If the temperature of welding is not high enough to melt the oxide this can cause defects such as inclusions in the re-solidified weld.

The second special property of aluminium is its solubility of hydrogen which is 20 times higher in liquid than in solid aluminium [4]. The effect of this in the course of welding is that hydrogen from the welding atmosphere and from the aluminium surface, which is dissolved in the melt at welding will precipitate at solidification and cause the formation of hydrogen filled pores in the final weld.

2 Commercial aluminium alloys
Since aluminium is a low strength metal in its pure state, alloying is performed with the object of increasing the yield and tensile strengths. For alloying to function, the alloying element used must have a solid solubility in aluminium and very few elements have a high solubility. Close to its melting point 83% by weight zinc (Zn) can be dissolved in aluminium whereas the solubility for silver (Ag) is 56%, gallium (Ga) 20%, magnesium (Mg) 15%, germanium (Ge) 6% and copper (Cu) 6% [4]. Of these elements Zn, Mg and Cu together with manganese (Mn) and silicon (Si) are used to create particular aluminium alloy groups as shown in table 2.

Table 2. Wrought aluminium alloy denomination according to Aluminium Association (AA) standard.

<table>
<thead>
<tr>
<th>Alloy group</th>
<th>Major additional element</th>
</tr>
</thead>
<tbody>
<tr>
<td>1xxx</td>
<td>None</td>
</tr>
<tr>
<td>2xxx</td>
<td>Cu</td>
</tr>
<tr>
<td>3xxx</td>
<td>Mn</td>
</tr>
<tr>
<td>4xxx</td>
<td>Si</td>
</tr>
<tr>
<td>5xxx</td>
<td>Mg</td>
</tr>
<tr>
<td>6xxx</td>
<td>Mg, Si</td>
</tr>
<tr>
<td>7xxx</td>
<td>Zn</td>
</tr>
<tr>
<td>8xxx</td>
<td>Other</td>
</tr>
</tbody>
</table>

Following solid solution hardening and dispersion hardening when alloying, the strength of the alloy can be further increased by strain hardening or precipitation hardening [4, 7].
Alloys of groups 1, 3, 5 and 8 do not respond to heat treatment by precipitation, so the mechanism for increasing the strength is strain hardening instead. By cold working the alloy, dislocations are formed, which hinder further strain and this makes the alloy harder, stronger and less ductile as shown in figure 1. The cold work is usually accomplished by rolling and the area of the alloy can be reduced up to 75% to reach a fully hard condition. The strain in the material induced by the dislocation zones can later be relieved by annealing at around 200°C. Strain hardened alloys are designated by the letter H followed by a number indicating the hardness. For example AA5052-H12 is an alloy with Mg as principle alloying element which has been cold worked to a quarter-hard condition.

![Figure 1. Cold work results in increased strength and decreased ductility.](image)

In alloys of groups 2, 6 and 7, elements are added in excess of the solid solution limit at room temperature. When the melt solidifies and cools, the solution becomes super-saturated and the excess amount starts to precipitate. If however the cooling is fast enough, there will be not enough time for precipitation. In this case precipitation can occur later in the solid material. This produces finer particles precipitated in a more controlled manner. This treatment is carried out at room temperature (natural ageing) for some alloys and between 150°C and 250°C for others (artificial ageing). Precipitation hardening can for some alloys be accompanied by cold work to produce an even higher strength. Precipitation hardened alloys are designated by the letter T followed by a number indicating what particular treatment has been performed. For example AA6063-T6 is an alloy with Mg and Si as principle alloying elements which has been solution heat treated and then artificially aged without cold working. The precipitates formed in this alloy are different shapes of Mg2Si.

Wrought sheets are produced by hot rolling and cold rolling the metal through narrower and narrower slots until the desired thickness and cold work is achieved. Since the sheet width is usually fixed, the sheet length will be extended resulting in grains directed in the rolling direction. Therefore the properties of a wrought sheet are not exactly the same in all directions; the sheet is anisotropic.
Extrusion of aluminium profiles is performed by pressing a hot ingot through a tool with the desired profile shape as shown in figure 2. Extrusion, like rolling, produces a material with prolonged grains in the extrusion direction, mostly near the surface where most of the forces act. There is also a chance that the high deformation at the surface promotes recrystallisation whereby all sorts of different grain sizes can evolve. The grains in a profile are usually larger than in wrought sheets because of the slow cooling experienced. With extrusion there is always a risk of getting impurities in the profile on the border between two ingots.

![Figure 2. Extrusion of aluminium profiles.](image)

Many aluminium objects for practical purposes are surface treated. One of the most common treatments is anodising, which can be used to give increased corrosion or wear resistance or a shiny and/or coloured surface. Anodising is a process which turns the surface layers of the aluminium into aluminium oxide by electrolysis. An anodised layer is an oxide much like the natural layer covering an aluminium surface but approximately a thousand times thicker. A layer of 10 µm is common for details used indoors while 20-25 µm thickness is used for outdoor purposes.

### 3 Light/material interaction

A material exposed to light can react in three ways: by absorption, reflection and/or transmission. Both Nd:YAG (1.06 µm) and CO₂ (10.6 µm) laser light is in the infrared region of the electromagnetic spectrum (see figure 3) and light of this wavelength penetrates only up to two atomic diameters in metals. Metals can therefore be considered opaque to this radiation which means that transmission can be ignored. Therefore an infrared laser beam directed onto a metal surface will only be absorbed and/or reflected.

The optical behaviour of metals is usually described by two values: the refraction index (n) and the extinction coefficient (k). These values have been experimentally determined for a number of pure materials with clean and smooth surfaces at room temperature [8-9].
The optical constants $n$ and $k$ can be used to calculate the absorptivity, which is a value of how much of the light of a particular wavelength is absorbed by a material at normal incidence ($\theta=0^\circ$). The absorption of a particular material with respect to the angle ($\theta$) of the incident light can be determined by using an approximation of Fresnel's formula

$$A_{\text{par}} = \frac{4n \cos \theta}{(n^2 + k^2) \cos^2 \theta + 2n \cos \theta + 1}$$  \hspace{1cm} (1)$$

and

$$A_{\text{perp}} = \frac{4n \cos \theta}{n^2 + k^2 + 2n \cos \theta + \cos^2 \theta}$$  \hspace{1cm} (2)$$

where

- $A_{\text{par}} = $ absorption of light with parallel polarisation,
- $A_{\text{perp}} = $ absorption of light with perpendicular polarisation,
- $n = $ material refractive index,
- $k = $ material extinction coefficient.

This approximation is valid for $n^2 + k^2 \gg 1$, which is the case for metals interacting with light with a wavelength exceeding 0.5 $\mu$m [10]. As shown in equations 1 and 2 the absorption is divided into light of parallel polarisation and light of perpendicular polarisation. Since laser light is normally used with circular (or no) polarisation, the average of equations 1 and 2 is calculated to yield the final absorption. The absorption of a certain wavelength $\lambda$ with angle of incidence $\theta$ in a material with optical constants $n$ and $k$ can therefore easily be determined if the optical constants are available. The absorptivity value is determined simply by setting angle $\theta$ equal to zero, which corresponds to normal incidence.
The absorptivity of infrared laser light on a metal surface at room temperature is generally low. Nd:YAG light in aluminium has an absorptivity of around 10% and CO₂ light around 5%. The absorptivity values in steel are approximately twice these. The low absorptivity value is however not a problem in laser welding since the absorbed amount of energy increases rapidly with the formation of a keyhole as will be described later.

![Absorptivity as a function of angle of incidence for plane polarised light](image)

**Figure 4. Absorptivity as a function of angle of incidence for plane polarised light using equations 1 and 2.**

Light of parallel polarisation, shown in figure 4, shows an increase in absorption with angle of incidence up to a maximum value close to 90° called the Brewster angle. The Brewster angle is defined as the angle of incidence where the reflected and the transmitted part of the beam are at right angles to each other. Unpolarised light being reflected on a surface at the Brewster angle will obtain a parallel polarisation.

### 4 Initiation of welding

When laser light is directed onto a metal surface, the portion of energy that is absorbed starts heating the surface. The heat is conducted (by lattice waves in combination with the movement of electrons) hemispherically into the bulk material.

Depending on the intensity of the laser beam the temperature on the surface can reach the melting point \( T_m \) or even the boiling point \( T_b \) of the material. If welding is performed below the boiling point, the welding is called conduction limited (see figure 5a). This is the normal case for conventional welding processes such as TIG and MIG but can also occur with a laser as the heat source.
If the boiling point of the metal is exceeded, the process changes into something called keyhole welding shown in figure 5b (the whole process of initiating the keyhole is believed to take in the order of 1 ms). When the boiling point of the metal is reached the absorption increases rapidly. A deep gas-filled hole called a keyhole is formed which traps the beam and absorbs energy for each reflection of the beam at the keyhole walls. The word keyhole is used because of the typical deep and narrow keyhole shape obtained especially for a laser weld in steel as shown in figure 6.
A keyhole when welding aluminium is shallower and wider but the basic characteristics of the keyhole process are the same. When the welding process is stable, the pressure from the metal gas in the keyhole is in equilibrium with the surrounding melt so that the melt produced in front of and beside the keyhole flows around it and later solidifies.

To initiate a keyhole in aluminium a higher power density (or intensity) is required than in steel. It has been suggested that the so-called threshold intensity is 5 to 25 times higher [12] based on reasoning that

\[
I \approx \frac{T_b k}{A}
\]

where

- \( I \) = intensity \([\text{W/m}^2]\),
- \( T_b \) = boiling point \([\text{K}]\),
- \( k \) = thermal conductivity \([\text{W/m K}]\),
- \( A \) = absorptivity.

In absolute numbers the threshold intensity for Nd:YAG lasers in aluminium is 1-2 MW/cm\(^2\) and for CO\(_2\) lasers 2-3 MW/cm\(^2\). The intensity range depends on welding speed and alloying content. Alloys containing a high amount of magnesium are in the low range.

5 Welding of aluminium

The shapes of typical laser weld cross-sections in aluminium and in steel differ due to several of the previously indicated properties. If aluminium and steel is welded bead-on-plate using the same welding parameters, the aluminium weld will generally be shallower and wider as shown in figure 7. Due to the higher surface reflectivity of aluminium, less energy is absorbed in the material even though the difference of absorption at keyhole welding is small. Furthermore, the energy absorbed in aluminium is conducted laterally from the weld position at a rate three times higher than that of steel. The increased reflective and conductive losses during aluminium welding limit penetrations with a 3 kW Nd:YAG laser to approximately 5 mm at a speed of 0.7 m/min. The welding depth in steel using the same parameters is around 6 mm but steel can be welded as deep as 25 mm using a 25 kW CO\(_2\) laser.

![Figure 7. Front-view of cross-sections of Nd:YAG welds in steel (left) and in aluminium of 2.5 mm thickness (Steel weld: 3 kW, 7.5 m/min. Aluminium weld: 2 kW, 2.5 m/min. Courtesy of HAAS).](image-url)
The absorption during CO₂ laser welding is increased by plasma absorption. CO₂ laser light reflected off the keyhole walls passes through the metal vapour and plasma (ionised vapour) in the keyhole and heats it by a mechanism called inverse Bremsstrahlung (photons of light hitting free electrons in the vapour and transferring their energy to thermal energy of the ionised vapour). In the case of Nd:YAG laser welding the plasma absorption of the laser beam is approximately two orders of magnitude lower because of the shorter wavelength of Nd:YAG laser light [13]. In effect this means that plasma absorption of Nd:YAG light can be neglected compared to Fresnel absorption during reflections in the keyhole.

The width of the weld cross-section is increased in the aluminium case, not only because of the thermal conductivity but due to the large melt temperature interval. As can be seen from table 1, $T_b - T_m$ for alloy AA2017 equals 1750°C while the interval for steel is 1400°C. The larger interval for aluminium makes the melt bigger.

Just as when welding steel there is liquid material flow (or convection) at the top of the weld causing the weld to widen. The convection on the surface is directed from the centre of the weld and sideways, shown in figure 8, moving metal liquid of higher temperature to the cooler surrounding. Since liquid lost in the centre must be replaced in order to keep the equilibrium, eddies are formed. The convection is driven by the surface tension gradient, which in turn is caused by the temperature gradient on the surface. This flow is generally referred to as thermocapillary or Marangoni flow.

![Figure 8. Front-view of cross-section of weld showing Marangoni flow in the melt caused by the temperature gradient.](image)

When laser welding there is the possibility of having keyhole or conduction limited welding as mentioned earlier. Since aluminium melts at 660°C it is not certain that the melting point for the surface oxide of 2050°C is reached in conduction limited welding. If the oxide is not molten, it will remain solid and can cause defects in the re-solidified weld as shown in figure 9. In keyhole welding the temperature in the vaporised zone is above 2400°C, so the surface oxide will not cause defects.
Precipitation or strain hardened alloys are generally expected to lose part of their strength on welding because the rapid heating and cooling destroys the hardening effect in the weld (fusion zone) and part of the heat affected zone (HAZ). Precipitation hardened alloys will have part of their precipitates dissolved while strain hardened alloys will lose their dislocations. For precipitation hardened alloys the part of the HAZ that reaches 500°C will be fully dissolved and will experience a lower strength than the surrounding. Very close to the fusion boundary a large amount of the alloying elements will remain in solid solution and experience natural ageing. The result is a narrow softened zone which is a weak link in the weld as shown in figure 10 [14].
Figure 11. Relationship between the laser weld microstructure and the phase diagram.

This softened area of the HAZ is wider in conventional aluminium welding because of the slower heating and cooling cycle. A typical width of the softened part is 0.5 mm for laser welding and 5 mm for TIG welding. The HAZ is by definition the part of the work-piece that has not only been heated by the welding process but also been affected by the heat. Depending on which alloy is discussed, the temperature limit for affecting the material varies but typical values for a heat treatable alloy are shown in figure 11 together with the corresponding microstructure.

All types of fusion welding of metals produce equi-axial grain structure as shown in figure 12. The size of the grains is dependent on the cooling rate. The grains grow perpendicularly from the interface between the melt and the solid towards the centre of the weld and in the direction of welding. The top surface of the weld is covered in chevron shaped ripples as shown in figure 13. These ripples represent areas of melt, which solidified simultaneously. The grain growth direction is always perpendicular to these solidification lines.

The yield and tensile strengths of laser produced butt welds in aluminium are typically in the order of the base material strength for alloys in the soft condition and around 80% of the base material strength for alloys hardened to H12, T4 or T6 [2, 15]. The reasons for the reduction are the softened zone close to the fusion zone described earlier and the stress concentration around the fusion zone due to the different microstructure and sometimes weld defects.
Figure 12. Front-view of cross-section showing the equi-axial grain structure [16].

Figure 13. Top-view of weld seam showing chevron pattern [17].
Nd:YAG laser welding of aluminium alloys

The strength of butt welds has been shown to increase by 10-20% with the use of filler wire of the same composition as the base material [2]. An increased cross-sectional area and a smoother weld top surface are believed to be responsible for the improvement.

Up to now practical applications of laser welding of aluminium alloys are not numerous. Laser welding seems to be fully accepted only in the automotive industry, where companies are investing in tens of machines at a time. For car manufacturers aluminium is a new material of interest. Most manufacturers are currently testing laser welding of aluminium for future solutions. Weight savings, total economy and recycling possibilities are among other parameters, which will determine if aluminium is a better choice than steel and what particular parts of the car that can be substituted.

Today only two examples are known of car companies performing laser welding in aluminium. One is Audi who uses CO₂ lasers to overlap weld a few details in the door frame of the A6 model [18]. Audi has been using aluminium in their cars for a long time and this determination last year resulted in their A8 model where the whole body is made of aluminium (without laser welding). The next Audi model to be released, the A12, is based on the same technique as the A8, the so called ‘space-frame’ which is a frame of aluminium profiles. The A12 is believed to have 35 metres of Nd:YAG laser welds between aluminium profiles and aluminium sheets. The other example is Porsche who chose Nd:YAG laser welding in the aluminium door of their recently released 911 Carrera [19]. A combination of high stiffness and the elimination of post-processing led to this choice.

6 Welding problems

There are many problems that can occur when welding in aluminium and the most important will be addressed here. Laser keyhole welding generally gives higher quality welds at a higher speed than conventional welding processes but in some cases the high power intensity associated with the laser process will increase certain problems. In this section the problems have been divided into two groups: welding process stability and welding defects.

For the laser welding process to function in the industry it must be stable, i.e. a high quality must be ensured and variations in process parameters must only result in small variations in the final product. Some of the properties of aluminium make it harder to produce a weld free of defects than is the case for steel. As shown earlier, the aluminium melt has a low density, low viscosity and low surface tension compared to steel. Altogether this has the effect that the natural motion of the melt is more pronounced and disturbed.

Spatter from the melt at welding can be a problem for industrial applications. Spatter can stick to the laser optics and destroy them in the long run as well as sticking to the work-piece and thereby demand cleaning. It is not totally clear what is causing the spatter but high-strength alloys or simply highly alloyed aluminium yield more spattering than softer or purer alloys. Alloys containing elements with a low boiling point such as Mg, seem to generate the most spatter. Smoke generated at welding can also stick to the shielding glass or the work-piece in the form of soot. Deposited soot has been shown to consist of oxidised alloying elements [20].
Random blow-outs are produced by explosions in the melt creating a pit in or a hole through the sheet. Blow-outs are caused by an excessive pressure or a collapse of the pressure equilibrium in the keyhole and can therefore never happen in conduction limited welding. The pressure instability is thought to be caused by easily evaporated alloying elements with high vapour pressures such as Mg, Zn and in some cases Li, table 3 [21].

Table 3. Boiling point and vapour pressure for some alloying elements [21].

<table>
<thead>
<tr>
<th>Alloying element</th>
<th>Boiling point [°C]</th>
<th>Vapour pressure at 900°C [N/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>2490</td>
<td>$10^3$</td>
</tr>
<tr>
<td>Cu</td>
<td>2570</td>
<td>-</td>
</tr>
<tr>
<td>Fe</td>
<td>2750</td>
<td>-</td>
</tr>
<tr>
<td>Li</td>
<td>1350</td>
<td>$10^5$</td>
</tr>
<tr>
<td>Mg</td>
<td>1090</td>
<td>$10^4$</td>
</tr>
<tr>
<td>Mn</td>
<td>1960</td>
<td>-</td>
</tr>
<tr>
<td>Si</td>
<td>2350</td>
<td>-</td>
</tr>
<tr>
<td>Zn</td>
<td>910</td>
<td>$10^5$</td>
</tr>
</tbody>
</table>

One problem with the study of blow-outs is that they occur in such a random fashion that very long welds are required in order to measure their average frequency. Remedies for blow-outs that have been suggested include using a twin focus laser beam to weld with one spot trailing another to create a prolonged and more open melt [22] and using Nd:YAG instead of CO₂ laser to avoid influence of the plasma [15].

Welding defects give the weld an undesirable appearance and reduce its strength. Defects in laser welding of aluminium have been defined and described in a preliminary European standard called prEN 12185:1995. The defect types include cracks, pores, undercut and sagging.

One defect that can be encouraged by using a laser when welding aluminium is the formation of hot cracks in the weld. The laser welding process is characterised by high cooling rates (100-200 times higher than TIG welding [23]) and since aluminium has a relatively high coefficient of thermal expansion, there is a risk that the shrinkage at cooling is too fast and therefore induces cracks. Laser welding is usually the best fusion welding process despite this because of the low heat input involved, shown in table 4, which will decrease the probability for cracks.

Table 4. Typical values of heat input for some welding processes in 2 mm thick aluminium.

<table>
<thead>
<tr>
<th>Process</th>
<th>Heat input [kJ/m]</th>
<th>Heat input (normalised)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nd:YAG laser</td>
<td>18</td>
<td>1</td>
</tr>
<tr>
<td>TIG</td>
<td>144</td>
<td>8</td>
</tr>
<tr>
<td>MIG</td>
<td>164</td>
<td>9</td>
</tr>
</tbody>
</table>
Several studies have been performed in order to rank the aluminium alloys in cracking susceptibility [15, 24] and a general conclusion is that most of the heat treatable 6xxx alloys are susceptible to hot cracks. These alloys can be welded without cracks by decreasing the power intensity and the speed simultaneously. By this procedure the heat input will increase but at the same time the cooling rate will decrease.

Porosity in the weld is a problem if the biggest pore or the total amount of pores is large enough to decrease the strength of the weld. The European standard states, that if the biggest pore has a diameter of less than 4 mm or 0.3 times the sheet thickness whichever is the smallest and the total amount of pores is no more than 2%, then the weld is considered a high quality weld as far as porosity is concerned.

There are two principally different types of pores that can develop when welding aluminium as shown in figure 14. One is formed by precipitation of hydrogen and has a spherical shape and the other is formed by the dynamic motion of the keyhole and is cylindrical and situated close to the root of the weld.

![Figure 14. Side-view (left) and front cross-section showing spherical and cylindrical pores in an aluminium weld.](image)

Pores created by precipitated hydrogen (70-80% H [25]) are avoided or at least minimised if the sheet surface is free from hydrogen sources such as grease, oil or paint and the shielding gas used is inert and pure. The excess hydrogen accumulates in hot areas, which explains why the pores tend to end up in the middle of the weld where the cooling is the slowest.

Pores created by the dynamic keyhole motion can occur when welding high depth-to-width ratios [21]. This type of pore can be avoided by decreasing the ratio for example by decreasing the power intensity and the speed simultaneously. This is only a problem for non-penetrating welds. The vapour pressure at the bottom of the weld is much reduced if the weld penetrates the bottom of the sheet and pores of this type do not form.
Analytical models
Analytical modelling is performed in order to find the answer to questions about laser welding, which are not possible to answer otherwise. When experimental welding is performed only the normal process parameters such as power, speed, etc can be varied. Based on experiments the reached results are examined and conclusions are drawn. Using analytical models it is possible to show in advance that certain parameters have no influence. Such a parameter can therefore be left out of the experiments and time will be saved. Another way to save experimental time is to calculate in advance what the power and speed should be, in order to reach a certain temperature or a certain welding depth.

Analytical models can also be used to get a deeper understanding of the welding process. Typical welding questions that have been answered analytically are: the causes of the widening at the top of the weld, how to minimise heat deformation and forecasting the dimensions of the weld.

The basis for analytical models of welding is the understanding of heat conduction which is described by Fourier’s 1st law of steady state in three dimensions

$$q = -k \left( \frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} + \frac{\partial T}{\partial z} \right).$$

Equation 4 states that the flow of heat $q$ in directions $x$, $y$ and $z$ is proportional to the temperature gradient in these directions. The proportionality constant $k$ is the thermal conductivity of the material.

Based on equation 4 analytical models have been derived for stationary heat sources and for moving heat sources, the most common of which will be discussed here.

A continuous stationary point source, i.e. an infinitely small source, acting on the surface of a material will heat the material to a temperature of

$$T(r,t) = \frac{q}{4\pi \alpha t} \text{erfc} \left( \frac{r}{\sqrt{4\alpha t}} \right)$$

(5)

where

$$\alpha = \frac{k}{\rho C_p} = \text{thermal diffusivity [m}^2/\text{s}],$$

$$\rho = \text{density of material [kg/m}^3],$$

$$C_p = \text{specific heat [J/kg K]},$$

assuming the source $q$ is constant [26-27]. In equation 5 the temperature is simply a function of distance $r$ from the source and time $t$. When the heat source has been running for a long time, i.e. $t$ goes to infinity, equation 5 reduces to

$$T(r) = \frac{q}{4\pi \alpha r}$$

(6)
which is a constant temperature field solely a function of \( r \). In ordinary metal material the time needed to reach a steady state is in the order of a few seconds.

Since a laser beam is not a point source but often has a Gaussian (or normal) energy distribution across the beam, the point source model has to be integrated over an area to yield a model for a continuous stationary Gaussian surface source. The temperature on the surface in the centre of the beam is

\[
T(0,0,t) = \frac{2qA}{\pi Dk\sqrt{\pi}} \arctan \left( \frac{2\sqrt{\pi}t}{D} \right)
\]

where

\[
D = \text{beam diameter [m]}, \\
A = \text{absorptivity}.
\]

When time goes to infinity equation 7 reduces to the constant expression

\[
T(0,0) = \frac{qA}{Dk\sqrt{\pi}}.
\]

By integrating the point source solution (which resulted in equation 5) over time and setting \( x = (x_0 + v_t t) \) to simulate movement, Rosenthal [28] developed the welding equations. The equation suited for conduction limited welding or keyhole welding in thick material is the moving point source equation. It is based on three-dimensional heat conduction and can be written

\[
T = T_\infty + \frac{qv}{4\pi k\alpha} \frac{e^{-\frac{\text{Pe}_x^2 + \text{Pe}_y^2 + \text{Pe}_z^2}{\text{Pe}_x^2 + \text{Pe}_y^2 + \text{Pe}_z^2}}}{\sqrt{\text{Pe}_x^2 + \text{Pe}_y^2 + \text{Pe}_z^2}}
\]

where

\[
T_\infty = \text{room temperature [K]}, \\
\text{Pe}_x = \frac{vx}{2\alpha} = \text{Péclet number}.
\]

When calculating the temperature field for a keyhole weld through a thin material, two-dimensional heat conduction is assumed resulting in the moving line source equation

\[
T = T_\infty + \frac{q}{\sqrt{8\pi k\delta}} \frac{e^{-\frac{\text{Pe}_x^2 + \text{Pe}_y^2}{\sqrt{\text{Pe}_x^2 + \text{Pe}_y^2}}}}{\sqrt{\text{Pe}_x^2 + \text{Pe}_y^2}}
\]

where

\[
\delta = \text{thickness of work-piece [m]}.
\]
8 Conclusion
In summary the joining of aluminium alloys presents a challenge for science and industry. It is predicted that joining methods such as riveting and clinching in many cases will be replaced by the more cost-effective fusion welding processes in the future. Laser welding of aluminium will be increasingly used in automated factories as knowledge about the process is increased. In cases where thin section aluminium sheets are to be welded at high speed lasers are likely to dominate.

9 References
1. STANNER, R, J, L. American scientist. 64 (1976) 258.
5. LYNCH, C, T. Handbook of materials science Vol 1. CRC press, Cleveland, USA.
6. Handbok för konstruktörer – hur man lyckas med aluminiumprofiler. SAPA.
23. KATAYAMA et.al. ICALEO’84 (1984) 64.
28. ROSENTHAL, D. Welding journal. 20 (1941) 220s.
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(alloys of titanium, aluminium, magnesium and polymers)

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Paper I – A review of laser welding of low density structural materials
A review of laser welding of low density structural materials
(Alloys of titanium, aluminium, magnesium and polymers)

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Abstract
This paper presents a literature review of the major findings of work investigating laser welding of:
- titanium alloys,
- aluminium alloys,
- magnesium alloys and polymers.

Over the past twenty years laser welding has achieved a high success rate in joining these materials, some of which are considered unweldable by alternative methods.

1 Introduction
Laser welding involves the melting and evaporation of the workpiece material by the absorption of high intensity light. CO₂ and Nd:YAG lasers are the only light sources suitable to the welding of metals as they are capable of generating power densities of between 10¹⁰ and 10¹² W/m² [1]. The most commonly welded material is, of course, steel and thousands of lasers are now dedicated to this industrial application [2]. The automotive and aerospace industries which have the largest interest in the process have, over recent years, focused their laser welding research on materials with lower densities than steel (i.e. 7900 kg/m³). The structural materials which have considerably lower densities than steel include those given in table 1.

Table 1. Low density structural materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium alloys</td>
<td>~4540</td>
</tr>
<tr>
<td>Aluminium alloys</td>
<td>~2700</td>
</tr>
<tr>
<td>Magnesium alloys</td>
<td>~1740</td>
</tr>
<tr>
<td>Polymers</td>
<td>900-2500</td>
</tr>
</tbody>
</table>
The following sections of this work will review the state of the art of laser welding with regard to the materials identified in table 1.

2 Laser welding of low density structural materials

2.1 Laser welding of titanium alloys

General metallurgy
Titanium alloys are attractive to the aeronautical and chemical industries because of their good creep and corrosion resistance together with a high strength to weight ratio [4]. Titanium alloys are usually divided into groups depending on their crystal structure. Commercially pure titanium has a hexagonal close-packed (HCP) structure (α phase) at room temperature but transforms to a body-centred cubic (BCC) structure (β phase) at 882°C [3]. Alloying elements which dissolve in the α phase and raise the β transformation temperature and thus stabilise the α phase, are called α stabilisers. Examples of such elements are aluminium, oxygen and nitrogen. Alloys containing α stabilisers are called α alloys. β alloys, consequently, are alloys containing elements stabilising the β phase, such as molybdenum, iron, vanadium, chromium and manganese. In between α and β alloys, there are alloys with mixed crystal structure denoted near-α alloys (< 2% β), α/β alloys and near-β alloys.

The weldability of titanium alloys decreases with increased levels of β stabilisers. All α alloys and α/β alloys are weldable but β alloy welds tend to be brittle and become even more brittle with ageing. It is important to realise that the fusion zone (FZ) and heat affected zone (HAZ) microstructure in welded titanium usually bears little resemblance to the pre-processed one [5] and that room temperature microstructure and resulting mechanical properties are a function of the cooling rate from the β transformation temperature.

Potential welding difficulties
Titanium is called a reactive metal because it reacts violently with atmospheric oxygen and nitrogen at elevated temperatures. The main concern when welding titanium alloys is contamination of the weld pool with oxygen and nitrogen since these elements decrease the alloy toughness. An additional problem is grain growth which becomes more of a problem with slow heating/cooling cycles [4].

Laser welding of α alloys
Pure titanium finds extensive use in aerospace applications such as fire walls and engine rings while other α alloys are used where increased toughness and low temperature strength is needed.

Laser welding of pure titanium has been only sparsely reported. 13 kW CO₂ laser welding has been successful but resulted in an increased FZ hardness and a slightly decreased HAZ hardness caused by changes in microstructure [6]. Welding with a pulsed 90 W average Nd:YAG laser gave sound welds without porosity or cracks [7].
Hirose et al. [8] laser welded the alloy Ti-32Al-5Mo and produced crack-free welds with a joint efficiency exceeding 100%. The addition of molybdenum was reported to improve room temperature ductility and high temperature oxidation resistance.

**Laser welding of near-α alloys**

These alloys show the greatest creep resistance of titanium alloys at elevated temperatures and are used in aircraft gas turbine compressors.

Baeslack et al. [9] investigated the laser weldability of the rapid solidification processed (RSP) alloy Ti-8Al-2.8Sn-5.4Hf-3.6Ta-1Y-0.2Si and found no evidence of cracking. By RSP it is possible to produce dispersion-strengthened elevated-temperature titanium alloys.

**Laser welding of α/β alloys**

Most research in laser welding has concentrated upon the α/β-alloy Ti-6Al-4V which is natural since it is the most used titanium alloy (representing 50% of titanium sales in Europe and USA). α/β alloys combine high strength, good formability and reasonable weldability. Typical applications include forged jet engine components.

All studies on Ti-6Al-4V have reported good quality welds using both CO₂ [6,10] and Nd:YAG [7] lasers in plate thickness of up to 12 mm. A theoretical model predicting depth, width and area of the weld with an error of less than 5% was developed by Bonollo et al. [10]. Denney [6] reported little variation in strength throughout the weld thickness following continuous wave (cw) CO₂ laser welding but an increase in HAZ hardness.

Titanium alloys with a high content of alloying elements, such as Ti-15Al-21Nb, have been successfully laser welded using both CO₂ [11] and Nd:YAG lasers [5,12]. Martin et al. [11] reported no cracks, pores or other defects and a FZ ductility in the range of the base material. Cieslak et al. [5] found no solidification cracking or hot cracking and a microstructure as fine as 1 μm. Two of the studies [5,12] reported decreased FZ hardness and indicated the possibility of tailoring the microstructure by postweld heat treatment. In Ti-Al-Nb alloys, niobium lowers the martensite formation start temperature, Mₛ, [11] and raises the melting temperature whilst aluminium lowers it [5].

**Laser welding of β alloys**

Alloys of this group have found few applications but their combination of very high strength and excellent formability could result in greater use in the future.

Beta-C, a metastable β alloy, has been joined by CO₂ laser welding to Ti-6Al-4V, producing fine-grained welds [13].

**Discussion**

Both CO₂ and Nd:YAG lasers have shown successful in welding the most common titanium alloys. Surprisingly, welding of titanium using Nd:YAG lasers with high power has not been reported.
2.2 Laser welding of aluminium alloys

Aluminium alloys are divided into groups representing the major alloying element used as shown in table 2. 1xxx, 3xxx and 5xxx alloys make up 95% of all flat rolled aluminium products [14]. Only wrought alloys will be discussed since laser welding of casting alloys is virtually non-existent.

Table 2. Wrought aluminium alloy groups.

<table>
<thead>
<tr>
<th>Class</th>
<th>Alloying element</th>
<th>Example of alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1xxx</td>
<td>min 99.00% Al</td>
<td>Al</td>
</tr>
<tr>
<td>2xxx</td>
<td>Cu</td>
<td>Al-Cu, Al-Cu-Mg</td>
</tr>
<tr>
<td>3xxx</td>
<td>Mn</td>
<td>Al-Mn, Al-Mn-Mg</td>
</tr>
<tr>
<td>4xxx</td>
<td>Si</td>
<td></td>
</tr>
<tr>
<td>5xxx</td>
<td>Mg</td>
<td>Al-Mg</td>
</tr>
<tr>
<td>6xxx</td>
<td>Mg, Si</td>
<td>Al-Mg+Si</td>
</tr>
<tr>
<td>7xxx</td>
<td>Zn</td>
<td>Al-Zn-Mg, Al-Zn-Mg-Cu</td>
</tr>
<tr>
<td>8xxx</td>
<td>misc.</td>
<td>Al-Fe, Al-Li</td>
</tr>
</tbody>
</table>

General
The majority of aluminium alloys can be welded using MIG or TIG techniques. The exceptions are most 2xxx alloys and the high strength 7xxx alloys, both of which contain copper. These alloys are generally considered to be unweldable because of their susceptibility to solidification cracking [15], see figure 1.

Laser welding has been tried on alloys from most of the groups, often with good results such as improved microstructure in the fusion zone as well as in the HAZ, due to the fast heating and cooling in laser processing. There is a power density threshold required to produce keyhole welding in aluminium alloys and the ease of evaporation of the alloy rather than thermal conductivity has been showed to govern this threshold. A higher content of evaporating elements such as magnesium and zinc decreases the threshold [16]. The keyhole threshold for 5xxx and 6xxx alloys is around $2\times10^{10}$ W/m$^2$ using both CO$_2$ and Nd:YAG lasers but at this intensity the process is unstable. To obtain stable keyhole welding using Nd:YAG lasers, an intensity of $3\times10^{10}$ W/m$^2$ is enough whereas CO$_2$ laser welding requires a much higher power density [17].

Potential welding difficulties
Metals such as aluminium and copper have a very high electron density and this gives them a high thermal conductivity and low absorptivity to infrared light. It is thus more difficult for (infrared) Nd:YAG or CO$_2$ lasers to initiate keyhole welds on these materials than on lower conductivity/reflectivity metals such as steels. When exposed to Nd:YAG laser light the absorptivity of aluminium is less than 10% at room temperature [17,18]. For CO$_2$ laser light this value is even lower but depends on surface condition (it is worth mentioning at this point that an anodised aluminium surface can be up to 100% absorptive). The high thermal conductivity of aluminium always results in a molten pool which is considerably broader than
the keyhole [19] even though the conductivity decreases by a factor of two at the solid-liquid transition.

![Figure 1. Two examples of solidification cracking (a and b) and one of hot tearing (c).](image)

Other problems are hot cracking such as solidification cracking and hot tearing [20,21] (hot cracking in FZ and/or HAZ caused by the inability of the liquid region to support the strain imposed by solidification shrinkage), figure 1. These problems exist because of the high thermal expansion of aluminium. In 4xxx, 5xxx and 6xxx alloys, resistance to hot tearing was found to increase with alloying element content which lead to the development of several more weldable alloys [22]. Kutsuna [23] proposed a formula to calculate the solidification crack index (SCI) giving the susceptibility of a binary alloy to solidification cracking. The formula is based on the alloying elements used, solidification morphology and segregation of impurities during solidification. Table 3 shows the solidification cracking susceptibility of a few binary alloys according to the formula using average alloy compositions [14]. The formula indicates that there is a critical concentration of silicon, copper and magnesium leading to highest cracking susceptibility, in this case 0.7%, 2.0% and 1.5% respectively. The critical concentrations were experimentally detected and the cause has not been reported. Jones [24] also found a peak value for magnesium, but at slightly less than 2%.

**Table 3. Ascending order of solidification cracking susceptibility of wrought binary alloys.**

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Cracking Susceptibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>2219 &amp; 2021</td>
<td>Intermediate</td>
</tr>
<tr>
<td>2011</td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td></td>
</tr>
<tr>
<td>5456</td>
<td></td>
</tr>
<tr>
<td>2025</td>
<td></td>
</tr>
<tr>
<td>5082</td>
<td></td>
</tr>
<tr>
<td>5083</td>
<td>High</td>
</tr>
<tr>
<td>5086</td>
<td></td>
</tr>
<tr>
<td>5454</td>
<td></td>
</tr>
<tr>
<td>5052</td>
<td></td>
</tr>
<tr>
<td>5005</td>
<td></td>
</tr>
<tr>
<td>3003</td>
<td></td>
</tr>
<tr>
<td>5050</td>
<td>Very high</td>
</tr>
</tbody>
</table>
As a result of their low ionisation energy, aluminium alloys have a high tendency to form a plasma plume above the keyhole [25]. The plasma plume facilitates keyhole formation but then prevents parts of the laser beam penetrating the keyhole, thereby diminishing keyhole stability.

Weld porosity can develop in two ways; either gas is trapped in the molten pool at solidification [26], or the keyhole can collapse because of instability resulting in holes or cavities [18,27]. Porosity can originate from hydrogen which is highly soluble in liquid aluminium or from volatile alloying elements such as magnesium and zinc [16,28]. Kutsuna et al. showed that the pores in welded 5083 alloy contained around 80% hydrogen [29]. Surface oxides, moisture or impurities can also give rise to porosity.

Recent advances

An interesting remedy for cavities caused by keyhole instability is the dual beam approach reported by Glumann et al. [30]. Whilst laser welding of aluminium, the best results were achieved when the first laser beam was focused at the workpiece surface and the trailing beam (3 mm behind) was focused 2 mm above the surface. The stabilising effect is thought to be caused by the open shape of the keyhole, created by the two beams, which facilitates the outflow of vapour thereby preventing an excessive vapour pressure.

Rapp et al. [31] listed hardenable 6xxx alloys, alloys 2024, 7075 and 8090 as being highly susceptible to hot cracking. Alloys 1050, 5754, 5182 and 5083 were found to be not susceptible. It was stated that in full penetration welding, cracks occur at traverse speeds exceeding 5-7 m/min. To achieve higher speeds without cracks, a silicon rich filler should be used. The same report showed that in overlap welding, the strongest joint is produced when the weld width equals the sheet thickness.

One of the few studies to concentrate on the choice and application of the shielding gas is the CO2 laser investigations of Hyppölä [32]. For sufficient shielding, a special nozzle was used, having a diameter of 6 mm. The nozzle was constructed to protect the sides and top of the weld. The choice of gas was found to depend on the purpose of the user. Argon gave the best surface quality but poor penetration. The addition of helium increased the penetration but also the porosity. Nitrogen gave the deepest penetration but poor surface quality and high levels of porosity.

The molten pool in laser welding of aluminium has been shown to have a round shape and be much more static than that experienced in the welding of steel [33]. Aluminium melt was found to be rather motionless in contrast to steel melt which is known to move around in the keyhole. This difference means that it should be possible to model the heat transfer and distribution in aluminium welding by simple heat conduction.

1xxx alloys

1xxx alloys or pure aluminium, contain at least 99% aluminium and the main application is electrical conductors. Because these alloys are not heat treatable, strength is developed by strain hardening.
Pure aluminium has been successfully welded using both CO$_2$ [16] and pulsed Nd:YAG lasers [18], the latter showing an increased formation of porosity with increased weld depth to width ratio (aspect ratio).

2xxx alloys
2xxx alloys respond well to age hardening and exist as Al-Cu alloys used for example in fuel tanks and Al-Cu-Mg widely used for aircraft construction. Al-Cu alloy 2019 is an exception among 2xxx alloys in that it is readily welded by traditional methods.

Copper-containing 2xxx alloys have proved to be difficult to weld by traditional methods but have been successfully welded by laser. 2219-T3 showed excellent welding performance with a 10 kW CO$_2$ laser [29]. Lithium-containing 2090-T8E41 also welded with CO$_2$ laser, showed few pores and the amount of porosity was unaffected by the penetration depth [34]. The joint efficiency (ratio of strength of weld to strength of base material) however was as low as 55%. CO$_2$ laser welding of lithium-containing 2195 gave occasional porosity [35]. High power pulsed Nd:YAG laser welding was reported to give sound welds in 2024-T3 when using pulse duty cycles exceeding 60% [36].

5xxx alloys
5xxx alloys are widely used for welded applications such as petrol tanks but are not heat treatable. The addition of magnesium raises the alloy strength and hardness, common magnesium contents are in the 0.8 to 5% range. Magnesium is considered as the causative factor of solidification cracking due to its low vaporisation point and high vapour pressure. Magnesium has also been found to segregate to grain and cell boundaries during welding, further promoting hot cracking [37]. During welding of a 5xxx alloy, magnesium evaporates or turns into plasma and its loss results in reduced joint efficiency and unacceptable porosity mainly consisting of hydrogen gas. Magnesium loss also reduces the effect of solid solution hardening.

Despite these problems, sound weld beads were reported in CO$_2$ laser welded 5052-O [29,38]. Pulsed Nd:YAG laser welding however resulted in magnesium vapour being shut in the molten pool, giving solidification cracks [39]. Alloy 5083 showed high quality welds using a plasma suppression technique and a cw CO$_2$ laser [28], but pores and solidification cracks resulted from the use of a pulsed Nd:YAG laser [27]. High power Nd:YAG lasers have produced butt welds without pores or cracks and overlap welds with small scale pores in alloys 5182, 5554 and 5754 [40]. Cieslak and Fuerschbach [22] found that 400 W pulsed Nd:YAG laser welding gave more hot cracking than 600 W cw Nd:YAG in alloys 5086, 5456 and 6061. Katayama and Lundin [37] also found more solidification cracking in 5456, when using a pulsed CO$_2$ laser than when using a cw laser. Both studies indicated that the rapid solidification associated with pulsed laser welding gave increased thermal shrinkage strains compared to cw laser welding and resulting in more cracking.

6xxx alloys
6xxx alloys containing both magnesium and silicon are heat treatable and widely used as structural material because of their combination of medium strength, good weldability and corrosion resistance. In alloys such as 6061 and 6063 a 2 to 1 ratio of magnesium and silicon is considered as giving optimal tensile properties [41]. Like 5xxx alloys they are also susceptible to hot cracking.
One Nd:YAG study showed that the excessive pressure generated in the keyhole when welding in 6061 was relieved by varying the beam focus depth [18]. Examination of CO₂ laser welds of 6063 revealed that the silicon content decreased towards the bottom of the weld [29]. The inhomogeneous silicon distribution was considered to be caused by rapid solidification before the molten pool had been sufficiently mixed. A high power Nd:YAG laser has been used to butt weld, giving no pores or cracks and to overlap weld, giving small scale pores in alloys Al-3Mg, Al-0.4Mg-1.2Si, Al-Mg-0.5Si, 6061 and 6062 [40]. Kim et al. [18] showed that porosity was formed in 6061 due to the collapse of the balanced forces in the keyhole.

7xxx alloys

7xxx alloys are known to increase their strength the most with age hardening of the aluminium alloys but the high-strength 7xxx alloys containing copper are not considered weldable.

Laser welding of zinc-containing 7xxx alloys has been sparsely reported on, probably due to the problems with vaporising zinc and magnesium. The 7xxx alloy Al-2.35Zn-0.83Mg was CO₂ laser welded using 1.5-6 kW but the weld appearance was not discussed [16]. The high strength alloy 7075 has been CO₂ laser welded using 10 kW and different shielding gases but the result was an irregular bead and high levels of porosity [29].

8xxx alloys

8xxx alloys contain miscellaneous elements for creating alloys with specific properties. Most of the alloys do not respond to heat treatment.

Studies on laser welding of 8xxx alloys have been limited to iron- and lithium-containing alloys. The 8090 superplastically formable lithium alloy gave keyholing at lower CO₂ laser power densities than normal but the weld contained pores along its centre-line [26]. Lee et al. [25] reported satisfactory CO₂ laser welds but increased undercut with increased power. CO₂ laser welding of 8090 gave coarse intermediate phase particles in the FZ [42] while pulsed Nd:YAG laser welding of Al-8Fe-2Mo showed 100% joint efficiency [43]. Cross et al. [44] found that the hot cracking susceptibility of high purity Al-Li alloys increased with lithium content up to 2.6% and then decreased but the reason was not reported. In addition, lithium can reduce the thermal conductivity of the Al-Li alloy by 30%, which implies that the weld penetration could be increased by adding lithium.

Lithium-containing alloys are believed to have higher hydrogen levels in their surface layers than other aluminium alloys, making weld porosity an increased problem [45]. Gittos [46] therefore suggested that 0.2 mm should be removed by from the surface prior to welding. Normal wire brushing removes less than this so machining would be needed.

Conclusions

- CO₂ or Nd:YAG lasers can be used to weld a wide range of aluminium alloys. Nd:YAG lasers can be effective at lower powers than their CO₂ counterparts because they generate a shorter wavelength light which is more efficiently absorbed by aluminium.
- Contrary to TIG and MIG welding, laser welding is possible in practically all alloys including copper-containing 2xxx alloys. High-strength 7xxx alloys however have not been successfully welded.
- High power cw Nd:YAG lasers have shown better welding results than corresponding pulsed Nd:YAG lasers and CO₂ lasers.
- A higher content of evaporating alloying elements such as Mg and Zn, reduces the power density threshold for stable keyhole welding.
- In overlap welding, the weld width should be equal to the sheet thickness to obtain the highest shear strength.
- By welding with one beam trailing another the vapour pressure in the keyhole is decreased and the process becomes more stable. The resulting weld has a low porosity.
- Argon as shielding gas gives the best surface quality but poor penetration. The addition of helium increases the penetration but also the porosity. Nitrogen gives the deepest penetration but poor surface quality and high levels of porosity.
- The weldability of aluminium alloys varies greatly and the biggest problems are process stability and hot cracking.

2.3 Laser welding of magnesium alloys

General
Magnesium alloys are usually denoted by codes representing the major alloying elements included and their respective weight percentages. For example; the code is A for aluminium and Z for zinc, so AZ91 stands for the alloy Mg-9Al-1Zn. Many metals have a high solid solubility in magnesium and common alloying elements include aluminium, zinc, lithium, cerium, silver, zirconium and thorium. In Europe 85-90% of all magnesium alloys used are cast and the principal cast material is a Mg-Al-Zn alloy. Applications for magnesium include the aerospace and automotive industries where low weight of cast components is crucial [47].

Magnesium is the most machinable of all structural materials and can almost always be machined without the need of cooling. Mechanical joining of magnesium alloys can be difficult because of the intense galvanic corrosion experienced when in contact with most other metals. Therefore joining by welding is an important process to develop.

Traditional welding of magnesium
Magnesium alloys are traditionally welded using TIG and MIG but less than half of the common alloys are considered weldable, see table 4 [14]. According to Paris et al. [47], WE54 has also been successfully welded by TIG.

<table>
<thead>
<tr>
<th>Casting alloy</th>
<th>Composition</th>
<th>Weldable</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ63</td>
<td>Mg-6Al-3Zn</td>
<td>No</td>
</tr>
<tr>
<td>AZ81</td>
<td>Mg-8Al-1Zn</td>
<td>No</td>
</tr>
<tr>
<td>AZ91</td>
<td>Mg-9Al-1Zn</td>
<td>No</td>
</tr>
<tr>
<td>EZ33</td>
<td>Mg-3Rare earth-3Zn</td>
<td>Yes</td>
</tr>
<tr>
<td>HK31</td>
<td>Mg-3Th-1Zr</td>
<td>Yes</td>
</tr>
<tr>
<td>HZ32</td>
<td>Mg-3Th-2Zn</td>
<td>No</td>
</tr>
<tr>
<td>QE22</td>
<td>Mg-2Ag-2Rare earth</td>
<td>Yes</td>
</tr>
</tbody>
</table>
AZ31 plates of 4 mm thickness were recently successfully welded by TIG, resulting in a fatigue limit reaching 92% of the base metal [48]. The FZ hardness was nearly equal to that of the base metal. The same research group used electron beam technology to butt weld 5-15 mm thick plates of AZ80 [49].

Laser welding of magnesium
Laser welding of magnesium has only been reported three times and in all studies the welding was successful. In 1986 Baeslack III et al. laser welded 2.5 mm thick coupons of WE54X using 550 W cw and argon shielding [50]. Full penetration welds of good visual status were produced but they contained grain boundary cracks as large as 100 μm, in the HAZ. The main conclusion was that WE54X is sensitive to liqutation cracking.

Chen et al. used a 10 kW CO₂ laser to weld 25 mm thick AZ91 plates [51]. With a traverse speed of 1.0 m/min, they reached a depth to width ratio of 4.5. The weld surface had a good appearance, no defects were found in the FZ and the HAZ was extremely narrow. AZ91 was found to be weldable by laser, using lower power intensities than when welding aluminium or even steel.

Weisheit et al. used a 2.5 kW CO₂ laser to butt weld cast alloys AZ91, AM60, ZC63, ZE41, QE22 and WE54 and wrought alloys AZ61, AZ31, ZW3 and ZC61 with a thickness of 2.5-8.0 mm [52]. The cast alloys showed an increase in hardness in the fusion zone while the wrought alloys were unaffected. All alloys except three gave a good weld result; the die cast alloys AZ91 and AM60 which had a high level of porosity and the age hardened QE22 which had a crack developing in the welding direction.
Discussion
The few studies performed on laser welding of magnesium have showed that welding is possible and that the welds look good. Unfortunately, none of them have reported on the strength of the welds, which is the main concern for use in industry.

The reason why magnesium welding can be carried out at a low power intensity compared to the welding of steel or aluminium, has not been discussed. A probable cause is the combination of low thermal conductivity, low melting and boiling point and a high laser light absorptivity.

2.4 Laser welding of polymers

Polymeric materials are comprised of thermoplastics (TP) which can be melted and reformed, thermosets (TS) and elastomers, both with unbreakable net structure. When heated, TS and elastomers will burn before turning into a liquid which make these materials impossible to weld in contrast to TP which can be readily welded. TP can be further divided into amorphous polymers and semi-crystalline polymers as shown in table 5.

<table>
<thead>
<tr>
<th>Amorphous polymers</th>
<th>Semi-crystalline polymers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Abbreviation</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>PS</td>
</tr>
<tr>
<td>Poly(methyl methacrylate)</td>
<td>PMMA</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>PC</td>
</tr>
<tr>
<td>Acrylonitrile-butadiene</td>
<td>ABS</td>
</tr>
<tr>
<td>-styrene</td>
<td></td>
</tr>
<tr>
<td>Poly(vinyl chloride)</td>
<td>PVC</td>
</tr>
</tbody>
</table>

When comparing the two types of lasers commonly used in material processing, the CO₂ laser light has higher absorption than the Nd:YAG in organic materials such as polymers. Since the Nd:YAG laser wavelength is very close to that of visible light, polymers which look transparent to the eye are usually also transparent for the Nd:YAG laser light.

Successful attempts
Only a few attempts have been made to laser weld polymers. As early as 1972, Ruffler and Gürs [53] as well as Duley and Gonsalves [54] first reported CO₂ laser welding of polymers. The studies showed that low density polyethylene (LDPE) could be butt welded in thickness up to 1.5 mm using a traverse speed of 10 mm/s and a power of 100 W. Mueller et al. [55] showed that polymers could be welded in varying gravity owing to its high viscosity as a liquid compared to metals. Duley and Mueller 1992 [56] reached the extended conclusion that surface tension effects dominate in the laser induced melt and that gravitational effects are insignificant. Their CO₂ laser welding experiments on polypropylene (PP) and PE also showed that powers exceeding 100 W could lead to thermal decomposition of the polymer, even with increased traverse speed. Very good quality welds in polycarbonate (PC) and PP tubes were reported by Atanasov [57], using a maximum of 30 W on a cw CO₂ laser in TEM₀₀ mode with traverse speeds reaching 80 mm/s. Atanasov also presented a theoretical model which appropriately
predicts the optimum processing time for a cylindrical part, given the rotation speed and laser power density.

The best welding results so far have been reached by Jones and Taylor [58,59]. They concluded that the CO$_2$ laser can be used for lap welding PE and PP of a thickness up to 0.2 mm with tensile strengths exceeding that of the parent material. Thicker sheets absorbed too much energy and material was lost by vaporisation resulting in a cross sectional 'ditch'. The Nd:YAG laser was used to lap weld up to 2 mm thick sheets of PE and PP, reaching strengths of 70%.

**Keyhole welding?**

Despite these successful trials, Nonhof [60] came to the conclusion that a 50 W halogen lamp could just as well be used as a heat source in welding of polymers. This statement is partially true but the use of lasers offers other advantages such as high speed, narrow HAZ and easy automation. In deep penetration welding of metals, the keyhole is maintained by the equilibrium between the molten metal pool and the pressure of the metal gas in combination with the plasma. The deep penetration is made possible by the concentrated heat from the laser beam and its multiple reflections inside the keyhole. Since polymers are organic materials they consist of long carbon molecule chains which are hard to move. In thermoplastic polymers, the long molecules start to move around when the material is heated above the melting temperature. Further heated, the polymer will either degrade or burn since the chains are too big and slow-moving to become a polymer gas [61]. Since a polymer gas cannot be achieved in the welding process, keyhole welding of polymers will not work in the same way as it does for metals; the welding must be conduction limited.

It is important to remember that the temperature range for a polymer melt is very narrow compared to the same range for a metal. PE, for example, melts at 140 °C and burns at 345 °C while iron melts at 1535 °C and boils at 2750 °C.

**Possible welding of polymers**

Deep welds can be performed in polymers using conduction limited welding [62], especially in semi-transparent polymers. Polymers usually show high absorption (often above 60%) for the CO$_2$ wavelength but openings in the radiation spectrum exist for each polymer where the absorption is very low, figure 2.

![Figure 2. Absorption spectrum in ABS polymer.](image-url)
Therefore it is important to know the absorption spectrum for the particular polymer and the laser light wavelength used in order to succeed in heating the material to a liquid without exceeding the burning temperature. In addition, clean basic polymers are hardly ever used and additives such as colours will turn most polymers into surface absorbers [60]. If only the polymer surface can absorb laser irradiation, heating of the rest of the material will be controlled by the heat diffusivity which for polymers typically is two orders of magnitude lower than for metals.

Even if polymers can be considered isotropic on a macro-scale, semi-crystalline polymers in particular are far from homogeneous when examined in detail, see figure 3. Because of the difference in refractive index in the amorphous and crystalline regions, laser light can be scattered in semi-crystalline polymers, making deep penetration difficult.

![Figure 3. Molecule order in semi-crystalline polymer.](image)

An intelligent way of using the transparency of the polymer to obtain a weld was recently suggested [63]. For example an ordinary lap weld could be performed by placing a transparent polymer sheet on top of an opaque one and then applying Nd:YAG laser light. The light will pass through the transparent material but will heat and melt the surface of the opaque material, thus joining the two sheets.

**Discussion**

When welding polymers, the material should be heated above the melting temperature but below burning temperature. The problem is that the absorption varies with material, additives and crystallinity which makes it necessary to perform welding experiments.

There still remain questions to be answered. How do variation in the percentage of crystallinity affect the laser beam? Does the molecular weight (i.e. the length of the molecules) of the polymer have any influence on the welding result?
3 General conclusion

CO₂ and Nd:YAG lasers have been found to be capable of successfully welding the vast majority of the alloys of titanium, aluminium and magnesium. Successful results have also been noted for certain thermoplastic polymers including polyethylene and polypropylene.

As designers and manufacturers turn away from traditional structural materials towards these lower density alloys and polymers it is clear that laser welding will become an increasingly useful tool. This is particularly true when otherwise un weldable materials or combinations are to be joined.

References

20. EASTERLING, K. Introduction to the physical metallurgy of welding. 1983, Butterworths & Co.
41. HATCH, J, E. Aluminum, properties and physical metallurgy. 1984, American society for metals, USA.
44. CROSS, C, E, OLSON, D, L, EDWARDS, G, R & CAPES, J, F. Welding research supplement. Jul (1985) 241s
46. GITTOS, M, F. Gas-shielded arc welding of the Al-Li alloy 8090. TWI members report 347. (1987)
47. PARIS, H, HUNT, W, H. Advances in magnesium alloys and composites. 1988, Minerals metals and materials society, USA.
53. RUFFLER, C & GÜRS, K. Optics laser technology. 4 (1972) 265.
Nd:YAG laser lap welding of coated aluminium alloys

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Nd:YAG laser lap welding of coated aluminium alloys

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Abstract

This experimental program investigated the production of lap welds between 1 mm thick sheets of aluminium alloys 5182 and 6016 which had previously been coated with Drylube. (Drylube is a polymer based coating approximately 1 μm thick which improves the formability of the aluminium alloy sheet). Successful welds were produced using a 2.5 kW Nd:YAG laser in conjunction with a 0.6 mm optical fibre. It was discovered that there is an optimum gap width between the two sheets which gives the best weld quality and strength. Pulsed and cw laser welds were produced and compared with respect to porosity and surface profile, etc.

1 Introduction

The area of the automotive industry which employs aluminium for body parts requires the material to be easily formable and weldable. The traditional method of forming aluminium sheet involves the use of oil based lubricants. These lubricants interfere with subsequent welding or painting and need to be thoroughly cleaned off before these operations. A new dry coating material called Drylube allows the aluminium to be formed without wet lubrication and removes the need for cleaning before painting. This investigation looks into the effect of the Drylube surface layer on the laser welding process.
2 Experimental work

Lap welds were produced between aluminium alloy sheets of two types with a number of surface preparations. The two alloys were:

a) AA5182, a commonly used alloy in automotive and aerospace applications noted for its combination of corrosion resistance and good welding properties [1]; thickness 1.0 mm.
b) AA6016, a heat treatable alloy with high corrosion resistance used mainly for extrusion [1]; thickness 1.1 mm.

Details of the alloys are given in table 1.

Table 1. Details of alloys.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Tensile strength</th>
<th>Mg</th>
<th>Mn</th>
<th>Fe</th>
<th>Zn</th>
<th>Si</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA5182</td>
<td>260 MPa</td>
<td>4.0-5.0</td>
<td>0.2-0.5</td>
<td>0.35</td>
<td>0.25</td>
<td>0.2</td>
<td>bal.</td>
</tr>
<tr>
<td>AA6016</td>
<td>185 MPa</td>
<td>0.3-0.6</td>
<td>0.2</td>
<td>0.5</td>
<td>0.2</td>
<td>1.0-1.5</td>
<td>bal.</td>
</tr>
</tbody>
</table>

The combinations of the materials being welded are given in table 2 and the process parameters in table 3.

Table 2. Combinations of materials.

<table>
<thead>
<tr>
<th>Combination</th>
<th>Description of treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5182 Drylube coated on 5182 Drylube coated</td>
</tr>
<tr>
<td>2</td>
<td>5182 pickled and Drylube coated on 5182 pickled and Drylube coated</td>
</tr>
<tr>
<td>3</td>
<td>5182 pickled, Zr passivated and Drylube coated on 5182 pickled, Zr passivated and Drylube coated</td>
</tr>
<tr>
<td>4</td>
<td>6016 Drylube coated on 5182 Drylube coated</td>
</tr>
<tr>
<td>5</td>
<td>6016 pickled and Drylube coated on 5182 pickled and Drylube coated</td>
</tr>
<tr>
<td>6</td>
<td>6016 pickled, Zr passivated and Drylube coated on 5182 pickled, Zr passivated and Drylube coated</td>
</tr>
</tbody>
</table>
Table 3. Process parameters.

<table>
<thead>
<tr>
<th>Shielding gas</th>
<th>Ar l/min</th>
<th>He l/min</th>
<th>70%He, 30% Ar l/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas flow with Ø10 mm nozzle</td>
<td>15</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>Gas flow with Ø4 mm nozzle</td>
<td>10</td>
<td>15</td>
<td>20</td>
</tr>
</tbody>
</table>

NB. The gas was applied at 45° to the work-piece either in advance of or following the laser beam.

<table>
<thead>
<tr>
<th>Laser power and mode</th>
<th>cw welding at 1950 W, pulsed at 160 Hz, min 720 W, max 2988 W, average 1800 W.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traverse speed</td>
<td>1.6 m/min for cw welding, 2.5 m/min for pulsed welding.</td>
</tr>
</tbody>
</table>

3 Results and discussion

3.1 Weld quality

Table 4 gives details of the factors used to measure weld quality in accordance with the relevant standard prEN 12185:1995.

Table 4. Measures of weld quality.

<table>
<thead>
<tr>
<th>Combination (from table 2)</th>
<th>Average porosity level [%]</th>
<th>Max pore diameter [mm]</th>
<th>Penetration variation [%]</th>
<th>Cracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cw gap 0.0</td>
<td>~1.5</td>
<td>0.05</td>
<td>±10</td>
<td>none</td>
</tr>
<tr>
<td>Pulsed gap 0.0</td>
<td>~1.0</td>
<td>0.05</td>
<td>±10</td>
<td>none</td>
</tr>
<tr>
<td>gap 0.1</td>
<td>~1.0</td>
<td>0.05</td>
<td>±10</td>
<td>none</td>
</tr>
<tr>
<td>gap 0.3</td>
<td>~0.5</td>
<td>0.05</td>
<td>±10</td>
<td>none</td>
</tr>
<tr>
<td>2 cw gap 0.0</td>
<td>~1.5</td>
<td>0.05</td>
<td>±10</td>
<td>none</td>
</tr>
<tr>
<td>Pulsed gap 0.0</td>
<td>~1.0</td>
<td>0.05</td>
<td>±10</td>
<td>none</td>
</tr>
<tr>
<td>gap 0.1</td>
<td>~1.0</td>
<td>0.05</td>
<td>±10</td>
<td>none</td>
</tr>
<tr>
<td>gap 0.3</td>
<td>~0.5</td>
<td>0.05</td>
<td>±10</td>
<td>none</td>
</tr>
<tr>
<td>3 cw gap 0.0</td>
<td>~1.5</td>
<td>0.05</td>
<td>±10</td>
<td>none</td>
</tr>
<tr>
<td>Pulsed gap 0.0</td>
<td>~1.0</td>
<td>0.05</td>
<td>±10</td>
<td>none</td>
</tr>
<tr>
<td>gap 0.1</td>
<td>~1.0</td>
<td>0.05</td>
<td>±10</td>
<td>none</td>
</tr>
<tr>
<td>gap 0.3</td>
<td>~0.5</td>
<td>0.05</td>
<td>±10</td>
<td>none</td>
</tr>
<tr>
<td>4 cw gap 0.0</td>
<td>~2.5</td>
<td>0.20</td>
<td>±10</td>
<td>micro</td>
</tr>
<tr>
<td>Pulsed gap 0.0</td>
<td>~2.5</td>
<td>0.15</td>
<td>±10</td>
<td>micro</td>
</tr>
<tr>
<td>gap 0.1</td>
<td>~0.5</td>
<td>0.05</td>
<td>±10</td>
<td>micro</td>
</tr>
<tr>
<td>gap 0.3</td>
<td>~0.5</td>
<td>0.05</td>
<td>±10</td>
<td>micro</td>
</tr>
</tbody>
</table>
It is clear from the above information that there was no significant effect of the different surface treatments on weld quality. According to the standard the welds were of an intermediate quality level. The largest pores were found at the root of partially penetrated joints. This is not surprising as it is in this region that the vaporised Mg and Zn elements can get trapped in the case of not fully penetrated joints.

The welds with the 6016 alloy on top appeared more stable than with the 5182 material during welding but metallurgical examination revealed the presence of micro cracks at the solid-liquid interface. A cross section of such a weld is presented in figure 1. The increase in cracking susceptibility in the presence of the 6016 alloy is attributable to increased hardness and reduced ductility in the joint caused by the presence of Si which can segregate to grain boundaries and cause embrittlement, figure 2.
Figure 2. Hardness profile in 6016/5182 weld joint.

### 3.2 Weld strength

Tensile test results of the welds are given in table 5.

Table 5. Tensile test results of weld joints.

<table>
<thead>
<tr>
<th>Combination (from table 2)</th>
<th>Workpiece material strength [MPa]</th>
<th>Weld strength [MPa]</th>
<th>% of average workpiece material strength</th>
<th>Type of failure</th>
<th>Position of failure (based on 18 samples of each combination, see figure 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cw</td>
<td>260</td>
<td>145</td>
<td>56</td>
<td>brittle</td>
<td>24% a, 35% b, 41% c</td>
</tr>
<tr>
<td></td>
<td>pulsed</td>
<td>260</td>
<td>154</td>
<td>brittle</td>
<td>0% a, 33% b, 67% c</td>
</tr>
<tr>
<td>2 cw</td>
<td>260</td>
<td>150</td>
<td>58</td>
<td>brittle</td>
<td>0% a, 67% b, 33% c</td>
</tr>
<tr>
<td></td>
<td>pulsed</td>
<td>260</td>
<td>152</td>
<td>brittle</td>
<td>0% a, 0% b, 100% c</td>
</tr>
<tr>
<td>3 cw</td>
<td>260</td>
<td>150</td>
<td>58</td>
<td>brittle</td>
<td>17% a, 83% b, 0% c</td>
</tr>
<tr>
<td></td>
<td>pulsed</td>
<td>260</td>
<td>159</td>
<td>brittle</td>
<td>11% a, 0% b, 89% c</td>
</tr>
<tr>
<td>4 cw</td>
<td>185/260</td>
<td>115</td>
<td>52</td>
<td>brittle</td>
<td>0% a, 100% b, 0% c</td>
</tr>
<tr>
<td></td>
<td>pulsed</td>
<td>185/260</td>
<td>139</td>
<td>brittle</td>
<td>67% a, 33% b, 0% c</td>
</tr>
<tr>
<td>5 cw</td>
<td>185/260</td>
<td>126</td>
<td>57</td>
<td>brittle</td>
<td>6% a, 94% b, 0% c</td>
</tr>
<tr>
<td></td>
<td>pulsed</td>
<td>185/260</td>
<td>141</td>
<td>brittle</td>
<td>94% a, 6% b, 0% c</td>
</tr>
<tr>
<td>6 cw</td>
<td>185/260</td>
<td>105</td>
<td>47</td>
<td>brittle</td>
<td>0% a, 100% b, 0% c</td>
</tr>
<tr>
<td></td>
<td>pulsed</td>
<td>185/260</td>
<td>139</td>
<td>brittle</td>
<td>94% a, 6% b, 0% c</td>
</tr>
</tbody>
</table>
The welds were generally in the order of 60% as strong as the base materials. Untreated sheets welded for reference also yielded tensile strengths of about 60% of the base materials. It is clear therefore that the presence of Drylube on the surface of the work-piece has had no significant effect on the strength of the welds produced.

### 3.3 Effect of inter work-piece gap width

Laser lap welding sheets of Drylube coated aluminium shares some of the problems associated with the welding of zinc coated steel. Both situations involve autogeneous welding in the presence of a contaminant surface layer. Earlier work [3-4] on lap welding of zinc coated steel identified that a small gap between the work-pieces allowed the zinc to escape from the weld zone as a vapour. The resulting welds were of higher integrity as the level of zinc contamination was reduced.

![Graph showing tensile strength vs gap width](image)

**Figure 4.** Average and 95 % LSD interval for combination 1 pulsed. The optimum gap width is 0.1 mm for high strength.
This study assessed the benefit of inter work-piece gaps and found a similar result to the case of zinc coated steel. Figure 4 demonstrates that there is an optimum gap width of 0.1 mm for maximum weld strength. If this gap is reduced to zero the Drylube material becomes trapped in the weld zone and contaminates the melt. The resulting weld has increased porosity and reduced strength. On the other hand an increase in gap width to 0.3 mm decreases the efficiency of the welding process and produces a weaker weld.

Figure 5 shows the presence of an open columnar pore along the interface between the two work-pieces at the edge of the melt. The shape of this pore is obviously related to the flow characteristics of the melt and the geometry of the pre welded joint. Under the correct conditions the curvature of this pore will strengthen the joint by minimising stress raisers in the area.

4 Conclusions

- A coating of Drylube on the surface of aluminium alloy sheet does not seriously affect the quality and strength of laser lap welds.

- The 5182 alloy was welded without cracks and porosity levels of the order of 1%. The 6016 alloy experienced micro cracking and an increase in the porosity level although these did not unduly affect weld strength. Weld strength in all cases was approximately 60% of the work-piece material. This is similar to the result obtained for no Drylube coated samples.

- An optimum inter work-piece gap (in this case 0.1 mm) allows the Drylube to leave the weld zone as a vapour and thus minimise weld contamination.
Acknowledgements

The authors would like to thank Johnny K. Larsson of Volvo Car Corporation and Bernt von Brömssen of IVF for their advice. This work was financially supported by Volvo Car Corporation, SSAB Tunnplåt, AGA AB, IVF, Luleå University of Technology and the Swedish National Board for Industrial and Technical Development (NUTEK).

References

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Nd:YAG laser welding of aluminium; factors affecting absorptivity

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Abstract
This paper investigates the factors affecting the absorptivity during Nd:YAG laser keyhole welding of a 6xxx aluminium alloy. The influence of surface condition on absorption is shown to be negligible. Experimental absorption measurements by calorimetry are compared to analytical absorption values using a simple model based on Fresnel absorption during multiple reflections in the keyhole.

1 Introduction
A material exposed to radiation can react in three ways: by absorption, reflection and/or transmission. Since infrared light penetrates only up to two atomic diameters in metals they can be considered opaque which means transmission can be ignored. Therefore an infrared laser beam directed onto a metal surface will only be absorbed and/or reflected.

Aluminium is usually described as being very reflective to laser radiation. Typical absorption figures are presented in table 1. This type of absorption measurement usually shows how low intensity radiation at normal incidence is absorbed on a flat aluminium surface at room temperature. The absorption has however been found to depend on the wavelength of the incident light [1-3], the angle of incidence to the surface [3], the surface temperature [2] and the surface roughness [4]. This makes it difficult to compare results and consequently they often differ.

Laser welding of aluminium typically demands a power density exceeding 1 MW/cm² to heat the surface to its melting point where welding can begin and often to the boiling point to create a keyhole.
Table 1. Absorption in aluminium; data from the literature.

<table>
<thead>
<tr>
<th>Absorption of Nd:YAG light (1.06 μm)</th>
<th>Absorption of CO₂ light (10.6 μm)</th>
<th>Comment</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>11%</td>
<td>5%</td>
<td>Calculated</td>
<td>[1]</td>
</tr>
<tr>
<td>5%</td>
<td>3%</td>
<td>Experimental</td>
<td>[5]</td>
</tr>
<tr>
<td>11%</td>
<td></td>
<td>Experimental</td>
<td>[2]</td>
</tr>
<tr>
<td>9%</td>
<td></td>
<td>Calculated</td>
<td>[3]</td>
</tr>
<tr>
<td>12%</td>
<td>4%</td>
<td>Experimental</td>
<td>[3]</td>
</tr>
</tbody>
</table>

Extensive research has been performed on the absorption of radiation but very few workers [6-7] have mentioned absorption of laser light on aluminium surfaces using real process conditions, i.e. high power density, heating of the work-piece and formation of an absorbing keyhole.

This study of energy absorption was performed to estimate how much of the incident energy is absorbed by the work-piece during laser welding of aluminium and to identify factors which can influence that absorption.

2 Experimental work

2.1 General

The experimental work concentrated on Nd:YAG laser welding of aluminium alloy AA6063 with different surface finishes. The four surface finishes investigated are listed in table 2. Low intensity absorption investigations have already established that surface roughness [4] and surface oxidation [8] can have a profound effect on absorption for CO₂ laser radiation. For this reason it was decided to compare ‘as received’ aluminium with a sand blasted (roughened) and anodised (oxidised) surfaces. Anodising effectively coats the aluminium with a layer of comparatively low conductivity oxide (Al₂O₃).

Table 2. Surface condition of aluminium sheets.

<table>
<thead>
<tr>
<th>Surface condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) As received</td>
</tr>
<tr>
<td>2) Sand blasted</td>
</tr>
<tr>
<td>3) Anodised; natural appearance</td>
</tr>
<tr>
<td>4) Anodised; polished or shiny appearance</td>
</tr>
</tbody>
</table>
A wide variety of anodised surfaces are available commercially and two typical finishes were tested. One of these had the same visual appearance as the as received material and the other appeared polished or shiny. In both cases the surface layer of Al₂O₃ was 10 μm thick. The presence of the oxide coating is clear in figure 1 which compares cross-sections of as received and anodised samples.

The sample size in each case was 3 mm x 70 mm x 70 mm. The laser was a HAAS HL3006D Nd:YAG with a maximum power of 4 kW. The absorption of the sample surfaces was investigated at low intensity at ambient temperature and at high intensity during welding.

### 2.2 Absorption of low intensity energy

![Figure 2. Set-up of low intensity absorption measurement.](image)

**Figure 1. Cross-sections of a) as received and b) anodised aluminium sheets.**
A collimated Nd:YAG laser beam with a diameter of 25 mm and a power of 500 W was reflected off the four different surfaces onto a power meter as shown in figure 2. The angle of incidence was kept inside the region where no increased reflection is to be expected for well polished surfaces [2].

The energy absorbed by the sheets was measured by calorimetry and the results are shown in table 3.

Table 3. Energy absorption of Nd:YAG laser light. The total energy involved was 36 kJ in each case.

<table>
<thead>
<tr>
<th>Surface condition</th>
<th>Energy absorbed by the work-piece [J]</th>
<th>Energy absorbed by the power meter [J]</th>
<th>Energy lost by diffuse reflection [J]</th>
</tr>
</thead>
<tbody>
<tr>
<td>As received</td>
<td>5216 (14%)</td>
<td>25200 (70%)</td>
<td>5584 (16%)</td>
</tr>
<tr>
<td>Sand blasted</td>
<td>11005 (31%)</td>
<td>4200 (12%)</td>
<td>20795 (58%)</td>
</tr>
<tr>
<td>Anodised 'natural'</td>
<td>4864 (14%)</td>
<td>20400 (57%)</td>
<td>10736 (30%)</td>
</tr>
<tr>
<td>Anodised 'shiny'</td>
<td>3659 (10%)</td>
<td>28500 (79%)</td>
<td>3841 (11%)</td>
</tr>
</tbody>
</table>

As can be seen from table 3, the sand blasted surface absorbed more than twice as much energy as the other surfaces. The absorption for anodised surfaces were similar to the as received material. The table shows substantial energy losses which can be attributed to diffuse reflections from the aluminium sheet which miss the power meter. This type of energy loss was naturally high for the sand blasted surface where the beam was scattered in all directions by the multifaceted surface.

2.3 Absorption of high intensity energy during welding

Bead-on-plate welding was performed on the same materials as before with the experimental parameters presented in table 4.

Table 4. Experimental parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>HL3006D Nd:YAG</td>
</tr>
<tr>
<td>Beam guidance</td>
<td>Optical fibre Ø0.6 mm</td>
</tr>
<tr>
<td>Focal length of lens</td>
<td>150 mm</td>
</tr>
<tr>
<td>Welding speed</td>
<td>4-10 m/min</td>
</tr>
<tr>
<td>Power</td>
<td>3000 W</td>
</tr>
<tr>
<td>Shielding gas</td>
<td>None</td>
</tr>
</tbody>
</table>
The energy absorbed by the different surfaces was measured by calorimetry as before and the results are shown in figure 3.

![Energy absorption as a function of welding speed for different surfaces.](image)

**Figure 3.** Energy absorption as a function of welding speed for different surfaces.

![Cross-sections of welds in sheet with anodised natural surface at speeds.](image)

**Figure 4.** Cross-sections of welds in sheet with anodised natural surface at speeds a) 5 m/min b) 6 m/min c) 7 m/min d) 8 m/min e) 9 m/min and f) 10 m/min.
Regardless of surface condition the absorption was around 60% of the incident energy for low speeds (~4 m/min) and around 50% for the higher speeds investigated here (~10 m/min). Even though the four surfaces showed large differences in energy absorption for low intensities there are minimal absorption differences when welding.

Figure 4 shows the change in cross-sectional geometry of a typical series of welds as the welding speed is increased. There is a notable change from a deep keyhole weld profile at the lowest speeds to a shallow weld at the highest speeds.

To determine the relationship between the absorbed energy and the melting rate for each welding speed figure 5 was produced. In this figure the weld cross-sectional area has been multiplied by the welding speed to give a melting rate in mm³/s. This value drops on average by ~30% over the range of welding speeds shown here but the reduction is concentrated in the speed range from 8 to 10 m/min.

![Figure 5. Cross-sectional area times speed as a function of welding speed for different surfaces.](image-url)
3 Theoretical work

3.1 General
The authors have constructed a simple theoretical model with which to investigate the absorption of Nd:YAG laser light during the welding of aluminium. Previous work [9-10] has demonstrated that during CO₂ laser welding the laser beam is absorbed by a combination of two phenomena:

a) direct absorption during multiple reflections off the keyhole wall,

b) absorption by the plasma cloud inside the keyhole which then re-radiates energy to the keyhole wall.

In the case of Nd:YAG laser welding the situation is simplified because plasma absorption of the laser beam is minimal. This is because the wavelength of Nd:YAG laser light is 1.06 μm rather than 10.6 μm for CO₂ lasers. At this lower wavelength absorption by the plasma cloud becomes negligible [11]. The model can therefore concentrate purely upon multiple reflections and their related absorption events.

Figure 6. Keyhole shapes and typical multiple reflections in keyhole for speeds 5, 7 and 9 m/min for the corresponding experimental weld seam cross-sections from figure 4.
The keyhole shape was approximated by a cone as shown in figure 6. Its real shape is complex and fluctuates during welding, particularly for aluminium, but the conical shape can be considered as an average. The depth of the keyhole was approximated by taking the penetration depth and subtracting half the base width since below the keyhole three dimensional heat flow will take place and thereby create the hemispherical shape in the bottom. This reasoning resulted in the keyhole shapes shown in figure 6.

A number of assumptions were made to simplify the model. First, the keyhole diameter was assumed to be equal to the beam diameter, i.e. 490 µm. All radiation was also assumed to enter the keyhole even though in reality a small portion is reflected off the solid material in front of the keyhole.

![Diagram](image)

**Figure 7.** The angle of incidence between the light beam and the target (θ).

The level of absorption of light during a reflection event is determined by the optical properties of the target material and the angle of incidence between the light beam and the target (see figure 7).

Figure 8 demonstrates that light is absorbed at different levels depending on the angle of incidence. The absorptivity of a surface remains at approximately the $A_0$ value (the absorptivity at normal incidence where $θ=0°$) up to angles of incidence of 60° but there is a sharp rise as the angle approaches the Brewster angle between 85 and 90°.

Bearing in mind the geometry of the keyholes shown in figure 6 we can, as a first approximation, assume that after the first reflection the angle of incidence is considerably lower than the Brewster angle. These subsequent reflections can therefore be considered to have an absorptivity which is not angle-dependent and is equivalent to $A_0$. The initial reflection takes place at nearly the Brewster angle and must have its absorptivity calculated separately (see later this section).
3.2 Calculation of absorption during initial reflection

Figure 8 originates from the simplified form of the Fresnel absorption equations (valid for \( n^2 + k^2 \gg 1 \))

\[
A_{par} = \frac{4ncos\theta}{(n^2 + k^2)cos^2\theta + 2ncos\theta + 1} \tag{1}
\]

and

\[
A_{perp} = \frac{4ncos\theta}{n^2 + k^2 + 2ncos\theta + cos^2\theta} \tag{2}
\]

where

- \( A_{par} \) = absorptivity of light with parallel polarisation,
- \( A_{perp} \) = absorptivity of light with perpendicular polarisation,
- \( n \) = material refractive index,
- \( k \) = material extinction coefficient.
Since laser light is usually used with circular polarisation the resulting absorptivity will be the average of $A_{\text{perp}}$ and $A_{\text{par}}$. Unfortunately the material optical constants $n$ and $k$ are not known for Nd:YAG laser light. In order to generate useful absorptivity curves despite this $n$ and $k$ were chosen to yield an upper limit absorptivity over the whole range of incidence angles. This resulted in the curves in figure 8 where $k=0$. These curves represent the maximum absorption of the initial reflection for the different incidence angles relating to different keyhole geometries (see figure 6).

### 3.3 Calculation of absorption during internal reflections

If one keyhole experiences a higher number of internal reflections than another it will also absorb more energy. For this reason it is important to calculate the average number of internal reflections for each keyhole shape. The incident beam will leave the keyhole after being reflected through $180^\circ$ minus the wall angle. Each time the beam is reflected its angle of incidence increases by twice the wall angle as shown in figure 6. From these two points and an estimation of the keyhole wall inclination, the number of reflections can be calculated [9-10] according to:

$$n_{mr} = \frac{\pi}{2\theta} - \frac{1}{2}. \quad (3)$$

The overall absorptivity of the multiple reflections can now be expressed as follows:

$$A_{mr} = (1 - A_{ir}(\theta))(1 - (1 - A_0)^{n_{mr}-1}) = (1 - A_{ir}(\theta))\left(1 - (1 - A_0)^{\frac{\pi}{2\theta}}\right)^{\frac{3}{2}}. \quad (4)$$

where

- $A_{ir}$ = absorptivity at first reflection,
- $A_{mr}$ = absorptivity at subsequent multiple reflections.

Note that in equation 4 the radiation subject to multiple reflections is reduced by the factor $(1 - A_{ir})$ which is absorbed at the first reflection. This means that $A_{mr}$ will never reach 100% irrespective of the number of reflections.

Equation 4 needs a value for $A_0$, the absorptivity for normal incidence. Experimental results and the literature (see table 1) suggests that a value between 10% and 14% is reasonable and this range has been used to generate the results in figure 9.
3.4 Total absorption

Figure 9 contains the following curves:

1) $A_{1r}$ - absorptivity at first reflection
2) $A_{mr}$ - absorptivity at subsequent multiple reflections (from equation 4)
3) $A_{tot}$ - sum of $A_{1r}$ and $A_{mr}$ to give the total absorptivity of the keyhole.

Figure 10 shows the relationship between the absorptivity of the keyhole and the welding speed. The absorptivity values derived from the model used cross-sections such as those shown in figure 4 to estimate the keyhole geometry (see figure 6). The theoretical $A_{tot}$ is compared with the average experimental values taken from figure 3.
Figure 10. The relationship between keyhole absorptivity and welding speed. Shaded ranges correspond to the uncertainty of $A_0$.

4 Discussion

Arata et al. [8] demonstrated that although aluminium was highly reflective at the CO$_2$ laser radiation wavelength of 10.6 µm it became completely absorptive if it was coated with an anodised (oxidised) layer more than 5 µm thick. As table 3 shows this is not the case when Nd:YAG laser radiation is considered. In fact, ceramics such as Al$_2$O$_3$, MgO and SiO$_2$ are transparent in three ranges of the electromagnetic spectrum [12];

a) UV between 0.2 and 0.4 µm,
b) IR between 0.7 and 3.0 µm and
c) radar $>10^3$ µm.

Clearly the Nd:YAG wavelength of 1.06 µm lies in the IR transparent region which is why table 3 records similar absorption values for as received and anodised specimens. It is this transparency which makes the use of optical fibres possible for Nd:YAG lasers but not for CO$_2$ machines.
Comparison of table 3 and figure 3 makes it clear that although surface condition can effect absorption at low intensities it has a negligible effect when welding is taking place. Figure 11 shows a cross-section of a keyhole and its associated weld pool. The keyhole is the hottest part of the laser-material interaction zone and, as no exothermic chemical reactions are taking place, must be associated with the centre of the laser beam. Although it is possible that some portion of the laser beam is impinging upon the solid base material in advance of the welding zone, this must constitute a minor part of the beam. If this proportion of the energy absorbed played a substantial part in the welding process figure 3 would present higher absorption figures for the sand blasted specimen as welding speeds are increased. (At higher speeds the proportion of incident beam in advance of the melt would increase). Figure 3 does not show a significant absorption advantage for sand blasting and so it can be assumed that solid material laser beam absorption is negligible during laser welding.

In figures 3 and 10 the general decrease in absorption observed as welding speeds are increased is related to a decrease in the amount of internal reflections experienced by the beam as the keyhole becomes shallower as shown earlier in figure 6.

The overall reduction in melt rate with welding speed shown in figure 5 is greater than the reduction in energy absorption demonstrated in figure 3. This is due to a diminution in the level of thermo-capillary stirring which takes place at higher speeds. At lower speeds this surface tension/thermal gradient driven stirring helps accelerate the melting process at the edges of the melt pool. At higher speeds this effect becomes less effective as melt lifetimes are reduced.
Although there is a fair agreement between the theoretical and experimental results given in figure 10 there is clearly room for further work. The discrepancies between the $A_{\text{ro}}$ curves are probably related to changes in keyhole geometry not forecast by the present set of assumptions. It is likely, for example that the keyhole will become narrower at higher speeds and this will give higher absorptivities as the keyhole wall becomes more vertical (see figure 6).

5 Conclusions

- Surface finish has a negligible effect on the absorption of aluminium when it is welded by an Nd:YAG laser. If melting does not take place however, rougher surfaces absorb better than smooth ones.
- The level of laser absorption in the keyhole is determined by the number of internal reflections experienced by the laser beam. This tends to decrease with increasing welding speed.
- The melting efficiency of the welding process tends to decrease with speed as a result of a decrease in thermo-capillary stirring. This stirring acts to increase the extent of melting but is suppressed at high weld speeds because of the reduction in melt lifetime.

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References

8. ARATA, Y & MIYAMOTO, I. Some fundamental properties of high power laser beam as a heat source. Transactions of the Japan welding society. 3 No 1, Apr (1972).
Initiation and termination phenomena in laser welding of aluminium

T. Forsman, A. F. H. Kaplan, J. Powell & C. Magnusson
Paper IV – Initiation and termination phenomena in laser welding of aluminium
Abstract
This paper solved a defect problem related to laser welding of tailored aluminium blanks. During the initial 30 mm of butt weld the melt fell out leaving an intermittent weld. By applying an analytical line source model the weld was shown to experience overheating close to the starting edge. The overheating was reduced by ramping the power during the initial 100 mm and this made the defects disappear.

1 Introduction
The production of tailored blanks is a technique which is constantly gaining in commercial interest. Tailored blanks are made by butt welding metal sheets of different thickness or alloy contents together. The blank is subsequently formed into its final shape and has a thickness or alloy distribution which is tailored to its eventual application. The use of welded tailored steel blanks in the automotive industry [1] has already led to advantages such as decreased final product weight, decreased material waste, decreased tool- and assembly costs and increased fatigue and corrosion resistance.

Laser welding of tailored aluminium blanks is a promising process but some problems remain to be solved [2]. Of particular concern is the tensile strength as well as the fatigue life of such blanks. The tensile strength of aluminium laser welds is typically of the order of the base material strength. In the case of hardened alloys laser welding typically decreases the strength to around 80% of its original value [3-4]. The fatigue life of aluminium does not increase linearly with base material strength as is the case for steel. Instead it levels off for higher strength alloys [5]. Welded aluminium will experience even worse fatigue properties because of the high sensitivity of aluminium to defects.

For a tailored blank to withstand the forming process and for the final detail to withstand its applied stress, the weld must contain minimal defects. This particularly applies to the sheet edges where failure is usually initiated [5-6]. At sheet edges, where the weld is either starting or
terminating, the heat flow characteristics are different from the steady state which is eventually established. Because of this it is possible that defects such as undercut etc may be concentrated at the sheet edges. This work includes a preliminary experimental examination of the problem which is supported by a theoretical model. Finally, a practical remedy has been evolved to overcome the problem of weld overheating during initiation of the weld close to an edge.

2 Experimental examination of the problem
Aluminium sheets of 1.0 mm thickness with milled edges were butt welded and bead-on-plate welded using the experimental settings shown in table 1. For the conditions shown a suitable speed for full penetration was found to be 12 m/min. The bead-on-plate welds were free of visible defects but the butt welds showed a number of small holes during the initial 30 mm of weld as shown in figure 1.

Table 1. Experimental settings.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>HAAS HL3006D Nd:YAG</td>
</tr>
<tr>
<td>Power</td>
<td>3000 W</td>
</tr>
<tr>
<td>Speed</td>
<td>12 m/min</td>
</tr>
<tr>
<td>Beam guidance</td>
<td>Optical fibre Ø0.6 mm</td>
</tr>
<tr>
<td>Focal length</td>
<td>150 mm</td>
</tr>
<tr>
<td>Spot diameter</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Focal plane</td>
<td>On the work-piece surface</td>
</tr>
<tr>
<td>Shielding gas</td>
<td>He 20 l/min</td>
</tr>
<tr>
<td>Material</td>
<td>AA5052-H12 (AlMg2.5 alloy)</td>
</tr>
<tr>
<td>Size</td>
<td>1000x150 mm</td>
</tr>
</tbody>
</table>

Figure 1. Photographs of the beginning of the weld (left) and of the entire welded sheet. (Butt weld performed in 1.0 mm thick AA5052-H12 with a speed of 12 m/s.)
It is clear from figure 1 that the 1.0 mm thick butt weld suffers from porosity for the first few millimetres but this phenomenon disappears as a steady state weld zone is established. To investigate the thermal input to the weld zone during start up and steady state welding a theoretical model was developed which is presented in the following section.

3 Theoretical examination

In order to theoretically describe the weld initiation defects a heat conduction examination was performed. It is assumed that laser light is absorbed on the surface of a metal work-piece [7] and is then conducted in all directions as shown in figure 2. If the heat source is continuous and the speed with which it is moving is uniform the temperature field will soon become constant with respect to time, i.e. it will assume a steady state.

The temperature in any point \((x,y,z)\) of an infinite metal sheet absorbing light from a passing laser can be calculated using equation 1 [8] which is a solution for a moving continuous infinitely small point source. Full penetration laser welding of sheets is usually modelled simulating a line source instead because of the deep and narrow keyhole weld produced and the mainly two-dimensional heat conduction which takes place laterally. Even if the sheet thickness is in the order of the beam diameter the line source is used because the absorbed power is distributed over depth and the heat is constrained by the upper and lower surfaces of the thin work-piece to flow in the horizontal plane. A line source approach is therefore more appropriate than a point source with its associated three-dimensional heat conduction.

A solution for a moving continuous line source is given in equation 2 [8] which can be used to calculate the temperature at any point \((x,y)\) on an infinite sheet of given thickness during laser welding.

\[
T = \frac{QV}{4\pi k\alpha} \frac{e^{\left(-Pe_x - \sqrt{Pe_x^2 + Pe_y^2 + Pe_z^2}\right)}}{\sqrt{Pe_x^2 + Pe_y^2 + Pe_z^2}} + T\infty
\]  

(1)

\[
T = \frac{Q}{2\pi k\delta} e^{(Pe_x)} K_0 \left(\sqrt{Pe_x^2 + Pe_y^2}\right) + T\infty
\]  

(2)
where

\[ Pe_y = \frac{V_y}{2\alpha} \]  \hspace{1cm} (3)

\[ Pe_x = \frac{V_x}{2\alpha} \]  \hspace{1cm} (4)

\[ K_0\left(\sqrt{Pe_x^2 + Pe_y^2}\right) = \frac{\pi}{2} e^{-\sqrt{Pe_x^2 + Pe_y^2}} \]  \hspace{1cm} (5)

\( T \) = temperature in work-piece [K],
\( T_\infty \) = room temperature [K],
\( Q \) = power absorbed by work-piece [W],
\( k \) = thermal conductivity of work-piece [W/mK],
\( V \) = velocity of moving source [m/s],
\( \alpha \) = thermal diffusivity of work-piece [m²/s],
\( \delta \) = thickness of work-piece [m],
\( K_0 \) = modified Bessel function of second kind and order zero,
\( Pe \) = Péclet number (form of dimensionless velocity),
\( x \) = distance from laser source along path [m],
\( y \) = distance from laser source perpendicular to path [m].

The Bessel function \( K_0 \) from equation 2 can be derived from equation 5. The approximation shown here is valid for high Péclet numbers which is the case for the small thickness and high speed used in this case [9]. For this investigation we need to consider a semi-infinite metal sheet of a given thickness. (A semi-infinite sheet extends to infinity from the edge we are considering). Although a minor amount of heat will be lost from the welded sheet by convection and radiation, the main thermal transport mechanism will be by conduction within the sheet. Considering only this conduction, it is clear that heat can flow away from the weld zone in all directions when we are a considerable distance away from the edge. Close to the edge however, the thermal flow is restricted by the edge which can be considered a thermal barrier of very low conductivity. The result is that there will be practically no heat flux across the sheet boundary.

To accurately determine the temperature in a sheet close to its edge the temperature given by equations 1 or 2 must be increased as a result of this decreased heat flux. One way of modelling this is to consider two heat sources: a real laser source and an imaginary source moving away from the starting edge in opposite directions as shown in figure 3. The temperature at any point is then simply the sum from both sources. (It is assumed that heat from the imaginary source is conducted away from it through an imaginary work-piece of the same thermal conductivity as the real work-piece and the sheet edge no longer acts as a thermal barrier).
Assuming a line source situation, equations 2 and 5 were used to yield the temperature field from the real source $T_r$:

$$T_r = \frac{Q}{\sqrt{8\pi k\delta}} e^{\frac{(Pe_x - \sqrt{Pe_x^2 + Pe_y^2})}{4\sqrt{Pe_x^2 + Pe_y^2}}} \tag{6}$$

The temperature field caused by the imaginary source is the same as equation 6 but with a different value for $Pe_x$. By adding line source equation 6 to its imaginary counterpart, the total temperature field (with a co-ordinate system moving with the real source) was created as:

$$T = \frac{Q}{\sqrt{8\pi k\delta}} e^{\frac{(Pe_x - \sqrt{Pe_x^2 + Pe_y^2})}{4\sqrt{Pe_x^2 + Pe_y^2}}} + \frac{Q}{\sqrt{8\pi k\delta}} e^{\frac{(Pe_a - \sqrt{Pe_a^2 + Pe_y^2})}{4\sqrt{Pe_a^2 + Pe_y^2}}} + T_m \tag{7}$$

where

$$Pe_{xi} = \frac{V(2d - x)}{2\alpha} \tag{8}$$

$d = Vt =$ distance from sheet edge [mm].

The temperature reached in different positions $(x,y)$ of the melt was calculated and plotted in figure 4 as a function of distance from the edge. To calculate the results shown in figure 4 the co-ordinate system was centred on the real source and the temperature was taken at a fixed point relative to the source, i.e. moving with $d=Vt$. It is clear that there was a temperature rise close to the starting edge and that the temperature then quickly diminished with increased distance. Very close to the edge the imaginary source accounted for approximately half of the total temperature but 50 mm away from the edge its contribution was down to only 10%.

Figure 3. Real source and imaginary source close to the edge in a semi-infinite sheet.
Figure 4. Temperature reached in four different positions of the melt as a function of edge distance (absorbed power 60% of 3000W, speed 12 m/min).

4 Experimental solution to the problem

This simple model clearly demonstrates the source of the overheating experienced by the weld pool during its initiation phase. This overheating is the reason why the weld is intermittent over the first 30 mm or so as shown in figure 1. The holes in the weld in this region are the result of the low viscosity of the overheated melt. The next stage in this investigation was to change the process parameters to minimise the overheating phenomenon.

To avoid the heat build-up close to the sheet edge it is necessary to adjust the energy input at the start of the weld either by varying the welding speed or the laser power. The ideal energy input curve to generate an invariant temperature field in the work-piece, will be non-linear. An input of this type would be complex to achieve and is probably unnecessary as long as certain thermal limits are not exceeded. An additional consideration is that the power density on the work-piece must be kept above approximately 1 MW/cm² so that the aluminium surface does not become totally reflective.

After a number of experimental solutions had been attempted a linear power ramping was used for the initial 100 mm of weld followed by a constant power level as shown in figure 5.
This simple power adjustment resulted in butt welds without the initiation defects in 1 mm thick material. Figure 6 demonstrates the drop in the weld temperature near the edge which is experienced if power ramping is employed. Figure 6 was derived by calculating the temperature field at 16 points during the initial 100 mm of weld using different power values according to figure 5. The values given in figure 6 are therefore only an approximation because equation 7, from which they were calculated, assumes a constant power level. As far as the calculation is concerned the power ramping affects the real and the imaginary sources and thus the peak temperature reached by the weld is considerably reduced. Although the temperature field established close to the edge of the sheet is different to the eventual steady state, it is close enough to produce a similar weld quality.

Note: a simplified model of this type gives an over estimate of the temperatures reached close to the source centre but the trends shown are qualitatively correct. A model of this type does however require caution very close to the edge of the sheet. At the edge the real and imaginary sources are superimposed and this gives false results.
5 Discussion and conclusions

This work has demonstrated that laser generated butt welds in thin section aluminium can experience overheating close to the edge of a sheet where the weld began. The overheating is a consequence of the reduced thermal heat sink available close to the start-up edge. The overheating can result in intermittent welds over the initial few millimetres. Ramping the power input to the weld for the first few millimetres can be used to eliminate the effects of overheating. This overheating effect is not observed on the terminating portion of the weld at the final edge of the sheet. This is because the thermal gradient is much higher in front of the weld than behind it. The theoretical model used in this work calculated that the temperature only 0.5 mm in front of the line source is very close to ambient for the high welding speed (and Péclet number) used here. This will remain the case until the final few milliseconds of welding and weld defects will therefore have no time to occur.

Although the start-up overheating of welds will happen in other materials, problems have not been reported for materials other than aluminium. This is probably because aluminium weld pools have a low, temperature related, viscosity and are therefore sensitive to overheating effects.

Figure 6. Calculated temperature reached as a function of distance from the edge (at x=1.0, y=0) when ramping the power (full line). Dashed line shows heat-up without ramping.
During the course of this work defects were identified in the start-up region of welds carried out in a number of aluminium alloys and when joining sheets of differing thickness (for the production of tailored blanks). In each case the defects could be overcome by suitable power ramping.

References

**Titel/Title**
Nd:YAG Laser Welding of Aluminium Alloys

**Författare/Author(s)**
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**Sammanfattning, högst 150 ord/Abstract, max 150 words**
This thesis presents the development of laser welding of aluminium and describes what can be performed with modern Nd:YAG lasers in the wide range of commercial aluminium alloys. Paper one is a review of laser welding of low density structural materials, i.e. aluminium, magnesium, titanium and polymers. The paper describes the properties of the different materials and explains how the properties influence the laser welding process and the weld results. Paper two investigates Nd:YAG laser lap welding between sheets of two different coated aluminium alloys. Successful welds were produced using a certain gap width between the two sheets. Paper three investigates the factors affecting the absorptivity during Nd:YAG laser keyhole welding of an aluminium alloy. Experimental absorption measurements by calorimetry were compared to analytical absorption values using a model based on Fresnel absorption during multiple reflections in the keyhole. Paper four solves a problem with initiation defects during experimental tailored blank laser welding. Using a line source model the weld was shown to get overheated during the initial 100 mm of weld.

**Nyckelord, högst 8/Keywords, max 8**
laser welding, Nd:YAG, aluminium, magnesium, titanium, polymer, absorption, tailored blank

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