Autogenous Laser Joining of Aluminum

David Havrilla
Manager – Products & Applications
TRUMPF Inc.
Contents

- The element
- Properties and comparison to steel
- Designations and uses
- Laser welding - principles and advantages
- Troublesome attributes and solutions
- Summary
The element

- Atomic number 13, melting point 660°C, boiling point 2519°C, mass density 2.7 gm/cm³
- Low mass density, high corrosion resistance \((\text{Al}_2\text{O}_3)\), excellent thermal & electrical conductivity (60% of Cu)
- Easily machined, cast, drawn & extruded
- The third most abundant element (after oxygen & silicon), and the most abundant metal comprising 8.2% of earth’s crust
- Almost all metallic aluminum is produced from the ore bauxite \((\text{AlO}_x\text{(OH)}_{3-2x})\).
Comparison to steel

<table>
<thead>
<tr>
<th>Property</th>
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<th>AISI 1020 Steel</th>
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<tr>
<td>Density (gm/cm³)</td>
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⇒ High corrosion resistance of aluminum
Comparison to steel

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⇒ General rule of thumb: 2x thickness, so about a 33% weight savings
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⇒ High thermal conductivity + high thermal expansion = more prone to distortion  
⇒ High thermal conductivity + high reflectivity = more power to start process  
⇒ Low melting temperature = less power needed to increase speed or depth  
⇒ Low melting temperature = less energy required for recycling
Wrought alloy series designations

Temper Designations:
- **F** – as fabricated
- **O** – annealed
- **H** – strain hardened
- **W** – solution heat treated
- **T** – thermally treated
## Wrought alloy series designations

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<th>Alloy Series [1][2]</th>
<th>Principal alloying element</th>
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<td>Some alloys fusion weldable, filler wire used to optimize weldability &amp; mechanical properties (prone to porosity &amp; blow holes)</td>
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### Notes
1. XXXX alloys heat treatable (age hardenable) / XXXX alloys are strain hardenable
2. Wrought alloys available in sheet, plate, extrusions, forgings, rod, bar and impact extrusions
## Wrought alloys in automotive

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| 1xxx         | Pure  | Low strength, excellent thermal / electrical conduction & corrosion resistance, highly reflective  
              |       | - fuel filters, electrical conductors, radiator tubing, lighting reflectors, decorative components |
| 2xxx         | Cu    | High strength, relatively low corrosion resistance, good elevated temperature strength  
              |       | - aircraft skin, aircraft fittings & wheels, ballistic armor, forged & machined components |
| 3xxx         | Mn    | Medium strength, good formability, good corrosion resistance  
              |       | - storage tanks, beverage cans, home appliances, heat exchangers, pressure vessels, siding, gutters |
| 4xxx         | Si    | High castability, high machinability, high fluidity, low ductility  
              |       | - variety of castings including large castings, filler metal (2xxx, 3xxx, 5xxx & 7xxx used for castings) |
| 5xxx         | Mg    | Medium strength, good formability, excellent marine corrosion resistance  
              |       | - interior automotive, appliance trim, pressure vessels, armor plate, marine & cryogenic components |
| 6xxx         | Mg,   | Med-high strength, good corrosion resistance, easily extruded  
              | Si     | - exterior automotive, automotive profiles, railcars, piping, marine, screw stock, doors & windows |
| 7xxx         | Zn    | Very high strength, prone to stress corrosion, poor corrosion resistance  
              |       | - aircraft construction, truck trailers, railcars, armor plate, ski poles, tennis rackets |
| 8xxx         | Li    | Very high strength, low density  
              |       | - aircraft & aerospace structures, foil, heat exchanger fin stock |

[UVa - June 2014]
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Drivers for the use of aluminum in automotive …

- Weight reduction $\Rightarrow$ increased fuel economy (54.5/’25) $\Rightarrow$ reduced CO$_2$ emissions
  - On meeting upcoming fuel-economy regulations …
  
  “In the long run, dual-phase and boron steels will contribute to that weight savings, but most of the reduction will come from aluminum.”

  *Richard Schultz, Managing Director - Automotive Materials Practice, Ducker Worldwide.*

- Corrosion resistance
- Structural performance
- Manufacturability
Drivers for the use of aluminum in automotive …

- Future expectations – aluminum content per vehicle (2012 Ducker study)
  - 150 kg per vehicle by 2015
  - 180 kg per vehicle by 2020
Drivers for the use of aluminum in automotive …

- Future expectations – curb weight (2012 Ducker study)
  - 3,600 lbs by 2015
  - 3,500 lbs by 2020
Why laser welding

Drivers for the use of lasers in aluminum joining …

- High throughput / high welding speeds
- Low heat input / high aspect ratio / small HAZ
- Low distortion
- Autogenous welding possible (vs. MIG)
- High degree of automation
- Process flexibility
Troublesome attributes

Aluminum attributes that contribute to welding issues …

- Tenacious & high melting temperature oxide
- High thermal conductivity
- High coefficient of thermal expansion
- High rate of solidification shrinkage (i.e. large change in volume upon solidification)
- Low viscosity
- High solubility of hydrogen in the molten state
- Wide range of alloy vaporization and solidification temperatures
  (Vaporization: Zn 907°C – Cu 2567°C / Solidification: Li 181°C – Si 1410°C)
  - Alloying elements
    - Zn, Mg, Li ⇒ tendency toward porosity, blow holes, spatter (low $T_{Vap}$)
    - Si ⇒ tendency toward hot cracking
## Welding issues

<table>
<thead>
<tr>
<th>Problem</th>
<th>Mechanism</th>
<th>Control measures</th>
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<tr>
<td>Hot cracking</td>
<td>a.k.a. Weld solidification cracking. Cracking due to the effects of solidification stresses on the microstructure, and exacerbated by the high thermal expansion and conductivity of aluminum.</td>
<td>Avoid crack sensitive chemistry by addition of appropriately selected filler wire or inlayed filler foil material. Optimization of pulse parameters for pulsed laser welding.</td>
</tr>
<tr>
<td>Hydrogen solubility</td>
<td>Moisture in oxide layer &amp; in atmosphere produces hydrogen which is highly soluble within the molten weld pool, but has low solubility in solid aluminum. Trapped hydrogen forms porosity and escaping hydrogen forms blow holes.</td>
<td>Material logistics, cleaning of weld joints / removal of oxides and use of shielding gas (He, Ar, or He/Ar mixture) can be beneficial.</td>
</tr>
<tr>
<td>Porosity / blow holes</td>
<td>Volatile alloying elements (e.g. Zn, Mg, Li), also trapped or enclosed air. Loss of Mg via vaporization can also degrade material mechanical properties.</td>
<td>Slowing down, twin spot, etc., especially in the case of vaporized alloying elements like zinc (7xxx) or magnesium (5xxx, 6xxx). Pore formation increases with weld penetration.</td>
</tr>
<tr>
<td>Underbead dropping</td>
<td>Extremely low viscosity of molten aluminum causes underbead dropping in through penetration welding approx. &gt;6 mm.</td>
<td>Joint design, partial penetration, through penetration welding with under bead backing material.</td>
</tr>
<tr>
<td>Reflectivity</td>
<td>High reflectivity of 10.6 μm compared to 1 μm wavelength, but 10.6 μm keyhole mechanism is best suited for deep penetration welding.</td>
<td>Use of 1 μm lasers for up to about 4 mm. 1 or 10.6 μm from 4-6 mm. 10.6 μm above 6 mm. Note: 1 μm has a larger process window at shallow penetrations depths &amp; 10.6 μm at deeper penetration depths.</td>
</tr>
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</table>
Hot cracking sensitivity can often be reduced by selecting a filler wire that alters the weld chemistry away from the crack sensitivity peak.

- Typical values for good weldability:
  - Silicon >2-3%
  - Magnesium >3-4%
Hydrogen solubility

- Sources of hydrogen: water, lubricants & air.

- Hydrogen dissolves readily into the molten weld pool

- Virtually no solubility of hydrogen into solid aluminum leads to defects upon solidification:
  - trapped hydrogen pores
  - out gassing of hydrogen (blow holes)

Preventative measures:

- Keep material clean & dry (incl. filler)
- Avoid ΔTs that cause condensation
- Cleaning of weld joints / removal of “porous” oxides
- Use of shielding gas
Porosity and blow holes

- Issue 1 – trapped gases due to volatile alloying constituents (e.g. Zn, Mg, Li) and keyhole instability
  - Enable path & time for vapors to exhaust
    - Reduce speed, twin spot

- Issue 2 – enclosed or expanding hot trapped air blows through keyhole at end of weld
  - Enable gases to exhaust or suppress expansion
    - Designed exhaust path (e.g. ventilation hole closed by laser pulse), pre-heat part

- General – pore formation increases with penetration depth
Underbead dropping

Strategies to avoid underbead dropping in deep penetration welding (> 6 mm) …

- Occurs in through penetration welds around > 6 mm
- Dependent on laser wavelength, alloying elements, power, speed, spot diameter, etc.
- Employ one of several strategies to avoid dropping in deep penetration welding

Partial penetration

Component re-design

Underbead backing material (e.g. Cu)
Reflectivity

- Aluminum highly reflective in general
- Absorption spike near 1 \( \mu \text{m} \) wavelength
- 1 \( \mu \text{m} \) lasers preferred for thicknesses up to about 4 mm
- \( \text{CO}_2 \) lasers (10.6 \( \mu \text{m} \)) preferred for thicknesses > 6 mm
## Specific welding recommendations

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<tr>
<th>Alloy Series</th>
<th>Welding depth free of blow outs (mm)</th>
<th>Filler wire</th>
<th>Shielding gas [4]</th>
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<tr>
<td>1xxx</td>
<td>&gt; 1</td>
<td>Not necessary</td>
<td>Not necessary, but better surface w/ He or He/Ar mix</td>
</tr>
<tr>
<td>5xxx [3]</td>
<td>3</td>
<td>4047 – good surface</td>
<td>He or He/Ar mix</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5356 – poor appearance, good strength</td>
<td></td>
</tr>
<tr>
<td>6xxx [2] [3]</td>
<td>4</td>
<td>4047 – good appearance, ave. strength</td>
<td>Not necessary, but better surface w/ He or He/Ar mix</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4043 – better seam elevation</td>
<td></td>
</tr>
<tr>
<td>Casting alloys</td>
<td>&gt; 2.5</td>
<td>Crack free without wire</td>
<td>Not necessary, but better surface w/ He or He/Ar mix</td>
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<tr>
<td></td>
<td></td>
<td>Fewer blowouts with 4047</td>
<td></td>
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**Notes**

1. Anodized aluminum prone to cracking and foams up
2. XXXX alloys heat treatable
3. Twin spot optics w/ 3 kW min. for 1 μm & 6 kW min. for 10.6 μm power can be used to increase process stability, decrease blowouts & increase weld pool homogenization, but decreases speed 20-30% compared to single focused spot
4. Helium is best (but most expensive) for avoiding inclusions, sink holes and for greater process stability. Argon generally recommended, but has a higher susceptibility to porosity. He/Ar mixes are generally 70/30. Nitrogen can be used to reduce porosity but results in a rougher weld bead surface. CO2 has been successfully used on 6xxx series aluminum but has negative effects on others series aluminums.
Material Selection

Notes for welding aluminum

- Critical issues – HAZ softening, blow holes, porosity, solidification cracking & in some alloys - loss of volatile elements (e.g. Mg, Zn) due to vaporization
- Natural oxides on surface + moisture from atmosphere produce hydrogen which is highly soluble in Al & causes porosity
- Anodized aluminum prone to cracking & foams up
- Remove Al oxide (AlO₂ @ T_{melt}=1800°C compared to 700 °C for Al) for overlap joints to increase weld width at interface
- 1000 series: (e.g. 1050=Al 99.5) welds good. Also 3003, 4032, 4047 okay.
- 5000 series: (e.g. 5005, AlMg5) most weld good. Filler wire if needed: AlMg5 or AlMg4.5Mn (e.g. AlMg3 + AlMg5 wire = poor appearance w/ good strength)
- 6000 series: (e.g. AlMgSi1 – silicon added for machinability) – not ductile enough to handle shrinkage stresses & is prone to cracking. Weldable when Si>3% & Mg>4.5% (e.g. 6061). Filler wire used to increase weldability (e.g. AlMgSi1 + AlSi12 wire = good appearance w/ average strength)
- Shield gas = generally Argon, Helium to avoid inclusions and sink holes
Myriad of proven applications

1. VW Phaeton door welding, hybrid welding, 6xxx
2. Shanghai Transrapid roof panels, 6xxx/5xxx
3. Audi A8 frame rail, hybrid welding, 4xxx
4. Daimler suspension link, hybrid welding, 6xxx
5. BMW steering column, 6 kW CO$_2$, bi-focal, 6xxx
6. Euro Fighter turbine air inlet vane welding, 6xxx
7. Fuel filter, 1xxx
8. Audi A2 30 m laser welding, 3 kW 1 jm, sheet to profiles, 6xxx
9. BMW 7 aluminum door welding & deck lid, 6xxx
10. Automotive wheel assembly, 6 kW CO$_2$, bi-focal, 4xxx
Joining situation and material.

Sheet material:
- AlMg4.5Mn (5083)
- Sheet thickness 1.5 mm and 1.2 mm
BMW aluminum door

Increasing cross-section => increasing stiffness => decreases flange width

Moment of inertia

Section modulus

$A = 2.94 \, \text{cm}^2$

$A = 3.48 \, \text{cm}^2$

$A = 5.23 \, \text{cm}^2$

$I_D = 0.74 \, \text{cm}^4$

$W_D = 0.90 \, \text{cm}^3$

$I_D = 0.92 \, \text{cm}^4$

$W_D = 1.0 \, \text{cm}^3$

$I_D = 1.67 \, \text{cm}^4$

$W_D = 1.57 \, \text{cm}^3$
BMW aluminum door

Conventional Laser weld with a Trumpf TruDisk 4002 and a Scansonic welding head with filler wire.
BMW aluminum door

Laser fillet weld on aluminum doors.

Min. requirement to the stability of a fillet weld seam

\[ a_{\text{min}} = 0.7 \times t_{\text{min}} \]
Pros and Cons of a laser fillet weld.

**pro:**
- Very high strength via large cross-sections and long welding seams
- Extreme flange reduction
- Weight and material reduction
- Minimum laser power necessary for joining
- Fast joining process

**con:**
- The laser beam and the filler wire must precisely be located at the joining position
- Seam tracking necessary ➔ higher investment costs
- Filler wire ➔ additional costs for the laser process
BMW aluminum door

7 Series Sedan
• 15.4 meters of laser seam

7 Series Sedan Long
• 16.2 meters of laser seam
BMW aluminum door

Laser welding of Aluminum doors BMW 7series sedan in production
Production experience …

… at TRUMPF

- Part: TruFlow resonator cover
- Material: 2 mm Al 5052
- Power: 3.4 kW (disk laser)
- Speed: 1.5 m/min
- Shield gas: 50/50 He/Ar
Summary

Fundamentals of aluminum and aluminum joining summary ...

- The weight to strength ratio and corrosion resistance makes aluminum an attractive metal for many applications

- Weight reduction for increased fuel economy & reduced emissions are primary drivers for use in automotive

- Most aluminum alloys are laser weldable

- Laser welding offers several advantages over conventional joining techniques

- The welding issues are well understood and in most cases readily overcome by a variety of proven methodologies

- Laser welded aluminum components have been in production for many years
Thank you for your attention!