Design Principles for Laser Welding

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Why employ laser welding?

Focus fundamentals, power and energy

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Keys for success
A vast array of applications
A vast array of applications
A vast array of applications
Advantages of laser welding

- **Minimum heat input and high aspect ratio resulting in …**
  - minimal shrinkage & distortion of the workpiece
  - small heat affected zone
  - narrow weld bead with good appearance

- **High strength welds often resulting in …**
  - improved component stiffness / fatigue strength
  - reduction of component size / weight

- **Ability to weld in areas difficult to reach with other techniques**
  - non-contact, narrow access, single sided process

- **Easily automated with accurately located welds**
  - consistent weld penetration / weld geometry / weld quality
  - ability to integrate into existing equipment / production lines
Advantages of laser welding

- **Flexibility …**
  - beam manipulation (beam switching and sharing)
  - variety of part & weld geometries and materials
  - ease of back-up (especially YAG)

- **Often faster than other techniques …**

  *What is throughput a function of (besides process engineering & optimization)?*
  - high power density weld process
  - high laser uptime (>98%)
  - high beam on-time via remote scanner welding, beam switching, etc.

- **Cost savings …**
  - high productivity >> faster cycle time = **less stations**
  - reduction of scrap and re-work
  - reduction of manual labor
  - reduction of component material and weight
  - can eliminate secondary processes
Laser welding vs. resistance spot welding

- **Reduced flange widths**
  - reduction of component size / weight
  - reduced cost
  - greater visibility / accessibility

- **Increased strength / stiffness**
  - localized increase of component strength / stiffness / fatigue strength
  - weld shape optimization for component loading / stresses
  - elimination of lower electrode access holes

- **Higher throughput**
  - less stations
  - less floor space

- **High accessibility to weld joints**
  - narrow access, single sided, line of sight

- **Low maintenance (non-contact)**
  - no tip wear, mushrooming, dressing or replacement (esp. hot formed parts!)
Laser as a tool

- relatively wide / narrow
- deep / shallow
- continuous / stitch / spot
- smooth & oxide free / non-aesthetic joining
- 1D / 2D / 3D
- through / partial
- line / optimized shape
- conventional / remote
- multiple layers

When would you want wide? When narrow?

What benefits does partial penetration have?
Why would you want a shape that is not a straight line?
1. **Causes of porosity, underfill, undercut:**
   - Volatile constituents (e.g. S, P)
   - Volatile coatings/surface contaminants (e.g. Zn, oil based lubricants)

**Notes for welding of Zn coated steels in overlap configuration**

a. If weld is non-aesthetic and has limited load functionality, perhaps no special action required

b. Increased weld length may compensate for porosity in non-critical components

c. Electro-galvanized & electro-galvaneal are better than hot dipped galvanized

d. Bare to Zn is often okay (especially electro plated)

e. Zn to Zn configurations usually require a gap and/or Zn exhaust path for reasonable results (e.g. dimples, shims, knurling, fixture/tooling, leading pressure finger, part design, joint design)

f. Other methods such as Zn removal (mech. or laser) and chemical pastes (interfacial alloying) also possible

g. Spatter protection critical

h. Watch out for patent infringements!
2. Britleness & cracking  
   - Can occur in steels when 
     \( >0.3\%C \) (>0.4\%C equivalent) 
     \( S+P+Se+Cd > 0.05\% \)  
   - 6000 series aluminum

3. Reflectivity  
   With high reflective materials  
   (e.g. Al, Cu) – 1 micron  
   wavelength has greater 
   absorption than 10.6 microns

*What are some ways to reduce quench rate when laser welding steels with high carbon content?*  
Preheat/postheat, reduce speed & power

*What are some other ways to reduce cracking tendency when laser welding steels with high carbon content?*  
Use filler wire, part design to relieve notches / residual stresses
Weld strength is greatly affected by weld joint fit-up because laser welding is most often an autogenous process (i.e. a welding process which does not use a filler material).

A gap (or mismatch) reduces weld strength because it can yield an underfill and/or undercut which …

a. Reduces weld area \( S = F/A \)

b. Creates a stress riser

![Stress concentration](image)

![Lines of force](image)
Rate the weld shapes from best to worst (1=best) and explain why?
Weld Shapes

What are the strengths and weaknesses of each flange weld shape (assuming all welds have the same length)?

- Minimum flange width
  - Anisotropic strength behavior

- Medium flange width
  + Average strength behavior

- Maximum flange width
  + Isotropic strength behavior
Seam and joint types

**Lap weld on lap joint**

**Seam weld on butt joint**
<table>
<thead>
<tr>
<th>Name</th>
<th>Example</th>
<th>Characteristics</th>
</tr>
</thead>
</table>
| Seam weld on butt joint     | ![Image](image1.jpg) | + Weld Fusion Area  
- less material = weight & cost savings  
- faster or less power  
- less HAZ / distortion  
- no issues w/ Zn  
- no step  
- Positioning Tolerance  
- edge requirements  
- fit up can be more difficult to obtain  |
| Lap weld on lap joint       | ![Image](image2.jpg) | + Positioning Tolerance  
- larger process window  
- can have aesthetic underside  
- Weld Fusion Area  
- more energy required = slower or higher power & more distortion / HAZ  
- inefficient process |
<table>
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<th>Name</th>
<th>Example</th>
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</thead>
</table>
| Seam weld on stepped lap joint           | ![Diagram](seam_weld_stepped_lap.png) | + weld fusion area  
- positioning tolerance          |
| Seam weld on T-joint                     | ![Diagram](seam_weld_T-joint.png)  | + weld fusion area  
- positioning tolerance          |
### Seam and joint types

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<thead>
<tr>
<th>Name</th>
<th>Example</th>
<th>Characteristics</th>
</tr>
</thead>
</table>
| Lap weld on T / border joint | ![Example](example1.png) | + positioning tolerance  
- weld fusion area |
| Seam weld on flange         | ![Example](example2.png) | + weld fusion area  
- positioning tolerance |
| Lap weld on formed seam     | ![Example](example3.png) | + positioning tolerance  
- weld fusion area |
Seam and joint tolerances

**Butt joint configuration:**
- Gap: 3-10% thickness of thinnest sheet
- Offset: 5-12% thickness of thinnest sheet

**Overlap joint configuration:**
- Gap: 5-10% thickness of top sheet

*Why is this general guideline not absolute?*
(What influences the amount of gap that can be bridged?)

- Focus spot size
- Edge geometry for butt weld
- Strength requirements
- Others: joint location (butt weld), volatility of mat’l, speed
Tolerance Compensation
Joint bridging techniques

**Autogenous**
- **Larger focus spot**
- **Twin spot**
- **Wobble**
  - Slower, more heat input
  - $2x$ higher power density
  - Less wasted energy
  - Faster!!
  - Directionality

**Non-autogenous**
- **Hybrid (laser + MIG + wire feed)**
  - Cost, complexity, may require vision system
- **Wire feed**
  - Gap & metallurgical bridging
- **LMD**
General Guidelines

- Butt joint provides higher strength, higher welding efficiency and reduced material usage, but requires greater positioning tolerances and better edge geometry and fit-up.

- Overlap joint provides greater process window regarding positioning, but generally yields lower strength, lower welding efficiency, and increased material usage.

- Weld in the thin to thick configuration whenever possible.

- Weld perpendicular to surface whenever possible.

- Use 50% minimum penetration (relative to top layer) into lower component when partial penetration welding is required.

- Don’t weld with focus optic facing upwards.

- Distortion can be minimized by: 1) smaller focused spot, 2) beam splitting, 3) high speed tack weld, 4) remote scanner welding w/ large field.
Design features

K- Joint in Application / Flange-reduced Design
Design features

Specialized cutting & bending of tubes

Multiple bend tubes:
Allows 3 dimensional structures.

Bend tubes:
Allows high quality on corners.
Design features

**Specialized cutting & bending of tubes w/ positioning aids**

Special bent tubes techniques create connections with the need of only a few welds.

- Positioning aids
Design features

Positioning tabs & bayonets for tubes

Perfect interface for welding operations

Precision location

Bayonet coupling ensures orientation and reduces need for precision fixturing.
Design features

More Tube Interfaces
Design features

Positioning tabs for tubes & plates

Mounting plate to tube:
Well suited for welding
High positioning accuracy
Design features

Interlocking tabs for tubes
Design features

Integrating locating & interlocking features
Design features

Underbody concept with K-Joint & Interlocked Joints

- Tunnel
- Cross Member (Seat)
- K-Joint
- Integrated Longitudinal Enforcement
- Interlocked Joints
Tolerance Compensation

K-Joint & Interlocked Design for Underbody
Principles of Programmable Focusing Optics

2D Scanner
- PFO 20
- PFO 33

3D Scanner
- PFO 3D
Advantage: Reduced cycle time

Conventional Laser Welding

Unproductive travel times

Laser Scanner Welding

Significant cycle time reduction
Advantage: Programmable Weld Shapes

Customized weld patterns for optimal joint strength:

- Distribution
- Orientation
- Shape
Scanner welding: VW Passat hat rack

Spot weld - production

34 ° + mech. shift code
4 robots, 5 welding guns
Welding time: 34.7s

Laser remote weld - production

34 ° + shift code
1 robot, 1 scanner optic
Welding time: 13s (4kW), <10s (6kW)
Remote scanner welding

High volume parts
- Doors (2 or 4 per vehicle)
- Side panels
- Seat frames, tracks, panels, recliners
- IP beams
- Parts common to several models

Zn coated steel
- On the fly laser dimpling

Uncoated, low carbon steel
- Excellent weldability
- No special considerations for Zn out gassing
Tailor welded blanks

Weight reduction
- Less material
- Less transportation weight

Higher stability
- Higher dynamic strength
- Higher crash performance

Reduced quantity of parts
- Less tooling cost
- Less forming cost
- Less logistics cost
Tailor welded tubes

Longitudinal

Transverse

Wall thickness

Material
Hybrid Laser Welding

Low Distortion
- Up to 90% lower heat input
- 50% less residual stress (magnitude)
- Very small HAZ

Uniform Welds
- Average fatigue life improvement- 2-3 times
- Low amplitude life improvement- 10 times

Gap Tolerance
- Better than autogenously laser welding

High Productivity
- 6 mm (1/4”) penetration at up to 5 m/min (200”/min)
- Up to 12.5 mm (1/2”) butt, single pass, single side at 2 m/min (80”/min)
Design for laser welding summary (pt. 1)

- Design & re-design components for laser welding
  - Reduce component weight & cost by reducing or eliminating flange widths \((\text{enabled by single sided, narrow beam access})\)
  - Increase vehicle accessibility & driver visibility by reducing or eliminating flange widths \((\text{enabled by single sided, narrow beam access})\)
  - Reduce component weight and cost by reducing gage thickness \((\text{enabled by increasing strength through optimized weld shapes and/or continuous weld seams in high stress locations})\)
  - Reduce component weight and cost, and increase strength \((\text{enabled by elimination of RSW lower electrode access holes in structural reinforcements})\)
Know & employ the strengths of the full variety of weld joint styles

Realize there are several ways to bridge the gap, … but don’t start there

Consider the variety of design features when designing for laser welding (e.g. K-Joint, positioning aids, tabs, bayonets, interlocking joints, tolerance compensation planes, etc.)
Keys to success

- Design components for laser welding
  (reduced flange widths/gauge thicknesses, lower distortion, single sided access, elimination of RSW access holes, elimination of secondary processes)

- Maximize laser “beam on” time
  (i.e. time sharing of beam to multiple stations, remote scanner welding)

- Good part fit-up req’d via part tolerances & fixturing
  Butt weld: edge preparation, gap <10% of $t_{\text{min}}$, seam location
  Overlap weld: gap < 10% of $t_{\text{min}}$

- Parts must be clean & dry for optimum results
  (no dirt, rust, rust inhibitor, coolant, grease, heavy oils, sand residue, paint/primer, adhesives, sealers, water, solvent)

- Zn coated steels in overlap configuration requires special considerations

- Assign laser welding champion at using plant
  (engineer, attitude/aptitude, teachable, can teach others)

- Early involvement of production personnel
  (ownership, design for service & maintenance, safety)

- Commitment to training & spare parts

- Partner with suppliers that have proven expertise, longevity & reputation
Continuous Education / Improvement

**Laser Welding**
Christopher Dawes
*Abington Publishing* (1992)

**Laser Welding**
Walter W. Duley
*John Wiley & Sons* (1999)

**Laser Material Processing – Fourth Edition**
William M. Steen / Jyoti Mazumder
*Springer* (2010)

**AWS Welding Handbook**
Welding Processes, Part 2
Ninth Edition, Volume 3

**LIA Handbook of Laser Material Processing**
John F. Ready – Editor in Chief
*Laser Institute of America* (2001)
Thank you

TRUMPF Laser Technology Center
Plymouth, MI
(734) 454-7200
Stiffness: Golf IV / Golf V

- Static Torsion Stiffness: +80%
- Dynamical Torsion Stiffness: +15%
- Dynamical Bending Stiffness: +35%

Golf IV  Golf V
Design Optimization

- Laser welding
- Resistance spot welding
- Laser welding

Flange Reduction or Elimination (flangeless design)
Better Accessibility
Less Interference
Principle of time sharing

⇒ Throughput maximization & manufacturing flexibility
Principle of energy sharing

→ Reduced distortion
PFO’s in a TRUMPF LASERNETWORK

Backup- and Redundancy Concepts
Reduction of flange width

Resistant Spot Welding

Laser welding

Weight Saving

c.a. 20.0 mm

c.a. 10.0 mm
Continuous weld & strength optimization
Elimination of lower electrode
Summary: Golf IV / Golf V

- Conclusions based on ½ year production

**Goals reached:**

- Increased process speed (joining).
- Increased productivity
- Short cycle times (30 Seconds)
- Increased strength of the modules compared to most alternative joining methods
- Reduced heat distortion
- Narrow or no flange => Weight reduction
- High flexibility due to the possibility to direct the laser beam by the means of Laser Light Cables into different work cells.
- Reduced floor space

<table>
<thead>
<tr>
<th></th>
<th>Golf IV</th>
<th>Golf V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor space Side panel</td>
<td>2816 m²</td>
<td>1472 m² (-50%)</td>
</tr>
<tr>
<td>Floor space Underbody</td>
<td>480 m²</td>
<td>320 m²  (-33%)</td>
</tr>
<tr>
<td># of Weld spots</td>
<td>4608</td>
<td>1400</td>
</tr>
<tr>
<td>Length of laser weld</td>
<td>1.400</td>
<td>70 m</td>
</tr>
</tbody>
</table>
Wide vs. narrow

**Wide**
- Overlap welding
- Poor edges
- Poor fit-up
- Poor beam to seam location tolerance

**Narrow**
- Low distortion, high speed welding w/ minimum power for butt welding configurations
- … but, good edges, excellent fit-up, & good beam to seam location tolerance required
Partial penetration vs. full penetration

**Partial**

- Aesthetics on back side of component
- Mating part considerations (fit-up & friction)
- Thickness of lower part (through penetration may be impractical or impossible)
- Protection of heat or spatter sensitive components
- Higher speeds (or lower laser power) w/ less HAZ & distortion
- No possibility for underbead dropping (issue for penetrations > 8 mm)

**Full**

- Visual weld verification possible
- Larger fusion area for butt weld configuration

*Compared to through penetration weld …*
*Compared to partial penetration weld …*
Advantage: Programmable Weld Shapes

\[ \text{Stress} = \frac{F}{A} \]
Advantage: Programmable Weld Shapes
Zn coated material: Gap for out gassing

- Evaporating temperature of zinc < melting temperature of steel
- Vapor pressure causes expulsion of molten steel in upper sheet
- Result: Welding seam becomes highly porous and weak
Gap for out gassing: Laser dimpling

- Pre-treatment of one sheet to generate 0.1-0.2mm standoff between sheets
- Use of same laser equipment and optics
Gap for out gassing: Laser dimpling

- Constant dimple height (depending on zinc layer approximately 0.15 - 0.2 mm)
- Dimple height adjustable via laser parameter
Gap for out gassing: Laser dimpling

**Step 1:**
Laser Dimpling

**Step 2:**
Placement of upper sheet

**Step 3:**
Scanner Welding