Practical Numerical Simulation of Laser Welding for Industrial Use

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Introduction

• Laser Welding of Metals
  – Advantages
    • Fast
    • Precise power input
    • Low distortion
    • Small fusion zone
    • Very high energy density
  – Main Modes
    • Conduction (low power)
    • Keyhole (> 1.0 e^6 W/cm^2)
  – Trumpf Trudisk
    • 1030 nm
    • 1000 W
    • 50 micron fiber
    • CW or Pulsed modes
    • 1.5-5.0 e^7 W/cm^2


Problem Considerations & Motivation

- Thin sections 0.003” – 0.15” (0.1 – 4 mm)
- Small parts with high precision
- Very high melting point alloys >3000 F (1650 C)
- Very high molten metal viscosity and surface tension
- Complex geometry, edges, circular sections, etc
- Deep penetration is necessary, requiring keyhole mode
- Some alloys are HAZ sensitive
- Very expensive alloys and high value added parts
- Very expensive experimentation to define weld parameters
- High Fidelity Simulations of the complete keyhole physics very complex, expensive, and slow.
Problem Considerations

- Problem considerations:
  - The simulation needs to predict the quantities of interest well enough to specify laser processing parameters.
  - Quantities of interest:
    - Weld pool diameter/ general fusion zone shape
    - Penetration depth
  - Process Parameters:
    - Start dwell and dwell power
    - Start ramp time/length and power
    - “Steady State” weld power
    - End ramp time/length and power
    - Traverse speed at all times
  - For development of industrial processes we need an economical solution: Fast, Robust, and Easy to use.
Problem Considerations

- Problem considerations:
  - Geometry
    - Tube and plate
    - Blind lap weld
    - Corner lap weld
    - Butt weld
  - Meshes
  - Keyhole
  - Overset
Problem Considerations

• Problem set-up:
  – Weld sections modeled as a single volume
  – Solid conduction only, high viscosity and high surface tension
  – Weld pool characterized as an iso-surface at melt temperature
  – Keyhole as a volumetric source
    • Diameter, shape, power distribution, and depth determined a-priori from literature references and experimental results.
    • Commonly simulated as a cylinder of 2x the radius of the beam at the focal point
  – Overset mesh used for the moving heat source
  – Mesh refinement in the weld zone path
  – Implicit unsteady solver
  – Weld speed, laser power, time step controlled by field functions.
Problem considerations: Keyhole Physics

- Energy transfer
  - Fresnel reflection
  - Inverse Bremstrahlung
- Pressure balance between vaporized metal and surface tension maintains the keyhole
- Energy transfer modeled as a cylindrical volumetric heat source with a non-uniform vertical distribution
- Cylinder 2x diameter of beam at focal point
- Cylinder length to focal depth
- Transfer efficiency modeled as a percent of total power
- Beam power uniform or as a function of depth

Gaussian Beam Energy Distribution

Volpp, J., and F. Volltersten. 2013


Problem Considerations

• Solution
  – Variable time step.
    • Small during initial heat-up and start ramp.
    • Larger during steady state movement
    • Smaller at turns and at the end ramp
    • Time step controlled to be less than ½ a cell size per move
  – Energy controlled inner iterations
    • Stop inner iterations with Energy monitor set at 1e-8
  – Under relaxation factor for energy set at 1
  – Ensure that the maximum temperature is set high enough to prevent clipping. $T > 20000$ K are expected.

• Good practice to do a time step study
  – Halve the time step and check solution several time to ensure the solution is temporally resolved
Typical Weld Cycle

- **Start Ramp**
- **Steady State**
- **End Ramp**
- **Start Dwell**

**Graph Details:**
- **Distance (in)**
- **Speed (in/min)**
- **Power (W)**
- **Time (s)**

- Distance:
  - 0 to 1.2
- Speed:
  - 0 to 1.2
- Power:
  - 0 to 1.2
- Time:
  - 0 to 0.025
Solutions

- Results - Simple butt weld
- Power levels and weld speed

Physical size 1”x1”x0.040” 123,000 poly cells, 0.25 s total welding time
Solve time: 1200 s (12 cores, Intel Xeon E5-2697 @ 2.70 GHz V9.06.011)

Too slow or too much power resulting in melt through

Optimal settings produce fastest weld with smallest HAZ and similar size molten zone
Solutions

Optimization of a circular weld of a tube into a plate

- **Power levels and ramps**
- **End overlap**

**Case 1**
- Initial setup
- Constant power

**Case 2**
- Optimized setup
- Ramped power

Optimized start dwell and ramp produces a full depth weld at the start. Decreasing power ramp through the circular weld maintains weld size and depth as heat builds up.
Solutions

• Results
  – Optimization of a circular weld of a tube into a plate
    • Power levels and ramps
    • End overlap

Case 2
• Optimized setup
• Ramped power

Final Pool
• Pool shown at start of end ramp
• Fully past initial pool at full penetration

Initial Pool
• Initial weld pool at the end of dwell
• At full penetration depth

End ramp and weld overlap ensures a full depth weld and complete welding at the start-end overlap. Especially important if the start dwell is too short.
Solutions

• Results
  – Optimization of a weld around a corner
    • Power levels and ramps

Case 1
  • Initial setup
  • Constant power

Weld pool melts through the corner at constant power and speed.

Case 2
  • Optimized setup
  • Ramped power

Optimized settings allow for a uniform melt pool throughout the weld cycle.

Additional cut plane to show the weld interior shape
Validation

- **Validation**
  - **Metallographic analysis**
    - Mount and etch cross sections of the weld zone using grain structure to compare and calibrate simulations
  - **Weld surface measurements**
    - Weld zone width measurements on the surface of the weldment
    - Easiest and quickest feedback from experiments
    - Accurate enough to guide the model
  - **Visual penetration**
    - Visual indication of full penetration of the back side of the weldment
  - **Imbedded thermocouples in the weldment**
    - Insert fine wire TC’s into drilled holes in the material near the weld zone to measure the thermal transient experienced by the workpiece.
    - TC’s in the welding fixture also can measure heat buildup in the fixtures.

Wang, R et al. Optics and Laser Technology 43 pp 870-873

Weld zone shape in stainless steel

0.0453 in
Closing Comments

• Applicability-Review of tested conditions
  – High melting point metals
    • Methodology not tested with lower melting point metals such as ferrous alloys, aluminum alloys etc
    • Validation must be conducted for each specific alloy
  – Thin sections
    • Methodology was tested with “thin sections” where the focal point and the molten zone nearly or fully extends to the back surface of the weld
  – Laser Power and Keyhole
    • Sub-kW laser power
    • 50-micron focal spot
    • Uniform and non-uniform keyhole vertical power distributions
  – Speeds
    • Less than 200 in/min (0.085 m/s)
  – Not meant to replace detailed VOF models of keyhole welding

• Utility
  – The method does a good job of predicting molten weld pool surface diameter and general shape with minimal computational effort.
  – Simulation allows prescription of welding parameters for experimental validation.
    • Steady state weld speed and power
    • Start and end ramp speed and power
    • Start dwell time and power
    • Steady state ramping of power and speeds at corners, during circular paths, etc
    • Overlap of closed weld paths
    • Heating of weldment and fixture for multiple welds
References

Bibliography

• StarCCM+ Help V9.06.011