Laser Solder Reflow: A Process Solution
Part I

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Abstract
EFD Inc. and Leister USA have collaborated to bust the myth that you cannot perform laser reflow with solder paste. Using Leister diode lasers, EFD has formulated solder pastes that survive the rapid reflow cycle typical of laser heating. These solder pastes reflow and wet well, without spatter, even when heating is accomplished in less than half a second. The flux core in wire solders cannot boast such flux spatter resistance in such an aggressive heating environment.

This paper explains why diode lasers have been identified as an excellent heat source for solder paste reflow. It reviews the heating options available, compares them to diode lasers, and assists in the decision making process to determine whether a diode laser is the better choice for a particular solder reflow application.

Soldering Method Review
Solder reflow can be accomplished with a wide variety of heat sources. Each heat source has advantages and disadvantages due to the mechanics of how energy is transmitted and absorbed. A short review of the most common heating methods used for solder reflow will allow for easier comparison for capability and applicability.

Equipment	Image	Area Heated	Key Features
Hot Bar/ Thermode		• Area of contact and surrounding area through conduction	• Contact heating • Heat transfer dependent on surface area of contact • Thermodes wear with use
Hot Plate		• Entire product through conduction from contact surface out to extremities	• Contact heating • Heating rate dependant on contact surface area • Heats from the "bottom" up
Resistance		• Conductive material between electrodes	• Contact heating • Performance partly dependent on contact area between part and electrodes
0Soldering Iron		• Point touched and surrounding area through conduction	• Contact heating • Heat transfer dependent on surface area of contact • Tips wear with use

Torch		• Area of flame focus and surrounding area through conduction	• No physical contact; flame touches part • Available in very high energy capacity; with increased capacity comes increased flame size • Open flame ignites flammable materials
Convection Oven		• Whole product	• Non-contact heating • Tight peak temperature control • Uniform heating across product • High throughput
Focused Hot Air		• Area defined by nozzle design, air dispersion, and conduction	• Non-contact heating • More local than a convection oven • Tight temperature control
Induction		• All conductive materials within inductive field and surrounding area through conduction • Field strength decreases with the square of the distance	• Non-contact heating • Available in very high energy capacity • Heats materials with higher electrical resistance faster (e.g. steel faster than copper) • Field shape is a function of coil shape
Infra Red (IR)		• Area of IR exposure and surrounding area through conduction	• Non-contact heating • Energy absorption is material dependant with metals being poor absorbers • Area of IR exposure can vary from as small as an 8mm spot to a theoretically unlimited area.
Diode Laser		• Area of laser focus and surrounding area through conduction	• Non-contact heating • Area of focus can be as small as 0.6mm • Precise energy output control • Energy absorption is material dependant

Solder Reflow Process Considerations
When considering what heat sources are viable candidates for an application, there are a few key concerns that can rapidly narrow the list of choices:

- Reflow cycle time requirements
- Product changeover and system flexibility requirements
- Temperature-sensitive components and materials
- Contact-sensitive components and materials
- Restricted access to soldered area due to component geometry
- Allowable temperature at "next operation"

Lasers lend themselves to addressing many of these concerns with their inherent features:

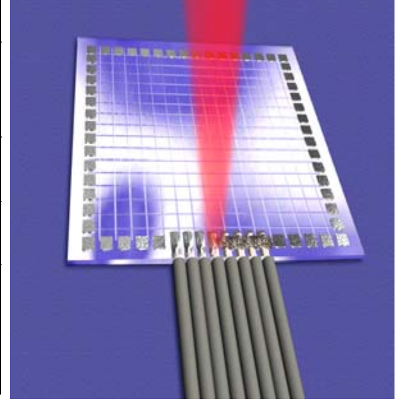
- A wide range of heat delivery rates from very fast (under 1 second) to very slow
- Capable reflowing all soft solder alloys
- Flexible heating area from 0.6mm diameter and larger
- Precise, repeatable heating
- Line-of-sight targeting
- Non-contact heating
- Easy to automate

Application Review
Some users choose laser heating as the best option from a field of many that can do the job. Other users find their viable heating options quite limited and discover laser to be the solution to difficult heating problems.
The most common reason for using lasers for reflow is the desire for non-contact, localized heating. While motivations vary, the goal is the same: reflow that spot there and nowhere else and do it fast enough to avoid excessively heating up the rest of the product via conduction.

In order to put the decision-making process that leads to this conclusion into perspective, a few real world examples will be evaluated to determine the best heating method. In each example, the key processing issues are identified and each of the previously mentioned heating systems is screened for incompatible heating effects.

Product 1: Ribbon cable to silver thick film pads on glass substrate

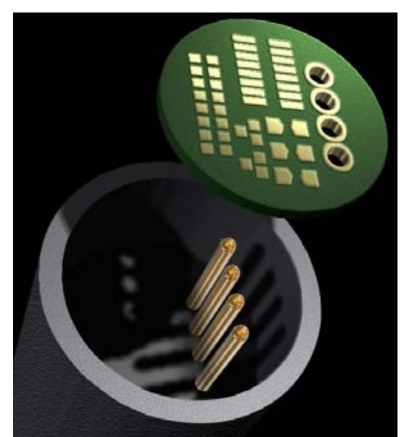
Product Feature	Process Limitation
Glass substrate	• Substrate will shatter due to thermal expansion if brought to soldering temperatures over a wide area too rapidly.
Silver Thick Film	• Silver thick film will dissolve into solder if exposed to liquid solder for extended time.
Ribbon cable insulation	• Cable insulation will char at 300ºC.
Solder joint visual appearance	• Using automated optical inspection to inspect solder joints. • Electrical test is not feasible. • Value-add in downstream operations is high.



Heating System	Viable	Advantages and Disadvantages
Hot Bar/Thermode	Yes	• Visual characteristics of top of joint have high variability due to contact area between thermode and solder. • Vision inspection has high false failure rate due to variability in visual characteristics.
Hot Plate	No	• Rapid, uneven heating cracks glass substrate.
Resistance	No	• No clear location to apply electrodes.
Soldering Iron	Yes	• High joint quality variability. • Operator performance has large impact on quality and defect rate. • Cycle time per part is longer than other heating methods due to point-to-point heating.
Torch	No	• Rapid, uneven heating over moderate size area. Area heated is surrounded by unheated glass. Glass substrate cracks due to constrained thermally-induced expansion.

Convection Oven	No	• Reflow cycle too long due to cable locating fixture requirements. Silver ink dissolves into solder during oven reflow.
Focused Hot Air	No	• Rapid, uneven heating over moderate size area. Area heated is surrounded by unheated glass. Glass substrate cracks due to constrained thermally induced expansion.
Induction	No	• Cable heats more readily than solder and ink, melting cable insulation.
Infra Red (IR)	No	• Infrared light most readily absorbed by cable insulation, melting insulation.
Diode Laser	Yes	• Energy transmitted directly to solder paste which conducts heat to wire and silver thick film, protecting glass from overheating and excessively long reflow cycle time.

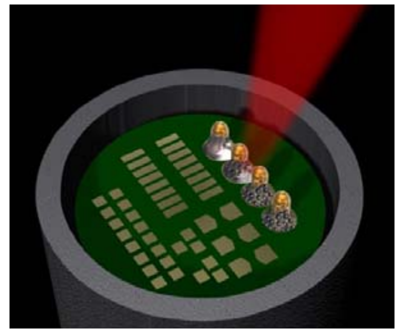
Viable Options: Soldering Iron, Hot bar/Thermode and Diode Laser
Best Fit Choice: Diode Laser



Example 2: Four gold plated brass connector pins molded in plastic housing with 2.5mm pitch. Solder pins to through holes in PCB.

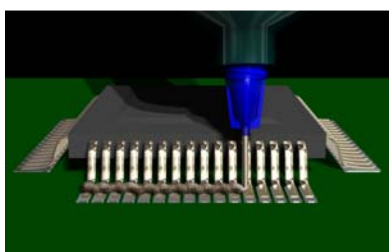
Product Feature	Process Limitation
Plastic Housing	• Will deform at solder reflow temperatures
Component location	• Component locations limits access to the pins
PCB is populated	• Must avoid disturbing parts already on PCB
Cost Sensitive	• Total cost of ownership for soldering process must be minimize to control part cost

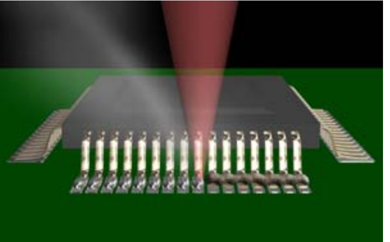
Heating System	Viable	Advantages and Disadvantages
Hot Bar/Thermode	No	• Heating element interferes with components and plastic housing due to size of element and proximity of components.
Hot Plate	No	• Unable to fixture part for heating with hot plate.
Resistance	No	• No clear location to apply electrodes.
Soldering Iron	Yes	• Reflow station cycle time with appropriate tip size is over 4 seconds. • Larger tips for faster heating interfere with components and plastic housing due to proximity.
Torch	No	• PCB and components burn in presence of open flame.
Convection Oven	No	• Plastic housing will melt during reflow process.
Focused Hot Air	No	• Air dispersion excessively heats surrounding area causing plastic housing to deform.
Induction	No	• Pins heat very readily with induction. Pin section within plastic heats enough to deform the plastic, misaligning the pins. • Electrical components on board are damaged due to overheating of conductive elements.
Infra Red (IR)	No	• Infrared light most readily absorbed by PCB material, overheating and damaging the PCB before reflow can be completed. • Solder flow is uneven around pin due to uneven heat distribution causing large voids in plated through-hole joint. • Total heat applied to board and pins sufficient to deform plastic at base of pins.
Diode Laser	Yes	• Energy rapidly transmitted directly to solder paste which conducts heat to pin and plated through-hole.



Viable Options: Soldering Iron (at lower production rate) and Diode Laser
Best Fit Choice: Diode Laser

Example 3: Selective soldering of QFP to a Printed Circuit Board (PCB)





Product Feature	**Process Limitation**
Over 1000 boards	• Throughput is a key concern due to the quantity of boards to be worked on
Double sided SMT	• Cannot support from bottom side or lay flat • Must avoid disturbing components on opposite side during reflow
QFP has 208 pins	• 0.5mm pitch leads
Small electrolytic can capacitors adjacent to QFP	• Electrolytic can capacitors will be damaged at reflow temperatures
Hand rework requires skilled operator	• Limited availability of highly trained operators in local employment pool

Heating System	**Viable**	**Advantages and Disadvantages**
Hot Bar/Thermode	No	• Component shifts under application of thermode first side of component. Different thermode required for each QFP size.
Hot Plate	No	• Unable to fixture PCB for heating with hot plate.
Resistance	No	• No clear location to apply electrodes.
Soldering Iron	Yes	• Pin count of QFP and quantity of boards makes manual soldering too time-consuming.
Torch	No	• PCB and components burn in presence of open flame.
Convection Oven	No	• Electrolytic can capacitors cannot survive a convection reflow process.
Focused Hot Air	No	• Heating rate is limited. • Relatively large area of board, including can capacitors, is heated to reflow temperature in process of reflowing QFP.
Induction	No	• All electrical components on PCB will be affected by induction field causing overheating of conductive elements in many components. • Unable to focus field on QFP leads and pads.
Infra Red (IR)	No	• Focused infrared light most readily absorbed by component body and PCB material. At energy levels required to meet cycle time requirement, the PCB and component are damaged due to overheating before reflow can be completed.
Diode Laser	Yes	• Energy rapidly transmitted directly to solder paste as diode spot traverses in a line across each row of leads. • Heating pattern causes solder alloy drawback to each lead in turn, preventing bridging.

Viable Options: Soldering Iron (at low production rate) and Diode Laser
Best Fit Choice: Diode Laser

In each of these examples of real life products, the inherent features of diode lasers lend themselves to solving difficult soldering problems. By combining solder paste dispensing and laser heating for reflow, these products are produced within target cycle times and at high first pass yields. While the other feasible heating methods can do the job, the disadvantages make them more costly due to expenses for operator training, consumable components and other maintenance items, duplicate production stations and additional staff required to meet throughput targets, and yield.

Laser Types

The next question that needs answering is "why diode lasers?" Several laser types are used in industry for a variety of applications, including medical treatment lasers, positioning lasers, lasers for welding and cutting metal, lasers for welding thermoplastics and laser used for solder reflow. LEISTER selected High Power Diode lasers as they offer high efficiency, long service life, compact size, and low maintenance.

This section will compare characteristics of High Power Diode lasers with those of CO_2 and Nd:YAG lasers. CO_2 and Nd:YAG lasers have been chosen for this comparison since they too can be used for selective soldering. LEISTER's decision to use High Power Diode laser was based on key advantages that will be highlighted in this paper.

Carbon Dioxide (CO_2) Laser

The Carbon Dioxide (CO_2) Laser, is one of the earliest lasers. It was developed in 1964 and is the most powerful continuous wave laser currently available. The CO_2 laser produces infrared light with wavelength around 10,600nm with up to 20% efficiency. CO_2 lasers are most often used for metal cutting and welding.

Nd:YAG laser

Another common laser type was developed in the same year as CO_2 laser. It is made from Neodymium-doped Yttrium Aluminum Garnet and is usually referred to as an Nd:YAG laser. Nd:YAG lasers can produce high power in the infrared spectrum at 1064 nm wavelength. Similarly to CO_2 lasers, they are primarily used for cutting and welding of metals in addition to marking metals and other materials.

Diode Lasers

High Power Diode Lasers (HDL) are mainly based on GaAs semiconductor bars. They entered the market in 1999, offering wavelengths ranging from 790 nm to 980 nm and power output of 50 watts per bar. Over the last several years, advances in diode cooling technology have dramatically increased diode power, life and efficiency through improved ability to maintain uniform diode temperature. [1]

The efficiency of High Power Diode Lasers can reach 63% in 940nm modules [2]. Currently there are commercially available HDLs capable of providing laser power of up to 400 W with life expectancy of over ten thousand laser 'on' hours. The most popular wavelength range for HDLs available on the market is from 810nm to 980nm although High Power Lasers may range from 630nm to 1900nm.

Laser Characteristics and Cost of Ownership

Over the years, Carbon Dioxide (CO_2) and Nd:YAG lasers have been significantly reduced in size yet both remain bulky and weigh upwards of eight pounds. During integration into a soldering station or production line the laser module will have to be mounted on a dedicated XYZ linear stage capable of moving the device to the desired location at acceptable speeds.

In comparison HDLs laser energy is delivered through thin and flexible fiber-optic cable allowing the cabinet with laser components such as laser diode module, power supply and water cooler to be located outside of the immediate working area. The fiber-optic cable is attached to a compact optics head that can be half the size of a soda can and weigh under a pound. Thanks to its compact size, HDL laser system can be easily integrated into existing soldering station where it is mounted next to a solder paste dispenser, utilizing the XYZ linear stage already in place.

Equally so, the HDL laser system beats CO_2 and Nd:YAG when it comes to maintenance. A CO_2 laser relies on a constant gas supply and Nd:YAG requires relatively frequent light bulbs replacement. HDLs run nearly maintenance free, requiring only a change of filters in the water cooler unit every 6 months and annual calibration of the system. Both procedures are fairly simple and can be accomplished within 20 minutes.

Energy Absorption

When it comes to solder paste reflow, the most significant advantage of HDL and Nd:YAG lasers over CO_2 is its shorter wavelength. The wavelength of 10600 nm produced by CO_2 lasers is highly reflective off metals while very absorptive in organic materials

used for making flux, printed and flexible circuit boards, and other substrate materials used in soldering applications. The high energy absorbance of surrounding materials causes burning in areas near solder joints while high reflectivity of metal requires wider process window or higher power levels to achieve a successful reflow. As the result, lasers operating in high wavelength spectrum have been identified as less capable candidates for laser soldering applications. Fortunately, the near infrared spectrum is less reflective on metallic surfaces and less absorbent on organic materials, making High Power Diode and Nd:YAG more desirable candidates for laser soldering.

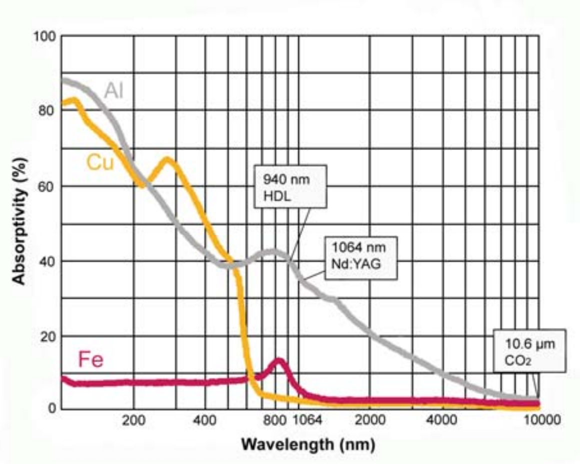
The "absorbance" of the laser energy is defined by the percent of photonic energy transformed into the metal by converting to heat, versus energy reflected away. Equation 1 describes energy absorptivity as a function of change in temperature over time when a certain amount of laser energy is applied to a particular body of metal

$$A = \frac{\text{absorbed energy}}{\text{laser energy}} = \frac{\sum_i m_i c_{pi}}{P} \frac{\Delta T}{\Delta t} \quad (1)$$

where A is the absorptivity, m_i is the mass, and c_{pi} the specific heat of each heated component i (in case of solder paste each component used in the alloy), ΔT is the difference in temperature achieved over time Δt by introduction of power P.

As has been mentioned previously, the majority of laser soldering applications involve soldering around heat sensitive components or reworking printed circuit boards with component already in place. In these applications high absorptivity of materials becomes crucial to protecting the surrounding components from extensive heat damage. This is achieved by using lower power and shorter cycle time.

From equation 1, energy absorbance is directly proportional to specific heat c, which is a measure of energy required to increase temperature of a given amount of material by one degree. Therefore the absorbance rate of laser energy at a given wavelength may significantly differ from one metal to another. The following graph summarizes absorptivity of aluminum, iron and copper at different wavelengths.

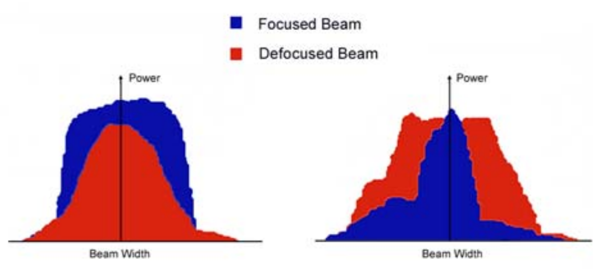


Another factor that greatly influences energy absorbance is roughness of the material. Naturally polished surfaces are more reflective than their rough or scratched counterparts. This occurrence is explained by multitude of reflections within cavities and scratches that trap additional photonic energy. As a result, the absorptivity of rough surfaces may be twice the absorptivity of polished materials. [3]

Comparison of Energy Distribution and Intensity

The laser beam, shaped by the end optics, forms a conical shape where the tip of the cone corresponds to the minimum spot size and is located way from the lens at its focal distance. The spot size can be increased by adjusting Z-height of optics head. With increase of spot size, the energy is distributed over larger area and energy density of laser beam is reduced. HDL and Nd:YAG lasers have different energy density distributions and exhibit significant differences in beam intensity away from focal point.

The energy density distribution of laser beam generated by High Power Diode remains uniform through the width of the spot regardless of its size. As result, laser energy is evenly spread over the target area. On the other hand, energy density distribution of laser beam generated by Nd:YAG laser changes from the top-hat profile to Gaussian with increase of spot size. [3] This results in decrease of overall amount of energy delivered by the laser and results in uneven energy intensity with the center of the beam receiving the most.



Further investigation has shown faster temperature rise of the solder joint area when illuminated with defocused HDL laser versus defocused Nd:YAG laser. This occurrence is attributed to overall energy loss of the defocused Nd:YAG beam. [3] In many laser soldering applications the spot size is kept close to the minimum; however, there are cases where a wider area of coverage is required and the ability to have larger spot size is necessary. A larger spot size is achieved by changing the focal distance from the minimum diameter focused spot size, defocusing the beam. In these applications HDL lasers have an advantage over Nd:YAG as they are capable of providing a larger spot size with even energy distribution without overall energy loss due to defocusing.

Conclusion

Through the work of EFD and Leister, the viability of laser light for reflow of solder paste has been established. Appropriately formulated solder pastes now allow for no-spatter, high-speed reflow with good wetting. The product features that make laser heating an attractive option have been defined. Side-by-side comparison with other heating methods identifies those methods that are feasible and the degree to which they solve a product's heating requirements. For those applications that can benefit from laser heating the remaining question is which type to use.

High Power Diode Lasers, in addition to their compact size and maintenance-free operation, offer many technological advances in laser soldering as compared to CO_2 and Nd:YAG lasers. The most significant of them is shorter wavelength that allows higher absorbance in metals and lower absorbance in organic materials usually used for making PCBs and other substrates. Combined with the appropriate solder paste formulas, diode lasers give manufacturers a flexible and powerful tool to solve difficult heating problems. As a selective heating system, diode lasers are hard to beat for flexibility, cycle time and total cost of ownership.

References:

[1] "Reliability of high power diode laser bars in industrial applications" D. Wolff, G. Bonati, P. Hennig, H. Voelckel (2005) http://www.jold.de/sites_basics/head-presse-veroeffentlichungen_en.htm#

[2] "Powering up - High-efficiency high-power diode lasers" D. Wolff, P. Hennig (2005). http://www.jold.de/sites_basics/head-presse-veroeffentlichungen_en.htm#

[3] "Soldering with solid state and diode lasers: Energy coupling, temperature rise, process window" M. Brandner, G. Seibold, C. Chang, F. Dausinger, and H. Hügel. Institut für Strahlwerkzeuge, Universität Stuttgart, Pfaffenwaldring 43, D-70569 Stuttgart, Germany. Journal of Laser Applications, Volume 12, Number 5, October 2000.