

Laser Reflow: A Solution for Medical Electronics Assembly

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Abstract

With the advent of RoHS legislation in Europe, numerous medical equipment manufacturers have found that the higher reflow temperatures required result in damage to their products using their existing heating methods. In the realm of medical micro-electronics, some parts are too small or too light to be soldered using contact heating. In the quest for miniaturization and ergonomics, access to solder connections can be restrictive by design. In all three cases, lasers offer opportunities in non-contact selective soldering that succeed where other methods fail.

Laser soldering is not new. Manufacturers have been experimenting with use of lasers for reflow

since the 1970s. Early CO₂ and Nd:YAG systems were both bulky and expensive. They also were designed for high power cutting and marking operations as opposed to lower power heating. At the time, and until recently, solder materials were not compatible with the extremely high heating rates typical of laser heating. Flux components would vaporize too quickly and explode, spattering flux and alloy away from the heated area. EFD has developed rapid reflow solder pastes that incorporate fluxes designed to provide good wetting and resist spattering in the short laser heating cycle.

Introduction

EFD, Inc. and Leister USA have collaborated to dispel 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 medical device application.

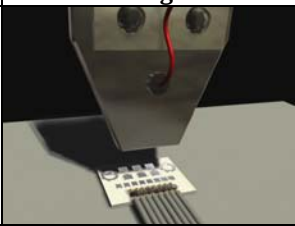
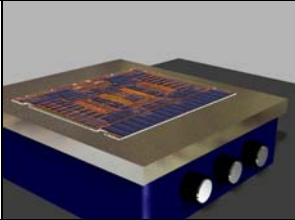
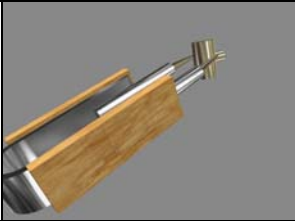
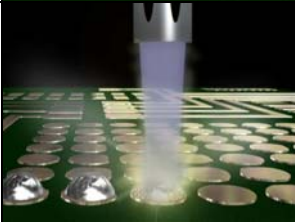
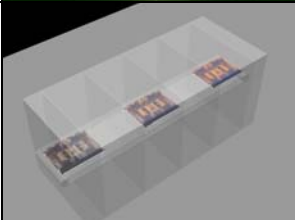
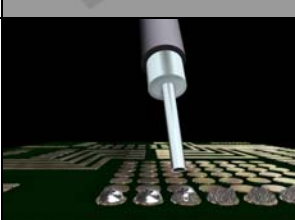
With the use of laser light for reflow having been established, all that remains is to apply it to best effect. Each time a laser is fired, it pumps a specific amount of energy at a particular wavelength to a particular point in space. Where technique comes in is choosing where and for how long to apply that light, along with the application of accessory equipment to optimize solder paste reflow. This presentation covers the specifics of how to determine which process choices are the right ones, based on the needs of your medical product to maximize yield and throughput.

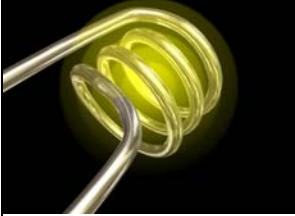
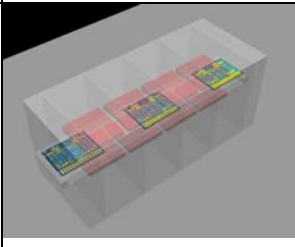
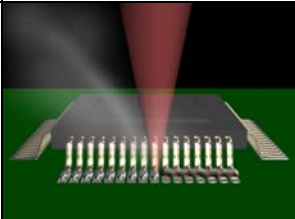
Since the reflow process of a laser is defined by equipment, manufacturing process qualification is easier to qualify than for a manual process. Process and performance data for the solder joints readily lend themselves to capability analysis.

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 (*Table 1*) used for solder reflow allow for easy comparison for capability and applicability.

Table 1: Heating Methods

Equipment	Image	Area Heated	Key Features
Hot Bar/ Thermode		Area of contact and surrounding area through conduction by product	- Contact heating - Heat transfer dependent on surface area of contact - Reflow profile capable - Thermodes physically wear with use and erode in contact with flux
Hot Plate		Entire product through conduction from contact surface out to extremities	- Contact heating - Heating rate dependent on contact surface area - Heats from the bottom up
Resistance		High resistance portion of resistance electrodes and high resistance portion of the product in conductive path between electrodes	- Contact heating - Performance dependent on contact area between part and electrodes - Quality of electrical connection degrades if electrodes are contaminated with flux
Soldering Iron		Point touched and surrounding area through conduction by product	- Contact heating - Heat transfer dependent on surface area of contact - Large degree of operator variability - Tips wear with use
Torch		Area of flame focus and surrounding area through conduction by product	- 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 through hot air or inert atmosphere convection	- 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 by product	- Non-contact heating - More local than a convection oven - Tight temperature control

Induction		• All resistive materials within inductive field and surrounding area through conduction by product • 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 by product	• Non-contact heating • Energy absorption is material-dependent, with metals being poor absorbers and dark surfaces being good 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 by product	• Non-contact heating • Area of focus can be as small as 0.6mm • Precise energy output control • Energy absorption and reflection is material-dependent

Heat Source Choice

When comparing the various heating methods available, it is important to make an informed choice. While a number of methods may be possible and one option may seem more economical than another on the surface, there are often hidden costs. For example, soldering irons have a moderate to low sticker price, but the cost of quality due to operator variability and cost of ownership due to tip replacement far outstrip the initial purchase price. With the advent of lead-free soldering this is truer than ever because of the higher reflow temperatures required.

Process Considerations

When considering what heat sources are viable candidates for an application, there are a few key process concerns that can rapidly narrow the list of choices. The concerns are independent of product design and material choices.

- Reflow cycle time: throughput capacity
- Product changeover
- System flexibility: more than one product in a family of products to be produced using the equipment
- Allowable product temperature at next operation

- Total cost of ownership: spare parts, maintenance downtime requirements, power consumption, etc.

Product Considerations

Product design can also play a significant role in heat source selection. Physical properties such as shapes and dimensions influence accessibility. Heat-sinking characteristics can take advantage of or require a particular heating method.

- Restricted access
- Component geometry
- Joint geometry
- Thermal load at solder joint
- Mass of solder required for joint
- Distance solder must travel to fully wet area

Material Considerations

Material choices in the form of temperature limits and physical vulnerability can also act to exclude heating methods.

- Thermally-sensitive components and materials
- Lead free regulatory requirements
- Contact-sensitive components and materials
- Dissolution of metals by molten solder alloy
- Deformation of plastics due to softening
- CTE induced stress stored in product

- Reflow temperature required

Features of Lasers as Heat Sources

When considering what heat sources are viable candidates, lasers lend themselves to addressing many of these considerations with their inherent features:

- A wide range of heat delivery rates from very fast (as little as 0.25 seconds) to very slow (several minutes)
- Capable of reflowing all soft solder alloys
- Flexible heating area of 0.6mm diameter and larger
- Precise, repeatable heating
- Line-of-sight targeting
- Non-contact heating
- Easily automated

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.

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 due to their high efficiency, long service life, compact size, and low maintenance.

This section will compare characteristics of High Power Diode lasers with those of CO₂ and Nd:YAG lasers. CO₂ and Nd:YAG lasers have been chosen for this comparison since they too can be used for selective soldering.

Carbon Dioxide (CO₂) Laser

The Carbon Dioxide (CO₂) Laser was developed in 1964 and is the most powerful continuous wave laser currently available. The CO₂ laser produces infrared light with wavelength around 10,600nm with up to 20% efficiency. CO₂ lasers are most often used for metal cutting and welding.

Nd:YAG laser

Another common laser type was developed in the same year as CO₂ 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. Similar to CO₂ lasers, they are primarily used for cutting and welding 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.

The efficiency of High Power Diode Lasers can reach 63% in 940nm modules. Currently there are commercially available HDLs capable of providing laser power of up to 400 W with a 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 they may range from 630nm to 1900nm.

Laser Characteristics and Cost of Ownership

Over the years, Carbon Dioxide (CO₂) 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, an HDL’s energy is delivered through thin and flexible fiber-optic cable, allowing the cabinet with laser components such as the 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, an HDL laser system can be easily integrated into an existing soldering station where it is mounted next to a solder paste dispenser, utilizing the XYZ linear stage already in place.

The HDL laser systems also require less maintenance than CO₂ and Nd:YAG systems. A CO₂ laser relies on a constant gas supply and Nd:YAG requires relatively frequent light bulb

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 CO₂ is their shorter wavelengths. The wavelength of 10600 nm produced by CO₂ 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 the high reflectivity of metal requires a wider process window or higher power levels to achieve a successful reflow. As a 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 transferred to 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

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

Equation 1

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

As mentioned previously, the majority of laser soldering applications involve soldering around heat-sensitive components or reworking products with components 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 the energy required to increase the temperature of a given amount of material by one

degree. Therefore the absorbance rate of laser energy at a given wavelength may differ significantly from one metal to another. Figure 1 displays the absorptivity of aluminum, iron and copper at different wavelengths.

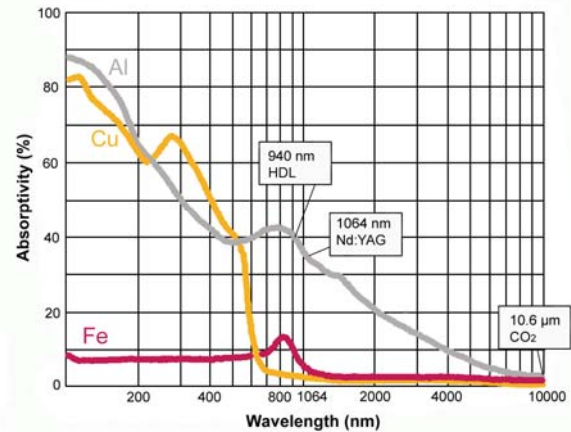


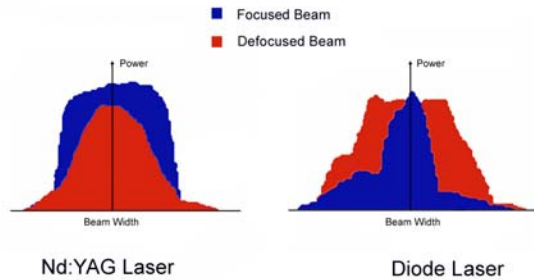
Figure 1: Energy Absorption

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

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 away from the lens at its focal distance. The spot size can be increased by adjusting the Z-height of the optics head. With increased spot size, the energy is distributed over a larger area and the energy density of the laser beam is reduced. HDL and Nd:YAG lasers have different energy density distributions and exhibit significant differences in beam intensity away from the focal point.

The energy density distribution of a laser beam generated by a 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 a laser beam generated by a Nd:YAG laser changes from the top-hat profile to Gaussian with increase of spot size. This results in a decrease of the overall amount of energy delivered by the laser and 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 a defocused HDL laser versus a defocused Nd:YAG laser. This occurrence is attributed to overall energy loss of the defocused Nd:YAG beam. 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.

Process Consistency Concerns

The consistency of the solder paste dispensing process can be critical to the consistency of the heating process due to the amount of heat absorbed by the flux and alloy during reflow. If insufficient solder paste is present overheating may result, as less heat is devoted to flux evaporation and alloy liquefaction. If excessive solder paste is present, incomplete reflow may occur, as there is not enough heat to reflow all the solder paste. Each product being different, there will be a range of solder paste deposit sizes over which the laser heating cycle produces perfect joints. On less thermally sensitive products, it may be practically impossible to cause overheating due to lower solder paste volume. Each product must be evaluated to determine the optimal solder paste deposit size range and the controls required to achieve that goal.

For product designs that do not allow for a consistent physical target for dispense and laser reflow, the exactness of the laser can be a disadvantage. Excessive physical variation from part to part can result in inconsistent dispense volume and laser heating of the wrong spot. For example, if a wire on a terminal is the target, variations in wire location can cause variations in how the paste sticks to the part and whether the laser spot adequately heats the wire. Using a larger spot size can

compensate for laser location inaccuracy to an extent. Vision correction can completely correct for physical misalignment, while a footed dispensing system (*Figure 2*) can compensate for inaccuracies in the Z-axis.

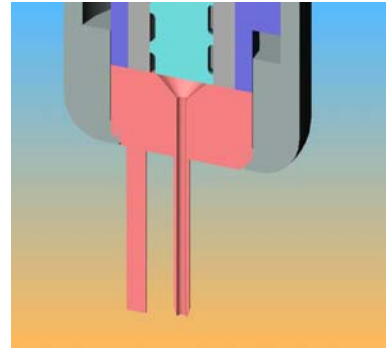


Figure 2: Footed Dispense Tip

General Principles of Solder Paste Reflow

With all the methods described in this paper, we take advantage of one predictable property of liquid flux and solder. This is the tendency to become thinner and flow towards areas with higher temperature. As a fluid gets hotter, it gets thinner and spreads more readily. This causes it to preferentially flow towards points of heat. The closer it gets, the hotter it gets and the faster it flows.

Another property of most solder pastes is that about half of the flux can evaporate during reflow, while the remaining flux is composed of solids that will not evaporate. These gasses are flammable and will ignite if overheated. They also slow the flux evaporation process by forming a super-saturated vapor layer above the joint. To maximize flux evaporation and minimize the chance of ignition, a moderate to strong airflow must be maintained across the area being reflowed. Proper venting will also protect the laser optics from possible flux redeposition as the hot flux vapor wafts and condenses around the cold laser optics.

The ability to vent flux vapor is critical for sub-second reflow times, as the probability of vapor ignition is higher. Once the vapor carbonizes, turns to ash and falls onto the product surface (*Figure 3*), it absorbs a much higher percentage of the laser light because it is black. Parts covered with ash and exposed to laser light will rapidly overheat, burning temperature-sensitive materials such as circuit boards and plastics.

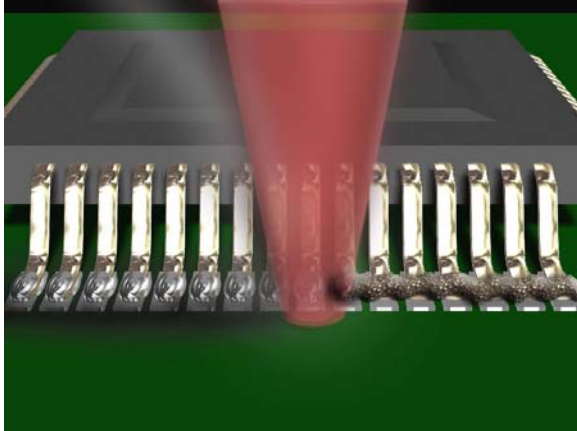


Figure 3: Burning Flux

Where to Heat

The next question is where to apply the laser light. The key features of lasers as a heating method are the non-contact, location precision and amount of heat applied. The laser projects a consistent quantity of light at a point in space every time. Possible target choices include the solder paste deposit itself, a portion of the area to be soldered that is initially void of solder paste and a combination of the two.

In many applications, the paste will be dispensed upon the area to be soldered and the laser can be targeted at the solder paste itself. The laser light is absorbed by the flux and alloy, vaporizing portions of the flux, liquefying the alloy, and conducting heat through the molten metal to the surfaces to be soldered. This technique works well on relatively low thermal mass components and in close proximity to thermally sensitive materials, as conductive heat transfer to areas beyond the joint is minimized.

More thermally massive components, components that heat sink well, and larger areas need more heat to achieve wetting. With these types of parts, some or all of the laser focus must be applied to the components and/or substrate to achieve more uniform heating. There are two phenomena that can interfere with wetting if heat is not distributed properly:

1. If all the heat is directed into the solder paste, the available flux can be fully consumed before the components reach reflow temperature and wetting begins.
2. The solder alloy can ball up on top of the components because they are not at a high enough temperature to wet out. In this case, the contact area becomes relatively small and the solder becomes a poor conductor of heat. The perfectly smooth molten solder sphere turns into more of a reflector than

absorber (Figure 4) and sends the laser light somewhere else.

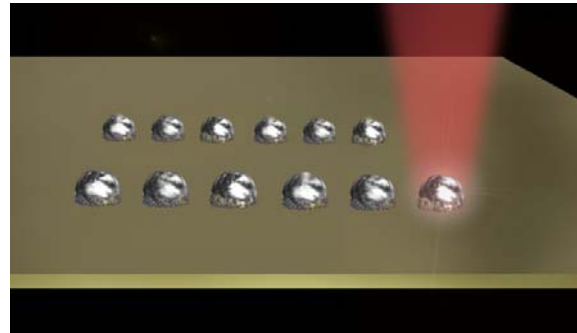


Figure 4: Ball of Solder Reflecting Laser

On some products, it is not practical to dispense solder paste everywhere it needs to spread. Applications like pin-in-hole where it is easier to dispense in one spot and heat the product in a way to make the solder paste wet completely around the pin is a prime example. The technique used for these types of joints will vary based on the thermal mass and heat sensitivity of surrounding materials.

Most work well with one of two options:

1. Focus the laser spot to heat both the solder paste deposit and pin at same time (*Figure 5*). Reflow is rapid and the flux and alloy will readily wet down the through hole following the heated pin. This method is less reliable for large features, as the far side of the through hole will be at a lower temperature than the side focused on by the laser. In this case it may be necessary to dispense on both sides of a pin.

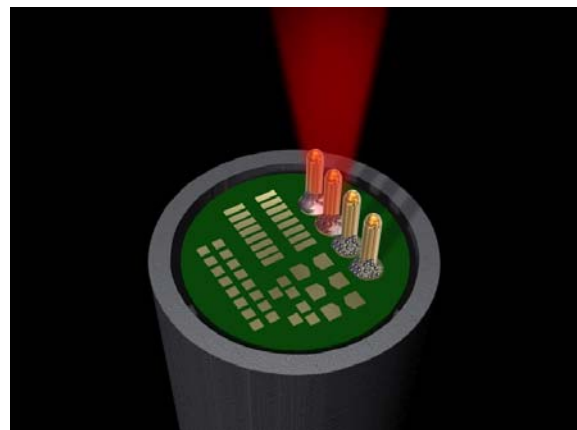


Figure 5: Heating pin and Paste at Same Time

2. Focus the laser spot on the opposite side of the pin (*Figure 6*) from the paste, heating

the pin and annular ring. If the surrounding materials are too sensitive to overheating, this process will typically take longer, as the heating rate must be slow enough to allow conduction to reflow the solder paste without damaging the surrounding material. The solder will reflow when the pin and ring achieve reflow temperature and run towards the area of highest temperature, where the laser light is focused.

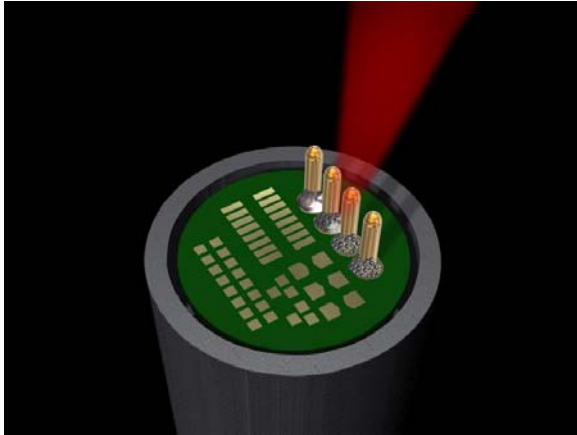


Figure 6: Heating Side of Pin

Spot Size

Spot size is a function of the optics used and the distance from the optics to the target point. In order to achieve more uniform heating over an area, a spot size of similar area may be used. If the spot is too small, all the heat is concentrated in one place and must spread through conduction. A larger spot can heat the entire area faster. A larger spot also keeps solder flow more uniform due to the absence of hot areas that might draw the flux and alloy as described in the section on General Principles Solder Paste Reflow.

The minimum spot size can vary from 0.6 mm to 1.5 mm, depending on the optics used. The smallest spot size is achieved with the shortest focal distance lens and becomes larger for lenses with longer focal distances. The spot size can be increased by adjusting the Z-height of the optics head. With an increase in spot size, the energy is distributed over a larger area and the power output of the laser system needs to be adjusted to maintain energy density. Another parameter that will vary with different end optics is the included angle of the cone-shaped laser light (Figure 7). The figure below shows a summary of the most commonly used focal lengths and their corresponding included angles.

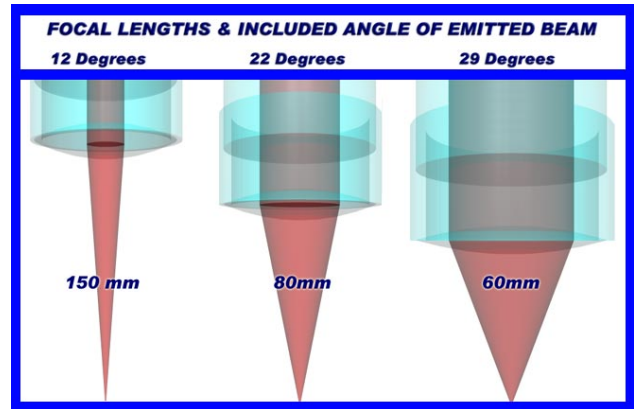


Figure 7: Focal Lengths of Optics

The considerations for choosing end optics are as follows.

- **Size of the heated area:** For applications with a small joint design it may be critical to maintain an adequately small spot size to keep laser energy off the area outside the joint to avoid damage to the surrounding materials.
- **Clearance:** Applications that require the laser head to be mounted at a certain height or angle to avoid bumping into the fixture or other objects need to use an end lens with an appropriately long focal distance.
- **Tall components:** The laser light forms a conical shape, therefore when soldering near tall components some clipping may occur (Figure 8). Choosing optics with a smaller included angle may be necessary (Figure 9).

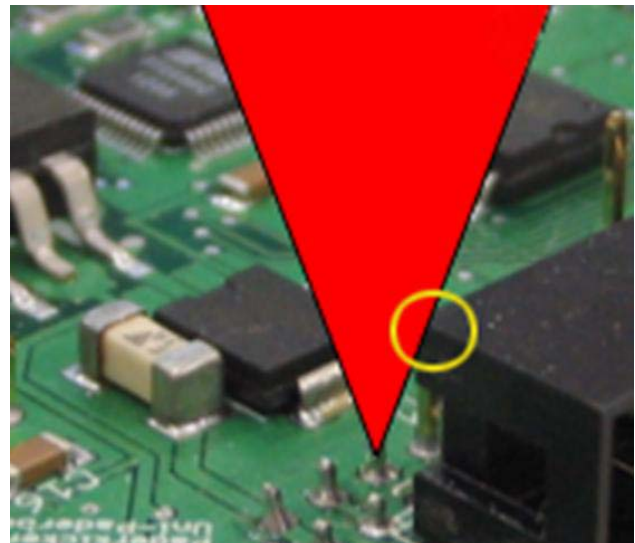


Figure 8: Clipping Components with Wide Beam Optic

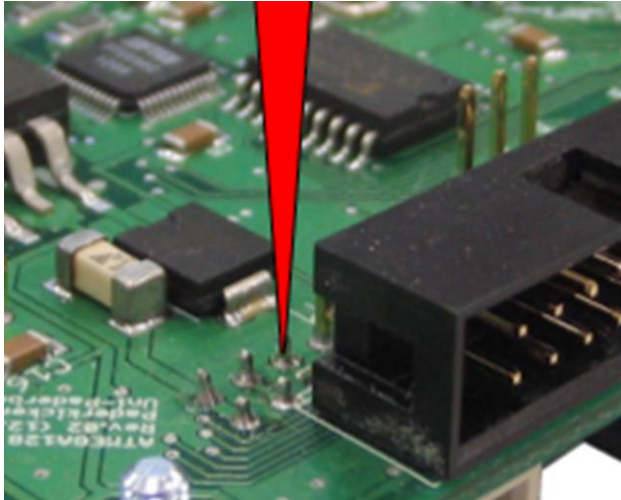


Figure 9: Narrow Beam Optic

Line Soldering

So far, only point-to-point heating has been addressed. There are two methods for line heating. In one method, the point of focus is moved across the area or row of points to be reflowed. In the other method, the laser light is shaped into a line by a special optic (*Figure 10*). The advantage to such an optic is that the entire area can reflow at once and may be faster than the moving spot technique. The laser line formed by standard optics is 25mm wide.

Applications requiring reflow over longer distances will need to be processed in a number of steps. Laser systems with a line module capable of providing up to 90mm wide lines are also available. The disadvantage is that the line optic or line module is limited to line reflow applications. For products with a variety of heating areas, the dedicated line optic, together with a separate laser system, are required in addition to a laser system with a spot optic.

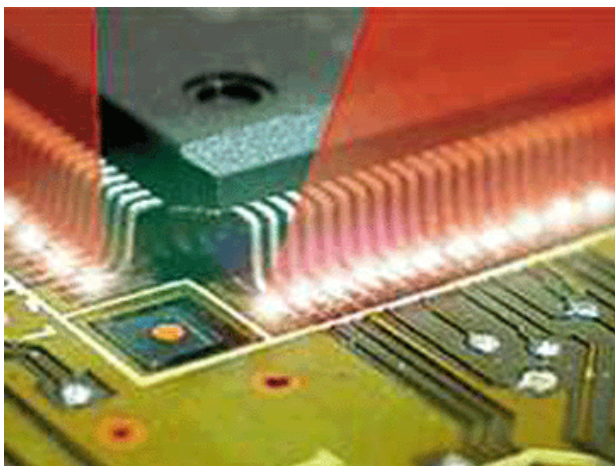


Figure 10: Line Generation Optic

One example of moving the point of focus is a Quad Flat Pack (QFP), SOIC, ribbon cable or other component with many terminations on a side. Solder is dispensed in a line across all the pads. The laser follows the same path (*Figure 11*). Each location goes through a mini reflow profile as the spot traverses the area. Solder is reflowed incrementally, forcing it to coalesce and draw back to each wettable point as it passes. Heating rate and total laser exposure time is a function of spot size and velocity. For this method to be viable, the material in between wettable points must not absorb so much light that it is damaged. Typically, the solder paste absorbs almost all the light, protecting the circuit board or other material in between.

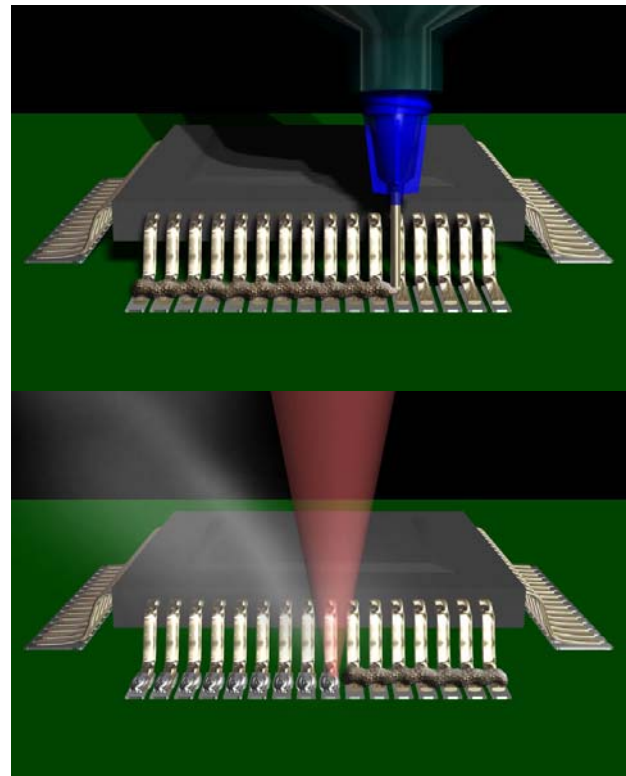


Figure 11: Line Dispense and Reflow with Laser

Reflow Timing

As has just been implied, sometimes the full power of the laser cannot be used. There is a practical limit of around $\frac{1}{4}$ second of heating time for even the most ideal laser soldering applications because it takes time for all the surfaces to heat the alloy to spread. Most point-to-point laser reflow applications will have a laser “on” time between $\frac{1}{2}$ and 2 seconds. The controlling factors are:

- **Thermal load of components:** More massive parts heat more slowly. Parts with high thermal conductivity act as heat sinks.

- **Mass of solder paste:** The laser must add enough energy to vaporize flux and liquefy alloy. Flux vapor affects heating rate and can auto-ignite.
- **Distance to wet:** The farther alloy has to flow, the longer it will take. Alloy must remain liquid long enough for it to finish flowing across surfaces and wetting.
- **Joint geometry:** Complex geometries like stranded wires take longer for alloy to wet out fully. Alloy must remain liquid long enough for it to finish flowing across surfaces and wetting.
- **Thermal sensitivity:** Parts and solder must be heated fast enough to limit total heat absorbed. Excess heat may conduct to and damage nearby materials.

Because lasers can control energy output in timed segments, heating can be profiled to take best advantage of the heating effects required (*Figure 12*). For simple point-to-point heating with no special considerations, a profile might be a single power level for a time. If cycle time is at a premium and parts need a minimum amount of time to fully wet, the laser could fire at a lower power level to partially dry the flux enough to restrict slump before reflow and raise power to initiate reflow enough to maintain reflow without overheating.

Power level can also be changed linearly over time, ramping from one output level to another. With all these power profiling options available, it is just a matter of testing to determine which gives the best performance.

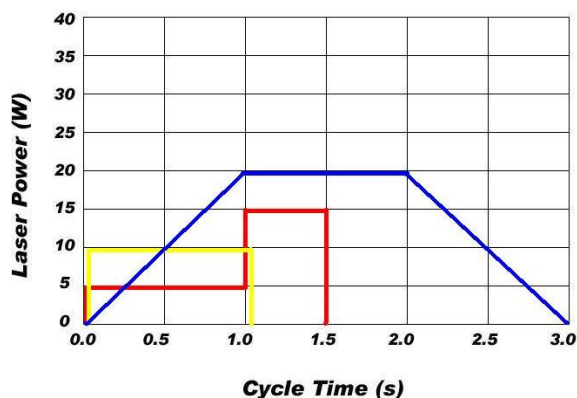


Figure 12: Reflow Profiles

Conclusions

A diode laser is a precision tool. In combination with well-formulated solder paste, it can be used to form solder joints using a wide variety of techniques based on the thermal requirements of a product. Misapplication of laser energy is a good way to burn parts, much like other heating methods. By creating a reflow environment that takes advantage of the characteristics of laser energy delivery and absorption, along with the reflow characteristics of solder paste, very difficult soldering tasks can be performed with high first-pass yields.

Performing sample reflow tests is a proven methodology for identifying whether laser reflow is suitable to a product and the process variables that must be controlled to produce the desired solder joint. A theoretical analysis of how lasers are likely to perform is one thing, but practical application is another. If laser reflow of solder paste is identified as a viable method for a product, work with the solder paste vendor and laser system supplier to identify the optimal combination of material and equipment for the product.