MD&DI
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Laser Welding: Metal Fastening with Microscopic Precision

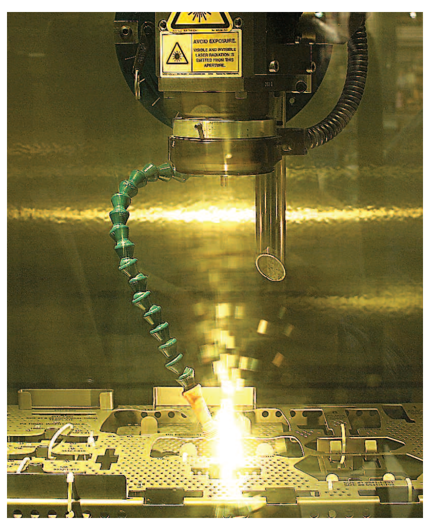
For medical applications such as surgical cases and trays, laser-welded joints offer many advantages.

James Whitcher

Surgical case and tray designs demand light weight with strength and precision with quick turnaround. Product platforms also need to be highly configurable. These qualities can be fully achieved with modern sheet-metal fabrication methods. When these techniques are used in conjunction with laser welding, the results can exceed the functional criteria demanded by most case and tray manufacturers.

A laser-welded medical instrument tray is usually built on a sheet-metal platform that can be removed from its case. Typical materials include titanium, stainless steel, or aluminum. A series of formed metal brackets of the same material reside on the platform. The brackets hold the instruments at precise locations while adding strength to the thin tray section.

The brackets are designed to use the edge-strength characteristics of sheet metal and to minimize areas of planar contact. This configuration provides maximum strength with minimal moisture retention during autoclave cycles. One or more angled forms can be added to each bracket to further enhance the strength of the final tray assembly. A number of tabs and slots are located at the interfaces between brackets and the tray platform. During the laser welding process, these interfaces form a series of laser plug-welded joints.



Laser welding causes vaporization and pooling of two identical materials along a joint, which forms a bond.

Depending on the complexity of the design, the number of brackets on a tray assembly can vary from six to 20. The number of laser-welded joints varies proportionally, from 20 to 60. When properly engineered, the end result is the precise fit of a tray to its supporting brackets. During loading, the stresses are evenly distributed without additional mass.

Laser welding creates a stronger and lighter structure than one assembled with conventional fasteners. Voids and planar contact regions are all but eliminated, minimizing residual moisture pooling and its associated risks. Such concerns are particularly important for surgical cases and trays. Aesthetically, the trays take on a clean appearance, free of rivets and screw heads. And, in terms of turnaround, a highly customized tray can usually be produced in a few weeks with a modest computer numerical control (CNC) sheet-metal platform. For medical device applications requiring quick turnaround, high strength, low weight, and precision, laser welding is a good choice.

How Laser Welding Works

Laser welding is typically a nonfiller welding technique, similar to gas tungsten arc welding (GTAW) in some regards and E-beam welding in others. Laser welding is, in essence, a highly controlled beam of energy applied to a material under a shield gas. It causes vaporization and pooling of two identical

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materials along a joint, which forms a bond. The intense heat generated on a very small area produces a narrow and deep weld. Rapid heating and cooling along the weld path produces a minimal heat-affected zone. The result is a strong, nearly homogenous attachment point without added cross section. The weld path is typically controlled by servo motion control, allowing for high accuracy and complex weld profiles.

Beyond control of the beam parameters, the critical factors affecting laser-weld quality are similar to traditional, or nonfiller, welding methods, including shield gas and feed rate.

Shield Gas. Laser welding can be employed in many applications that use E-beam welding with one key advantage: laser welding does not require a vacuum. As with other fluxless welding methods, however, it does require a shield gas. The shield gas prevents the introduction of atmospheric elements into the metal, which can weaken the joint. The shield gas used depends upon the material welded. The most common shield gases include CO_2 for low-carbon steel and blends of inert gases for nickel and aluminum alloys.

Feed Rate. An extension of beam parameters, feed rate can be adjusted to maximize the throughput of the laser welding process. In conjunction with power, pulse width, and frequency, the feed rate of a process contributes to the total energy applied to the weld point. The amount of energy required varies based on the material and the thermal mass at the weld interface. With appropriate precautions, typical case and tray materials such as stainless steel and titanium can be processed at high energy, and, therefore, at high feed rates. Care must be taken, however, to ensure that adequate weld penetration is achieved at higher feed rates.

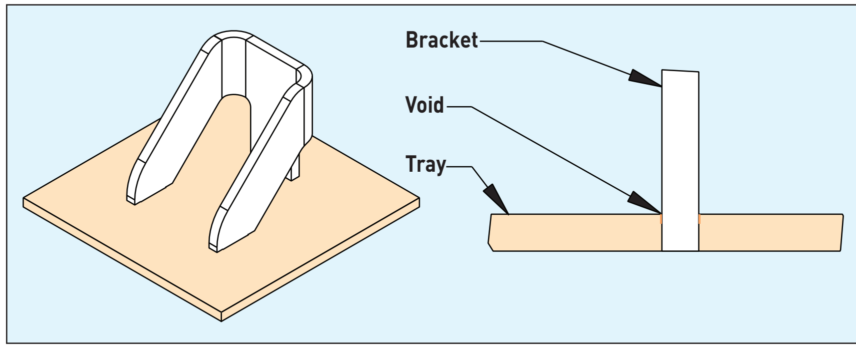

Figure 1. Laser welding can fill clearances, creating nearly homogenous joints.

The Laser-Welded Joint

The geometric configuration of a laser-welded joint is different from that of a conventionally fastened condition. In its strongest and lightest form, the tabbed edge of a formed bracket is inserted into a mating slot on a second component. The planar contact area is limited to the narrow edge of one mating component.

Clearances between the tab and slot, though relatively small in nature, are still required for assembly. The welding process, however, fills the clearances, eliminating all but the smallest of voids. If the settings are correct, the attachment point becomes nearly homogenous (see Figure 1). Destructive testing can validate the quality of the weld. Failure of the surrounding native material, rather than the weld itself, indicates adequate penetration.

Materials

Unlike structures that use conventional fasteners, laser welding requires careful material selection. Most dissimilar materials can be screwed or riveted together. However, laser welding applications are limited to areas in which it is possible to take advantage of the strength and consistency of nearly homogenous points of attachment.

The material selection process is application specific. In the most general sense, stainless steel is used for washdown or corrosive environments and titanium is usually used when high strength and light weight are critical. But again, these determinations depend on the specific application and its performance requirements.

Not all materials are suitable for laser welding. Materials such as high-carbon steels go through martensitic transformations when rapidly cooled, making the weld brittle. Type 304 stainless steel, however, is well suited to laser welding. The rapid heating and cooling inherent in laser welding minimizes the precipitation of chromium carbides in the sensitization temperature range of this alloy (between 870° and 425°C). The corrosion-resistant properties of the material remain relatively unchanged throughout the heat-affected zone, eliminating oxidation at the weld joint. In most applications using this nickel-chromium alloy, laser welding is superior to conventional welding methods.

With these limitations in mind, virtually any material that can be welded can be laser welded if the physical size of the structure is within process equipment limitations. Low-carbon steels, nickel-chromium alloys (stainless steel, titanium, and superalloys), and many aluminum alloys (with alloy fillers and experimentation) are candidates for laser welding. Typically available in sheet stock, these materials are also usually conducive to modern fabricated metal manufacturing and all of its advantages.

Precision

Another strength of laser welding is the precise control it can confer on a part. Laser-welded joints are clean, offering minimal intrusion outside the joint. Bead size can be controlled to provide a flush attachment point. The weld is narrow and deep, minimizing the heat-affected zone and creating a nearly homogenous metal structure at the joint. CNC processes enable highly repeatable weld paths across complex three-dimensional contours. On extremely thin sections, the weld distribution can be stitched across a broad bearing surface to produce an effect similar to hundreds, if not thousands, of spot welds per square inch.

Other Considerations

Metal fabrication technology, including CNC punch presses, laser cutting, and press-brake forming, is a necessary complement to laser welding. Together, they offer many product design and production advantages.

Scalability. One key benefit in leveraging metal fabrication methods in case and tray design is scalability, or the capacity to design highly configurable product platforms. When sheet-metal fabrication and common injection-molded components are combined, scalability allows designers to economically include product brand recognition, for example, across a broad and highly customized product family. As shown in Figure 2, custom-colored injection-molded corner bumpers can be mass-produced and used as a common component across a made-to-order, short-run sheet-metal product line. This allows product customization while maintaining the same look and feel across an entire product family.

With current CNC punch presses, laser cutting, and press-brake forming, myriad components can be created with little or no tooling investment. This allows component geometry to be changed inexpensively, if required by the application.

Combining this flexibility with the high-volume advantages of common injection-molded components, long project lead times and tooling investments happen only once in the life of a product family. Thereafter, every delivered product helps recoup initial tooling costs and also addresses the needs of a broader market. As a result, case and tray designs can often be turned out in as little as a few weeks.

Design. Of course, low cost, customization, and quick turnaround mean nothing if the desired quality characteristics are not achieved. Case and tray designs require precision, durability, light weight, and maximum ventilation. Therefore, careful attention must be paid to the construction methods and assembly processes employed.

Precision is required to effectively contain and present case contents. The units must be durable enough to survive harsh environments, extreme handling, and elevated temperature loading from repeated autoclave cycles. Mass must be minimized to facilitate ergonomically correct and easy handling. Finally, to properly sterilize the case, tray, and, most importantly, its contents, maximum ventilation and minimal moisture retention is key. To accomplish this, case and tray designs must minimize, if not eliminate, areas of planar contact and voids.

Planar Contact and Voids. Planar contact in a high-moisture environment presents a number of concerns from a structural standpoint in any application. Retained moisture causes corrosion around atmospheric interfaces, along with migration of water-soluble compounds across areas of planar contact. This can be observed easily by looking at a ring of rust around the head of a carriage bolt on a gas grill, or perhaps around the lug nuts on a car wheel. Corrosion caused by moisture retention and high stresses is manageable in most applications, resulting in an unsightly appearance, at worst.

Voids, while similar to planar contact areas in many regards, differentiate themselves by their volume. Typically, void volumes are several orders of magnitude larger than planar contact regions, providing locations for moisture and associated compounds to pool.

With regard to case and tray design, planar contact areas combined with adjacent voids can create oxygen-depleted, moisture-rich, dark environments in close proximity to surgical instruments. These areas can be a harbor for microbes. Minimizing this risk by limiting planar contact and voids is a major advantage of laser welding over conventional fastening methods for sheet-metal components.

Fasteners. Unlike laser welding, conventional fastening methods often produce voids that are created by shaft clearances. These voids combine with planar bearing areas to create structural challenges that affect the service life of a variety of structures without proper sealing or finishing precautions.

Conventional fasteners rely on the tensile strength of a screw or rivet to distribute a load between two bearing surfaces on mating components. The loading on the components, combined with sheet-metal hole-punching methods, creates imperfect planar contacts. The load is concentrated underneath the head of the fastener at the backside burr interface. This concentrated load creates high compressive stresses at the contact region. These stresses progress nonlinearly from the edge of the clearance hole to the boundary of the fastener head.

Discounting surface imperfections, this condition produces a small (up to 0.003 in.), but nonetheless present, dish effect. This means that clearances are created at the points farthest from the fastener. This condition is clearly apparent with thin materials, typically defined as being in the 0.040-in.-thick region. These small gaps, combined with minute amounts of warpage during the rolling of the raw material at the mill, allow the introduction of moisture beneath the planar interface.

In addition to the imperfect planar contact, conventionally fastened components require shaft clearances to assemble. Regardless of how well a conventionally fastened joint is engineered, these shaft clearances create enormous voids when compared with their

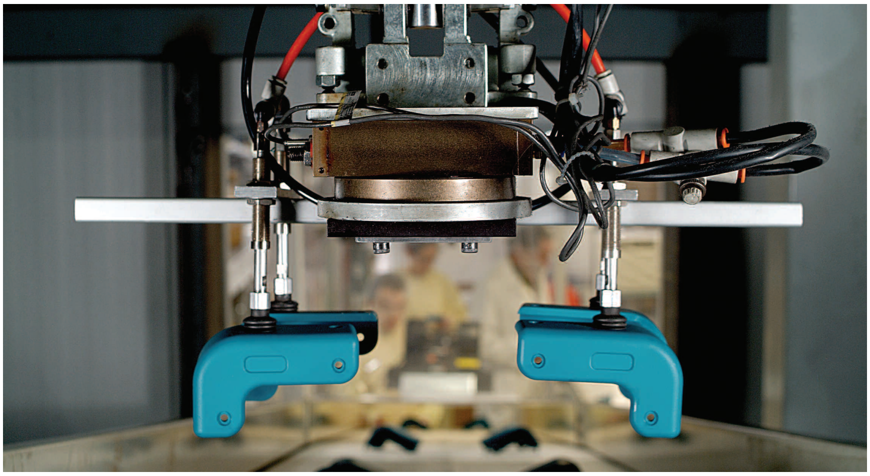

Figure 2. Scalable design enables parts such as high-volume case corners to be used on multiple surgical case and tray configurations.

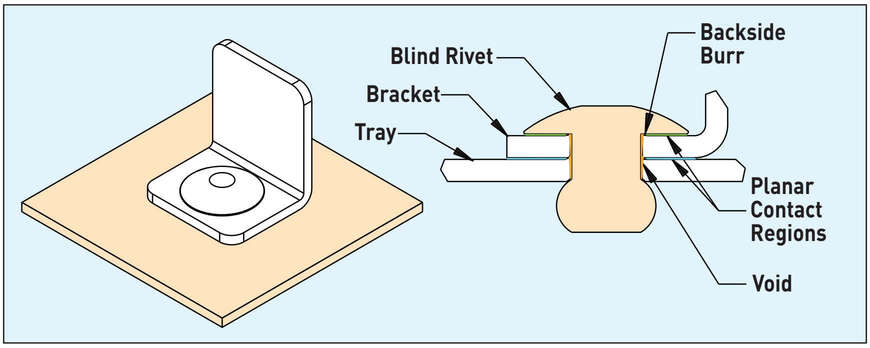

Figure 3. Conventionally fastened joints can create planar contact regions and voids, which can harbor moisture and microbes.

diameter. In conventionally fastened joints, shaft clearances become reservoirs of moisture, which precipitate out through imperfect planar contact regions well after the rest of the tray is dry (see Figure 3).

Beyond Case and Tray

Laser welding can achieve higher strength-to-weight ratios than can conventional fastening methods. One reason for this is the high level of control over the stress distribution in laser-welded elements.

With fasteners, control of stress distribution is required with each attachment. Each conventionally fastened attachment point consists of a combination of compressive and axial loads. Relatively large stresses are added to the components during the attachment process and remain present throughout the service life of the mating parts. As more attachment points are required to distribute stress during loading, more stresses are applied to the structural components. Furthermore, mass is added with each fastener, along with the mass of the associated bearing area, which must be increased to reduce localized stresses.

With thin components, washers are often needed to reduce distortion. This means that mass needs to be added to distribute stresses. As a result, the assembly process itself, prior to any loading condition, has already created local regions of high stresses. The sole function of these stresses is simply to keep the assembly together. When testing the design under load, reactions will often be inconsistent with finite-element predictive model indications.

Although unpredictable results can occur with any fastening method, laser welding offers flexibility in load distribution and its associated stresses. This is not to say there are no residual stresses in a laser-welded joint. However, these stresses are relatively insignificant when compared with conventional fastening methods, and they result in stronger yet lighter structures. If properly engineered, the internal stresses on a laser-welded joint remain insignificant, or at worst, manageable. The heat-affected zone, albeit small, does affect the performance of the joint. Rapid heating and cooling create small amounts of concentrated stresses along the weld joint. These stresses create an attachment that is not truly homogenous. However, with proper attention to stresses, materials, and weld settings, the effects of laser welding can be predicted and controlled.

Laser welding can distribute loads along a greater area of the native material, reducing localized stresses. Significant increases in strength can be achieved without collateral mass, as is required by fasteners. With proper design, laser welding produces lighter and stronger structures than can be achieved with conventional fastening methods.

Conclusion

When properly engineered, laser-welded joints offer a variety of advantages over conventional fasteners. Stronger, lighter structures are possible owing to greater control over load distribution and weld application. Mass is added only to the areas needed, without the collateral mass associated with conventional fasteners. Internal stresses are significantly lower, which enhances material strength.

When common molded parts are used in conjunction with fabricated metal components, these advantages extend into a strategy of scalable product families that combine the efficiencies of high-volume injection molding with the inherent flexibility of short-run sheet-metal equipment. These qualities, and many more, make laser welding an effective and microscopically precise tool for fastening applications, from the nanoscale to large medical equipment. ■