Remote laser welding with seam tracking and local beam oscillation – an economic feasibility analysis

Florian Albert, Alexander Müller, Pravin Sievi
Scansonic MI GmbH, Rudolf-Baschant-Str. 2, 13086 Berlin

Introduction

The importance of remote laser welding as an industrial process is growing as an increasing number of new applications are taking advantage of this technology. In addition to the automotive industry, smaller and mid-sized metalworking companies are now pioneering applications in this field. All users, however, are still confronted with the question – Which of these systems now available is best suited for my technical and cost requirements? This report will address this issue with support from specific system and process examples.

The principle of remote laser welding

The welding optics for remote laser welding consist of an optical system with one or more drive-powered deflector units (the so-called mirrors or scanner modules). They are used to position the laser spot practically instantaneously in the optic's working field. This makes it possible to apply arbitrary, strength-critical welding patterns and shapes onto the workpieces without having to move the optics. The welding optics are then normally mounted on a movable master machine (typically an articulated robot) so that versatile welding operations can be carried out in three dimensions on large workpieces.

<table>
<thead>
<tr>
<th>Component</th>
<th>Advantages</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robotics-adapted systems enable:</td>
<td>- Workpieces of almost any size</td>
<td>- The required robotic-specific controller interface must be taken into consideration.</td>
</tr>
<tr>
<td></td>
<td>- Versatile and economically efficient solutions</td>
<td></td>
</tr>
<tr>
<td>Scanners enable:</td>
<td>- Minimized travel times between the seams</td>
<td>- Field size</td>
</tr>
<tr>
<td></td>
<td>- Reduced cycle times</td>
<td>- System construction</td>
</tr>
<tr>
<td></td>
<td>- Very high production output</td>
<td>- Consumption costs</td>
</tr>
<tr>
<td>Sensors enable:</td>
<td>- Strength-critical welding contours</td>
<td>- Which sensor is needed?</td>
</tr>
<tr>
<td></td>
<td>- Workpiece-oriented solutions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Assured quality</td>
<td></td>
</tr>
<tr>
<td>A longer operating clearance enables:</td>
<td>- Good access to the workpiece</td>
<td>- Imaging and focal length</td>
</tr>
<tr>
<td></td>
<td>- Minimal obstructive contours and collision hazards</td>
<td>- Obstructive contour</td>
</tr>
<tr>
<td></td>
<td>- Increased protection of the optical elements</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Advantages and characteristic variables for robot-guided remote technology

Welding optics for remote laser welding are also characterized by large working clearances, made possible by focal lengths which are longer than \( f = 500 \) mm. Thus they can be led over clamping jigs without any collisions. When compared to conventional laser welding, there is no longer any need here for time-consuming re-positioning of the optics between the individual welding tasks. It is important to note that the robot and the re-
mote welding head represent a kinematically coupled system, whereby the control solution for this system is essential for the ultimate success of the joining. So this combination of the laser beam together with the remote optics represents an optimal combination, in which a "weightless" tool works in harmony with high-performance deflectors. Table 1 lists the advantages which the technical solutions offer and the cost factors and technical variables which should be considered.

However the question remains – Are all remote laser welding processes equal? Which process variants and technology packages are available and which are required? We will now consider the differences between the main process variants and examine the cost effectiveness of the options (such as butt joint detection, beam modulation and gap detection) that the various technologies provide.

**Variants of remote laser welding**

There are basically two different approaches here:

**Group 1:** **Post**-objective lens scanning (beam deflection in the optics after the focusing lens), see Figure 1 [8].
- The collimated laser beam is focused by the focusing lens and then deflected by a movable mirror (also, deflector unit or scanner module).
- The focus moves along a circular path. The laser spot must therefore be constantly tracked depending on the Z-position or scanner position.

**Group 2:** **Pre**-objective lens scanning (beam deflection in the optics before the focusing lens), see Figure 2 [8].
- The collimated raw beam is first deflected by a mirror (also, deflector unit or scanner module) and then focused using a flat-field lens (F-theta).
- The F-theta lens permits the laser spot to be moved along a plane on the working field. No further corrective actions or field equalizations are required.

Since users do not normally weld on flat workpieces, for both of these scanning variants it is necessary to constantly track the Z position with a corresponding actuator. This is accomplished using highly dynamic optical units, which are referred to as auto-focus modules. The numerical complexity of the post-objective lens systems is thus higher because the field equalization must be calculated and implemented not only based on the Z position, but also based on the mirror axis positions.

In addition to these two basic construction types, additional modules based on the post-objective lens remote lens (refer to Figure 3) are required. The example shows a colli-
mation, the auto-focus units, additional beam modulation units, the required quality sensors and the seam tracking along with the necessary lighting.

Figure 3: Pre-objective lens scanning: an example system with additional Scansonic modules

So it becomes clear that there are various technical solutions based on different approaches. But what are the implications of pre-objective lens and post-objective lens scanning for cost-effective technology solutions?

The working field versus the costs for consumables

The first factor when choosing processing optics for remote laser welding is the actual required size of the working field, i.e. the field that should be achieved via the deflection units without moving the master machine. This must be determined on an individual basis from estimates or even from workpiece simulations; the determination depends on the number of seams, the seam lengths, the position of the seams in relation to each other, the seam shapes, and the 3-D contour of the workpiece. Pre-objective lens scanning optics are capable of operating in very large work fields which, depending on the focal length being used, can usually detect fields of 200 x 300 mm. Post-objective lens scanning processing optics are not able to keep up in this regard, because they must perform post-tracking for the laser beam's Z position. They can typically detect only half of the field size mentioned above.

But how is this relevant in the real world? In many industrial remote-technology applications, the actual size of the working field being used is only 50% of the above value.
is because of the location and orientation of the welding seams on the workpieces and the welding speed (typically selected between 4 and 6 m/min) with robot feeding speeds around 8 m/min.

The actual position and number of welding seams are the factors that determine which type of system is suitable. And what's more: there are economical implications for getting a precise answer to this question!

In order to achieve the working field that is actually required by the user, a complex and large lens system is provided for the pre-objective lens scanning. This system is protected by correspondingly large safety glass (with diameters of approx. 5 to 6 inches). Their price is 8 to 10 times higher than the standard 2-inch safety glass which is typically used in post-objective lens scanning optics. This is an important cost factor for welding processes which create deposits or increased splatter. The problem of dirty safety glass is addressed with the use of cross-jets, for both pre-objective lens and post-objective lens scanning optics. The cross-jet distributes compressed air directly under the safety glass, thus blowing any deposits and splashes towards the suction extraction system. Due to the different dimensions of the safety glass used by both of these process variants and the requirement that the cross-jet must protect the entire width of the safety glass, these normally have a multi-stage construction.

It is helpful at this point to make a comparison. The large-sized cross-jet for pre-objective lens scanning optics has a compressed air consumption of up to 2200 l/min. The annual costs for only the compressed air can reach 25,000 € (based on a compressed air price of 0.1 €/m³, an assumed annual production of 230 three-shift days, a cycle time of 60 seconds, and a welding time per cycle of 40%). In direct comparison with a processing head that uses post-lens scanning (with much smaller safety glass), ongoing costs can actually be reduced by 30 – 50 % for this example. So it can be quite worthwhile to clarify the required size of the working field and the most appropriate process variant in advance.

**Which technology package can provide me with the best economic benefits?**

**The seam tracking package**

Almost all laser welding processes require that the laser beam is precisely positioned on the workpiece. This ensures that the correct welding depth is reached, that the joint micro-structure is correct, and that the correct seam type is formed. But this can be complicated, especially when dealing with remote processing. The workpiece and the clamping jig have tolerance variances. The master machine may be too inaccurate considering the large working distance between the optics and the workpiece. Up until now this meant that the laser beam hits the workpiece imprecisely, so that remote welding was really only useful for square-groove (I) seams on lap joints. A connecting flange must also be designed so that it is large enough to be located even after adding up all the dimensional tolerances. This can result in an indirect economic loss because more materials must be provided for the welding workpieces.
But what if it were also possible to precisely guide the laser beam during the remote welding process? What cost benefits would then be expected? To help answer this question, we shall take a look at the specific example of welding galvanized steel sheets.

When welding square-groove seams in galvanized sheets with lap joints, if the gap between the sheets is not large enough, seam defects (such as pores, or penetrations) will occur. Zinc that has evaporated during the welding process cannot be sufficiently removed (degassed) and thus seeks the path of least resistance through the molten pool.

Until now the only remedy for this was to set a defined gap (e.g. using laser studs in a separate processing station, or changing the angle of incidence for the workpieces). A separate processing station for laser studs means using a laser cell, with workpiece handling, clamping jigs, robotics, optics and the appropriate laser source. Such a cell involves investment costs 500,000 and 800,000 €. It is theoretically possible to achieve results through degassing or changing the angle of incidence, but due to the limited positioning accuracy of the remote optics, such efforts have shown unsatisfactory results in real applications. The welding of square-groove seams without degassing – in compliance with modern quality criteria and facility availability requirements – is currently not feasible. This means that costs for the (otherwise highly productive) remote technology in the facility are doubled just by the process requirements when welding galvanized steel sheets.

However, when considering seam-tracking processes (moving away from square-groove seams to fillet seams which are accurately hit by the beam), it is quickly evident that simply the precise positioning of the beam and thus the change in the weld type can result in much economic advantage. Figure 4 illustrates the number of pores / penetrations during the welding of two galvanized sheets, with and without seam tracking, as a function of the gap size. Only with seam tracking is it possible to achieve a fillet seam independent of all existing dimensional tolerances. The resulting zinc vapour can easily escape: thus the splashes and penetration tendency can be reduced significantly.

![Burn throughs / pores per 100 mm weld seam](chart.png)

- I-seam at lap joint
- Fillet seam at lap joint
- TruDisk 5001; LLK 200 μm
- RLW-A; $d_{w} = 0.56$ mm
- $P = 3.5$ kW; $v = 6$ m /min
- Sheet metal gauge: 0.6 mm / 0.6 mm
- Weld seam length 100 mm

---

**Figure 4**: Number of burn throughs / pores per 100 mm weld seam with and without seam tracking, as a function of the gap size. Only with seam tracking is it possible to achieve a fillet seam independent of all existing dimensional tolerances. The resulting zinc vapour can easily escape: thus the splashes and penetration tendency can be reduced significantly.
Figure 4: Number of penetrations / splashes when welding galvanized sheets with the Scansonic RLW-A

If one assumes that each splash has a volume of about 1 mm³, then for the example shown here: without seam tracking and with gap sizes between 0 and 50 microns, approximately 7 mm³ splash volume is produced over 100 mm of welding seam length. For a fillet seam which is always tracked properly due to the seam tracking, less that 1 mm³ of zinc vapour will be present in this specific example due to better venting (degassing). So it is easy to extrapolate from this example: if a 100-m seam is welded and the gap between the sheets is varying between 0 and 50 microns, then approx. 7,000 mm³ of splashing will occur when welding square-groove seams without seam tracking. With seam tracking and the change in the weld shape that seam tracking enables, the same example only yields one-seventh of the splashing. It is important to note that such splashes not only stick to the workpiece (thus complicating the cleaning process), but they also stick to the clamping jig and increase facility downtime. As discussed in the previous section, splashing may also occur in the beam direction and settle on the processing optics. Thus they reduce the service life of the safety glass and increase the cited ongoing consumption costs, depending on the processing variant of the remote optics. It is important to note again here that seam tracking is mandatory for this fillet seam welding. If this technology is not available or not in use, then inaccuracies at the facility level dictate that the laser beam be focussed on the upper sheet. Thus there is a combination of fillet seam and square-groove seam, or a pure square-groove seam, which results in increase splashing contamination. Real-world experience has shown that highly productive manufacturing facilities that have changed over from fillet seam to square-groove (I) seam without any degassing measures have been hindered by the unexpectedly high cost of consumables. The only possible solution in this case was a costly redesign of the workpieces and a change in the components delivered from the supplier. Figure 5 shows a microscopic image of a cross-section of a fillet seam and a square-groove seam at a lap joint.

Figure 5: Left microsection: Fillet-seam welding of galvanized sheet steel with seam tracking
Right microsection: Square-groove-seam welding of galvanized sheet steel without seam tracking [7]

What is required to implement this seam tracking? A well-functioning solution from real-world practice is based on a laser stripe sensor positioned in front of the laser beam which continuously detects the butt joint. The laser beam is deflected precisely on the joint's location, regardless of the robot path in the working field. A defined lateral dis-
tance to the joint can also be taken into consideration, for example, to always weld adja-
cent to the butt joint. So inaccurate robot programming or workpiece tolerances become
more manageable. Fillet seams can thus be reliably welded using remote technology.
This is a cost-effective solution that offers weight loss (from thinner flanges), reduced
defect rate, and reduced costs for safety glass, component washing, and equipment
cleaning.

The beam oscillation package – a gap-bridging example

When joining the weld, a need for gap bridging can already be seen starting at a height
offset of $h = 0.2$ mm between two workpieces (refer to DIN EN ISO 13919). Up to this
offset size, a stable laser joining process can be carried out without any parameter ad-
justments.

![Diagram](image)

Figure 6: Defining the height offset between two workpieces

Since welded joint are often designed beyond their rated values (and since properties
other than strength, such as density, are also critical), it is advantageous to bridge larger
gaps during laser welding. This topic is now even more important with the increased use
of high-strength and ultra-high-strength steels. Their characteristics can vary – for ex-
ample, varying spring-back behaviours after the forming process [1]. After several tol-
erances are added together, there can be a height offset of up to $h = 1$ mm. There are
different approaches towards dealing with such localized problems: including the use of
additional materials [2] or melting a "top sheet" without the use of additional material [3].
The state-of-the-art method is gap bridging using a filler wire; this method already
enjoys wide use [6]. During remote processing with a deflected laser beam, the use of
filler wire, however, is hardly possible due to technical constraints. Thus the material re-
quired to bridge the height offset/gap must be precisely melted from the top sheet.

Technically, the laser strip process (as described in use for the seam tracking) can also
be used for quantitative determination of the height offset. Thus, the laser beam is posi-
tioned on the top sheet and, using beam oscillation, material from the top sheet can be
melted and transported down towards the lower sheet. The option then is to create more
or less of this melted material.

How does it work exactly? The laser beam oscillation is characterized by a one- or two-
dimensional oscillating motion which is superimposed on the welding direction. This then
allows the oscillation amplitude to be changed so that the molten pool width can be
adapted to the particular gap situation. The intensity profile stays the same, and the re-
sulting process effects are considered to be one-dimensionally controlled.
As a supplement to this process, it is advantageous to choose a welding spot size that is slightly smaller than that used by conventional laser welding. Thus we see that the energy efficiency increases with respect to the amount of energy used to form the molten pool. According to [4], an increasing total absorption capacity is responsible for this.

Figure 7 illustrates a welding result that takes into account the combined process variants of seam tracking and beam oscillation, using the example of fillet welding of galvanized sheets. The result was achieved using a Trumpf 5-kW disk laser, a 100-micron fibre optic cable and welding optics for remote laser welding with seam tracking and an option and the local beam modulation ("Scansonnic RLW-A").

Figure 7: Cross-section of a weld seam on galvanized sheets, welded without filler material with beam oscillation and seam tracking; bridging gaps of up to $0.75 \times d_{08}$ (compare with Figure 6).

Thus local beam oscillation following cost-effective advantages:
- The ability to bridge gaps without a filler material
- More splash reduction, and reduction of ongoing costs for safety glass and cross-jet

**The outlook**

The economic potential and cost benefits of this system- and process-based technology for seam-tracked, remote-guided laser welding with beam modulation have not yet been fully exploited. Scansonnic MI GmbH is continuing to innovate technology for systems for laser welding. Figure 8 shows the underlying RLW-A processing head.
Figure 8: The RLW-A processing head with optical seam tracking and the beam oscillation option
Scansonic's in-house Laser Application Center is conducting further research in the areas of seam smoothing without the use of process gas, defined welding depth control and quality monitoring. Furthermore, parameter studies are investigating how to use process control strategies to automatically address certain starting situations (gaps, etc.).

**Literature, References**


