THE DEFINITIVE GUIDE TO AUTOMATION

For Welding and Metal Fabrication

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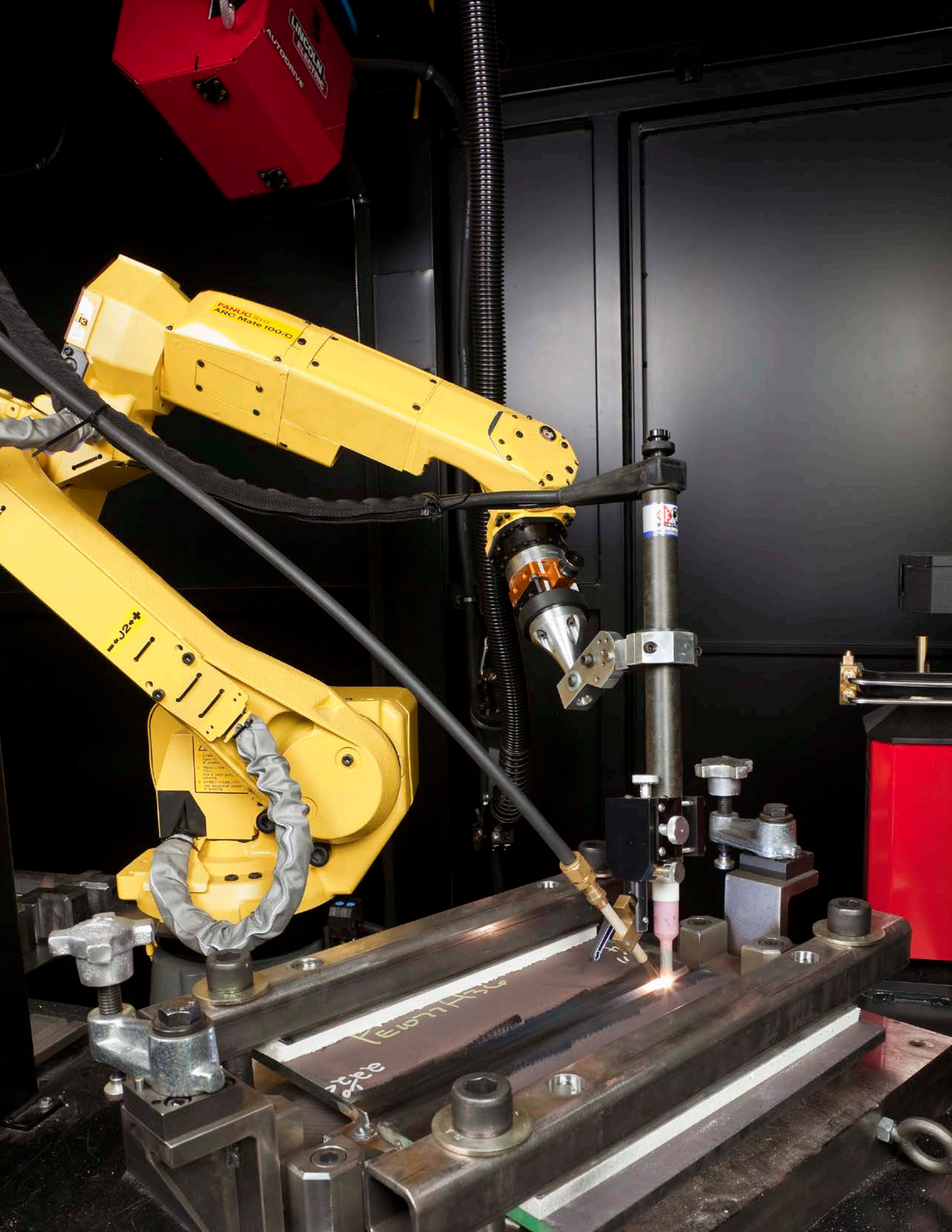
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Welding Automation
The Big Picture

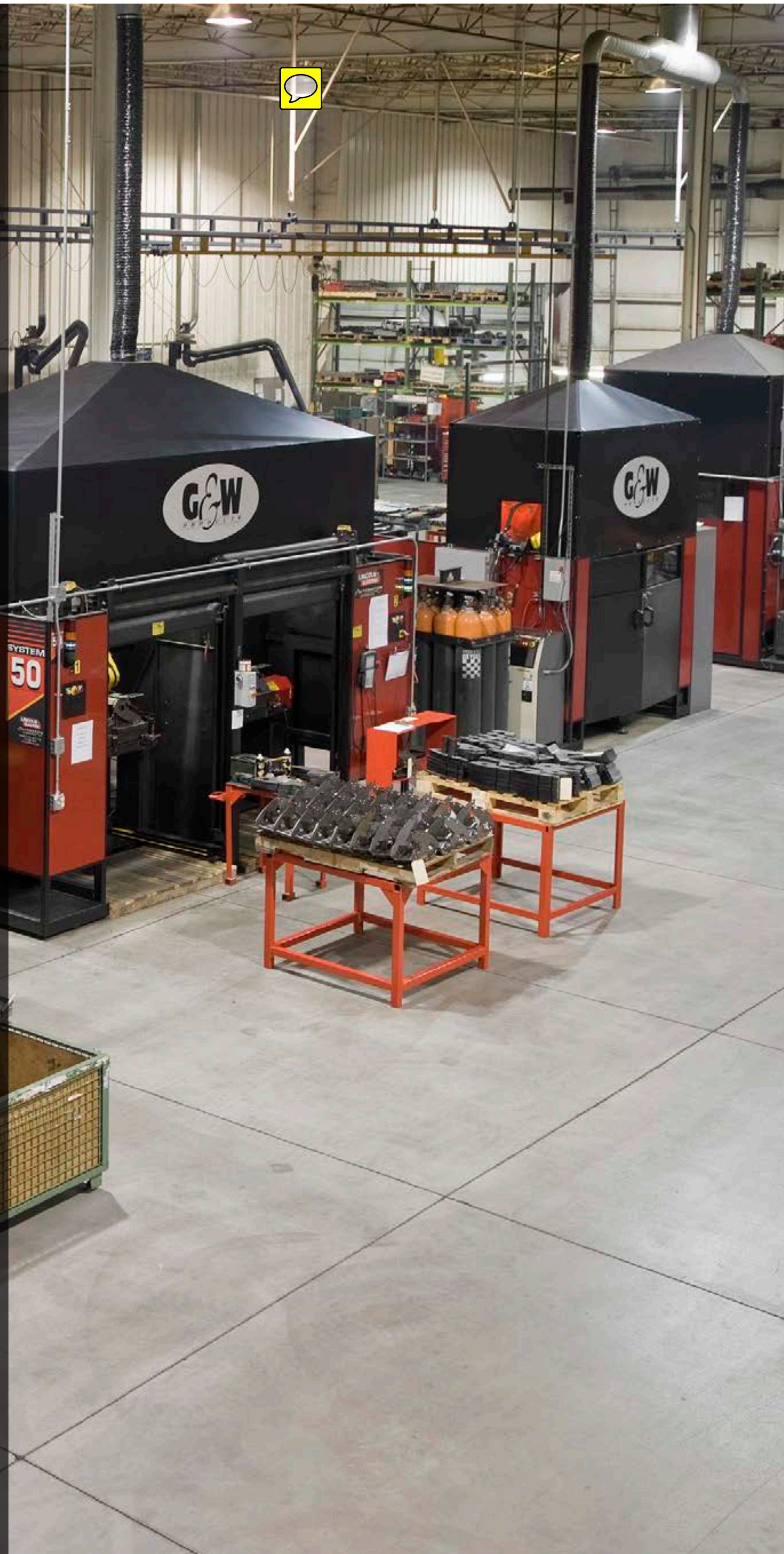
Did your machine shop look at welding automation in the 90's and decide that the payback wasn't there? Or, if you're currently automated, do you think that you've achieved every efficiency possible? It may be time to revisit those decisions.

Competition is fierce and global in manufacturing today, so now more than ever it's about a competitive edge. Exceeding quality goals and manufacturing deadlines is key to keeping your current customers and impressing the next ones. One sure way to improve productivity is to incorporate newer, more efficient technology into your production line. But for that kind of capital investment, the ROI has to be short term and clear-cut.

The good news is that major advances have been made in welding automation. There are now many more options available to create efficiencies on the line. What was not a viable investment thirty years ago could now be profitable in the short term. It may be time to consider whether the latest welding automation can be a fit for your plant.

The purpose of this publication is to guide you through that decision-making process. It will review all the latest technology in the welding automation field and serve as a technical reference. It will also address the business case to be made for the move to automation and provide practical ROI information.

When making a major manufacturing change, it makes sense to review your entire manufacturing process for potential efficiencies. You can no longer replace one item from column A with a new and improved item from column B and expect the best outcome. And you can't assume a bottlenecked manual process will automatically work when automated. You may need to upgrade upstream or downstream elements of the line to really get the payback you're looking for. It helps to work with a partner that can present a big picture vision for your upgrade and provide solutions for every part of that picture. This publication will review other cutting and fabrication innovations for the metalworking shop that have the potential to amplify ROI.



What is Welding Automation?

Welding is considered automated when part of the process is mechanized. It is considered completely automated when robots manage the entire process from start to finish, handling the part and executing the weld.

Robotic welding is commonly used in arc welding, gas welding, laser welding, and resistance spot, and can be effective with GMAW, GTAW and PAW welding. It has long been used in auto manufacturing, and is now routinely used in the manufacture of other durable goods such as appliances and furniture. Robot arc welding now represents more than 40% of all industrial robot applications and remains the fastest growing segment of the robotics industry.[1]

The major components of robotic arc welding are the mechanical unit that is used to manipulate materials and welding equipment and the programmable command unit that directs the robot's actions. The robot may weld from a pre-programmed position, be guided by machine vision, or by a combination of the two methods.[2]

Workflow can be customized, but there are two basic configurations:

1.) the robot handles the welding gun, and is positioned facing the static part and

2.) the robot handles the part facing a static welding gun

There are two commonly used types of industrial welding robots: rectilinear robots and articulating robots. Rectilinear robots can move linearly in any of three axes at right angles to each other (X, Y, Z) There is also a wrist attached to the robot to allow rotational movement. The working zone of this type of robot is limited to a box shaped zone.

Articulating robots employ arms and rotating joints. These robots move more like a human arm with a rotating wrist at the end. This creates an irregularly shaped and therefore more flexible working zone.

Welding robots today have much greater flexibility than they did thirty years ago. They can perform the same task all shift long, on every shift. Or, they can be programmed to weld multiple parts over the course of a shift. The robotic arm can also be fitted with a tool dock alongside the welding gun that allows for different functions at the end of the arm. For example, when the robot isn't welding it can be programmed to move parts with a gripping component so it isn't sitting idle. Vision systems are available that can monitor the part fit, weld placement and condition of the welds to ensure optimum quality and performance.

There are many other mechanized welding systems where certain parts of the process are automated but robots are not involved. In these applications, only a portion of the overall process is automated and human operators perform the remaining part. One example is orbital welding, which is used to construct large diameter tubes and pipes. These automated processes are used when parts are large or heavy or when the area to be welded cannot be reached easily, such as in work with wind towers and pressure vessels.

Optimizing the Factory Floor, End-to-End

There are productivity gains to be made with robotic automation, but it is not the only component of the production line. There are mechanized solutions for the non-welding portions of the production process such as cutting, bending and fabricating. A common oversight when making an upgrade is focusing too closely on improvements to the actual welding process and overlooking the potential to gain efficiencies in other parts of the line. Step back and take in the big picture — consider replacing other manual or bottlenecked processes when considering a modification of the line. Optimum product preparation means fewer part variations and more consistent fit-up, and as a result, greater weld accuracy. Here are some areas where there may be room for automation:

- Part holding (tooling and fixturing)
- Milling areas
  - Plasma cutting
  - Routing
  - Drilling
  - Engraving
- Servo transfer area
- Pipe and tube areas
  - Cutting
  - Bending
  - Fabricating
- Hydroforming area
- Press automation

A time or efficiency analysis of your production line can reveal potential areas for improvement. A full service vendor/partner can assist you with an overall plant review.

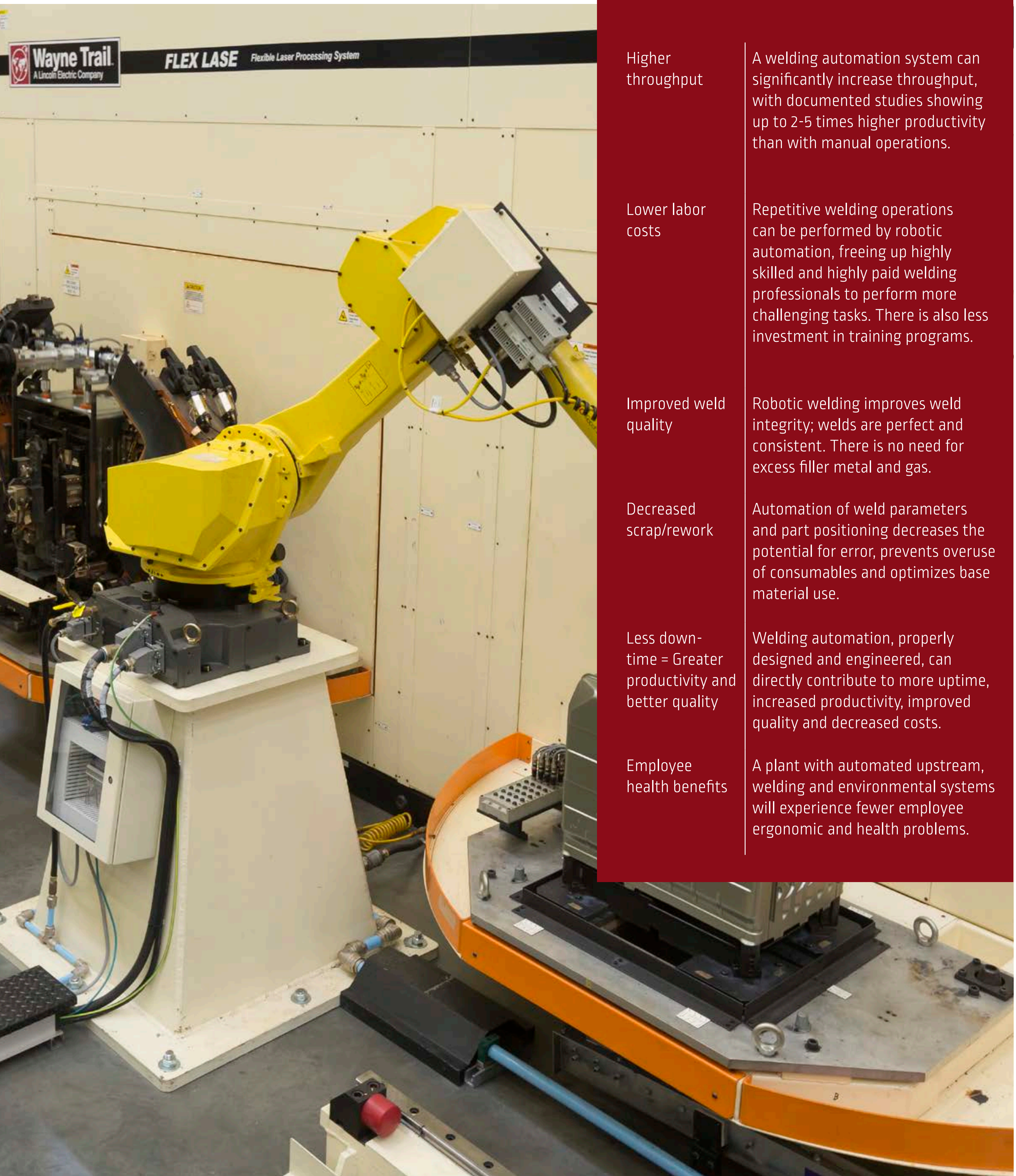
Some questions to ask when evaluating production process efficiencies:

- How does the material flow through the shop?
- Do some parts require more than one cutting operation?
- Are you moving the part to perform multiple cutting operations?
- Is all cutting prefabricated where possible?

How can welding automation help my company?

The key features of welding automation – precision, accuracy and repeatability – can create real value for metalworking operations.

Higher throughput	A welding automation system can significantly increase throughput, with documented studies showing up to 2-5 times higher productivity than with manual operations.
Lower labor costs	Repetitive welding operations can be performed by robotic automation, freeing up highly skilled and highly paid welding professionals to perform more challenging tasks. There is also less investment in training programs.
Improved weld quality	Robotic welding improves weld integrity; welds are perfect and consistent. There is no need for excess filler metal and gas.
Decreased scrap/rework	Automation of weld parameters and part positioning decreases the potential for error, prevents overuse of consumables and optimizes base material use.
Less down-time = Greater productivity and better quality	Welding automation, properly designed and engineered, can directly contribute to more uptime, increased productivity, improved quality and decreased costs.
Employee health benefits	A plant with automated upstream, welding and environmental systems will experience fewer employee ergonomic and health problems.



Myths About Automation

1. It takes a “rocket scientist” to program a robot

   Programming a robot today is very simple. A worker can learn to program a robot in two days, thanks to the simple interactive screen on the pendant.

2. Only high-quantity production runs justify installing a robotic welding cell

   It is not necessary to dedicate a robot to a single task such as making only one part. With the number of welding parts programs that can be stored in a robot control unit’s memory, it is possible to go from one part to another part very quickly if the tooling nests are properly designed for quick change. Several different parts can be made in the same welding cell in a given day.

3. Installing a robot will solve all welding quality problems

   No robot can solve a welding quality problem all by itself. If the parts are not designed or made properly, or the welding joints are not properly prepared or presented to the robot, there will be problems with quality.

4. The robot operator must be a highly trained, skilled and compensated employee

   Becoming a highly skilled welder takes years of experience, training and practice, whereas a robotic welding cell operator requires far less training. Operator training would include loading and unloading the part, operating the system, programming the system for changes and safety issues.

5. Robotic welding cells are very expensive and difficult to cost justify

   Just like personal computers and other maturing technologies, the actual dollar cost of a robotic welding cell has dropped dramatically in the past ten years. During the same period software capabilities, programming ease, motion speed and accuracy of robots for welding have all been enhanced. The upshot of this is that for a much lower cost, a robotic welding cell now offers far superior performance.

6. A robot can weld any part that can be welded manually or semi-automatically

   It is not true that a robot can weld any part that can be welded manually or semiautomatically. Clamping requirements, access problems or specific positioning requirements may make use of a robotic welding cell impossible or impractical.

7. Robots cannot be used to weld very large parts or assemblies

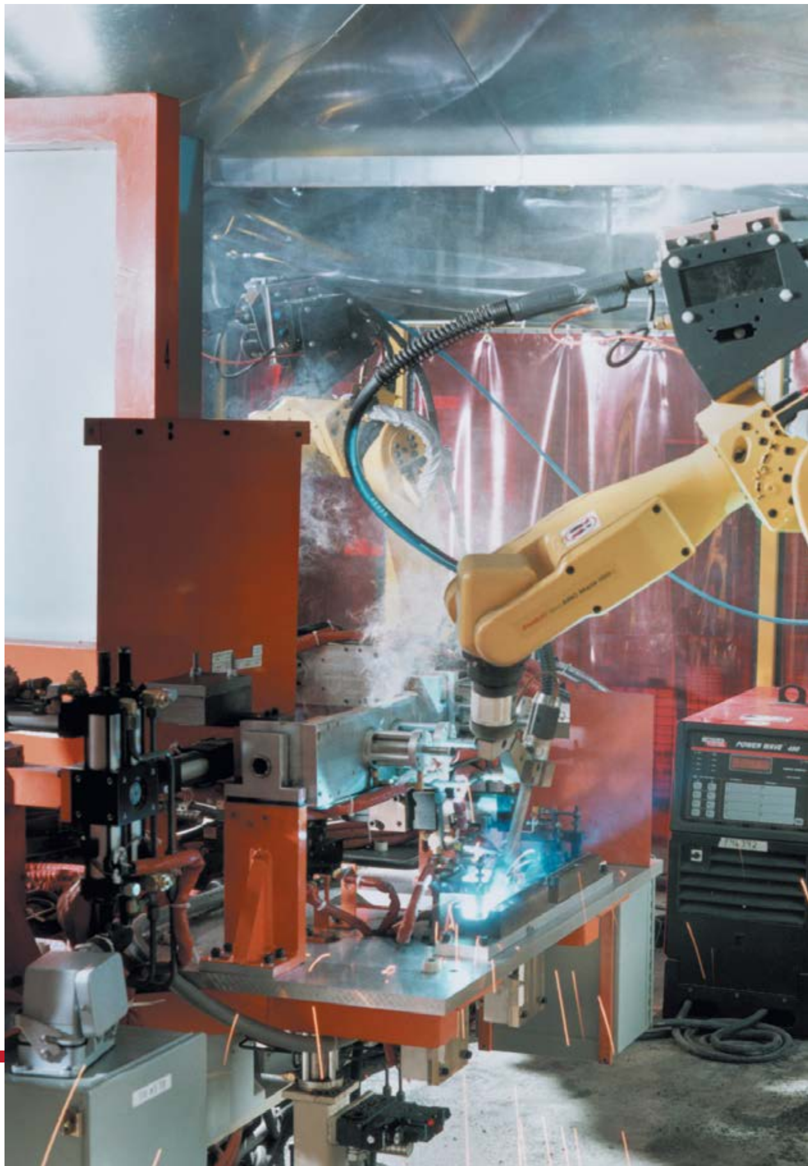
   Robots can be put on tracks or gantries, giving them the ability to weld parts that are 40 to 50 ft. long and 8 or 10 ft. wide.

8. The choice of a specific brand of robotic welding cell will be critical to success

   In most cases, a specific piece of hardware will not be a key success factor. Application expertise, software support and expert part design assistance are critical factors for success in robotic welding applications.

9. Robots eliminate jobs

   A February 2013 International Federation of Robotics research study reports that from 2000-2008 the robotics industry created 8-10 million new jobs, either directly or indirectly or the equivalent of more than 1 million jobs globally per year.[3]



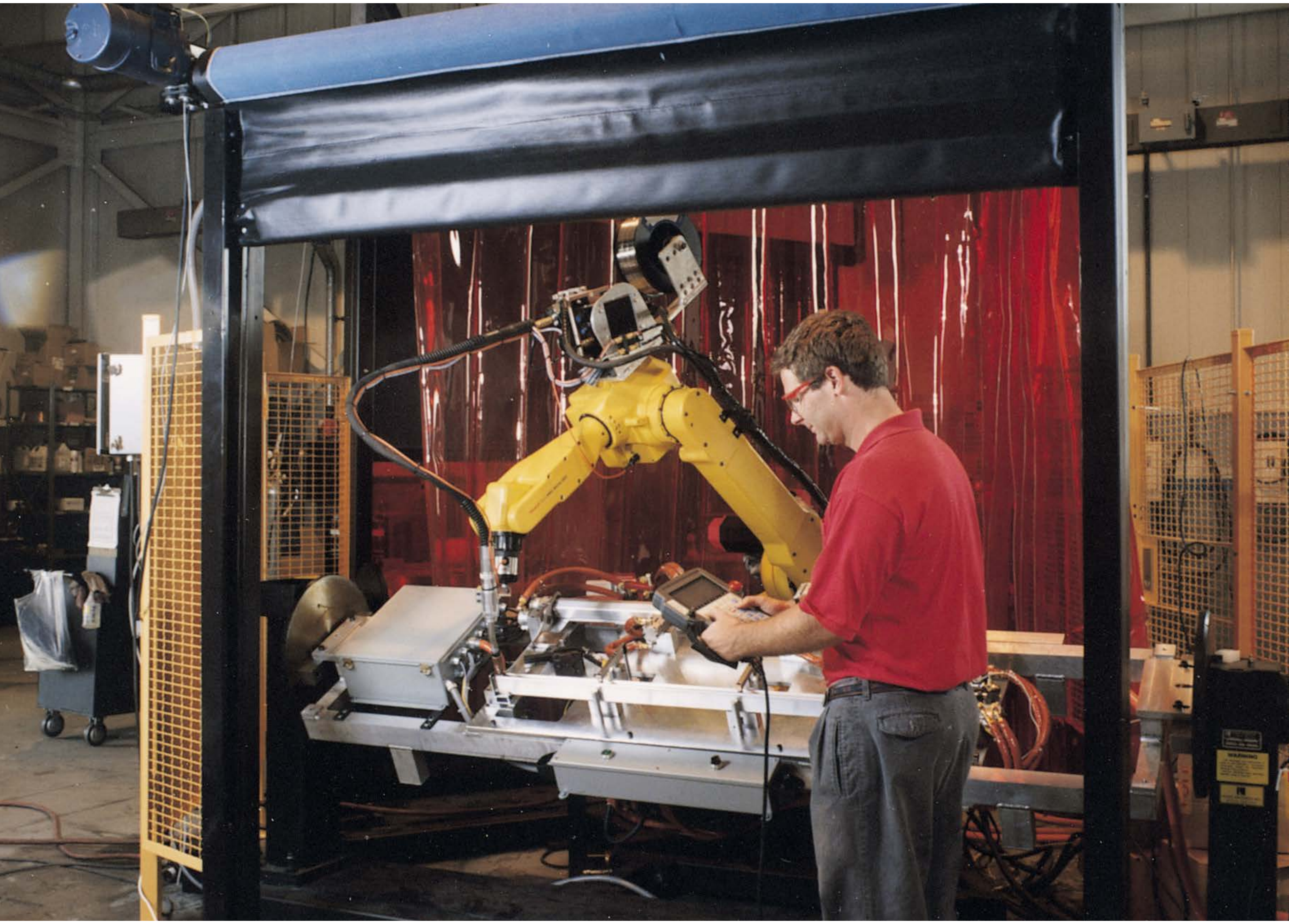
Are You Ready To Automate?

Take this short quiz to determine if welding automation is right for your application.	**Yes**	**No**
1. Is arc welding an integral part of your manufacturing process?		
2. Do the metals you're working with lend themselves to automation?		
3. Are you welding parts that are dimensionally repeatable?		
4. Are you welding complex sub-assemblies?		
5. Are you welding large or fixed materials?		
6. Are your welding fixtures capable of holding the component parts in the same place for welding each time?		
7. Are you producing custom parts in small runs?		
8. Are your welders having difficulty welding thin materials without burnthrough?		
9. Is there an issue with the joining process?		
10. Do you want to increase output?		
11. Do you want tconsistent quality?		
12. Do you have difficulty hiring qualified welders?		
13. When you hire qualified welders, does their pay rate have a negative impact on your profits?		
14. Are your labor costs increasing faster than the inflation rate?		
15. Are your training costs increasing?		
16. Are you concerned about efficiency and scalability?		
17. Are you experiencing quality issues that are affecting customer relationships?		
18. Are you experiencing cost pressures from your customers?		
19. Do you have a budget for the project?		
20. Are your competitors installing arc welding robots or other programmable welding systems?		

If you've answered YES to any of the questions above, adding welding automation to your plant floor could offer significant benefits over your current welding process.

The New Landscape in Automated Welding

In the past, welding automation systems were considered only for long-run and large volume applications. The automotive industry is an example of where robotic technology has long been a fit; images of robotic arms on the auto production floor have in fact become a symbol of modern, high tech manufacturing. But much about automation has radically changed since it was first introduced, making welding automation an option for the smaller shop and making efficiency upgrades feasible for already high tech automotive plants.



Big Gains Now Possible for Smaller Shops

To be considered for automation, the manual welding operation must be a repeatable process with relatively precise tolerances built into the parts to be welded. When robot welding was first introduced, the robot could perform only one operation and the tolerances were strict. Investment costs were relatively high, installation typically required special fixtures or work stations and sophisticated programming was required to support the system. All of these prerequisites put robotic systems outside the reach of the typical fabrication shop. Today's welding automation systems are much less costly, more flexible and more forgiving of part variations. With improvements in technology, small fabrication shops, even assembly lines executing 50-100 welds/shift, are adopting welding automation.

- More affordable — The price of a robotic system has been steadily declining since robots were first introduced. Capital investment for a small shop could now be as low as $50K.
- Easier programming — In the past thirty years, the gap between user expertise and robot manufacturer requirements has become less of an obstacle. The average plant worker uses a home computer and therefore is more comfortable with using software. And from the manufacturer's side, programming a welding robot has become much more user-friendly.
- More flexibility — The first welding robots were capable of performing repetitive operations over and over again a million times but required extensive reprogramming if the part size or shape changed. Today's robots can be easily reconfigured to accommodate size or shape variations of a single part or even similar parts. They can also be programmed to vary their mechanical movements. The gripper portion of the robot that handles the part can be changed out to different types of tools and the torch portion is also interchangeable. All of these features make possible automated production of a variety of parts in relatively low volumes.
- More robust communications - Communication across welding power sources, robotic mechanisms and plant monitoring systems is faster and more agile than in the early units, making robotic systems practical for manufacturing operations of any size, even those that may not have a robust technology infrastructure in place.
- Better data tracking and capture - Going from a manual welding operation to an automated system can greatly improve the quantity and quality of data available to plant management. With a robotic operation, data can be continuously collected about the work being performed. The system can also monitor the quality of the welds. All of this information can be networked across the plant floor, plant offices and mobile devices for better analysis and decision-making.
- Modular components or customized installations — Robotic welding systems are now offered in a variety of configurations, from pre-engineered cells to fully customized systems. This flexibility gives smaller shops options, to accommodate tight spaces or a small plant footprint.
- Modular or custom design of your robotic system also allows you the freedom to create a one-of-a-kind, cost-effective solution for your plant, with the options ranging from the robot executing one repeating weld to a more complex scheme, such as the robot making one weld, reorienting the part in the jig and then performing another weld.
- Greater reliability, with long service intervals — Robot welding systems are now known for their reliability, with regular maintenance only at long service intervals.
- One solution to the shortage of skilled welders — Strong growth in the adoption of welding automation by smaller manufacturers can also be tracked to the current challenges in finding skilled welders. While welding training programs are active, the shortage persists. A baseline robotic cell can be a durable workhorse for a smaller plant and can also contribute flexibility in support of future projects.[4]

Incremental Gains Now Possible For Automated Manufacturing

Improvements to robotic welding automation technology also make it possible to increase production line efficiency in an already efficient plant, as in the auto industry. Added automation will continue to keep productivity high and costs low.

- Faster and more accurate drives – Newer robotic systems incorporate faster and more accurate wire and wire feeds for greater productivity and better welds.
- Improved motors and motion controllers – Improvements to motors and motion controllers mean greater robotic system reliability and less maintenance time.
- Greater precision and repeatability – Greater precision and repeatability of the robot arm and welding torch means improved overall part quality and better part appearance. Since a robotic system is not subject to fatigue, the welds are consistent and repeatable for the duration of the run and for as long as needed.
- Waveform technology – In the years since robotic welding was first introduced, waveform technology has improved significantly. A single power unit in a system of automated welding equipment can now produce up to 8 processes and over 80 welding procedures. With the new systems, it is now possible to customize waveform output and manipulate the weld parameters to fit your application and optimize your process, creating efficiencies and potential cost savings. Plants also have more flexibility to change metals used or the design of the welds in their current and future projects.
- Travel speeds – With the newer systems that can customize waveform technology, a plant can make adjustments to their welding procedures that maximize travel speeds while maintaining the integrity of the welds.
- Coated metals/aluminum – With new standards for weight and corrosion resistance, there is increasing demand in automotive manufacturing and other industries for welds on coated sheet metal and aluminum. The newer robotic welding systems can produce optimum waveforms for coated materials and aluminum, executing travel speeds approaching those for uncoated steel.
- Bead appearance/anti-spatter – Robotic welding systems with their customizable waveforms produce welds for both look and function – near perfect in appearance with low spatter – contributing to first time through quality and improved productivity.
- Skills gap – There will simply not be enough skilled manual welders in the foreseeable future to meet the need. Coupled with industry's demand for higher productivity and reduced costs, the drive to automate where possible continues and the market for automated welding remains strong.

Where Are You In Your Automation Journey?

Step Change: Going From Manual Or Semi-Automated Welding To Automation

A small shop must remain nimble and responsive to customers' project timelines in order to thrive. Clearly, a move from a manual, labor intensive operation to an automated system is a step in the direction of greater speed and reliability.

The key to making the change profitable is to match the welding system to the types of jobs and the typical volumes that you usually run. Robots have transitioned from stationary and performing one specific task to mobile and multitasking, with the ability to change in response to monitoring sensors. They are now variable in size and configuration. A small assembly plant can benefit from the flexibility that is now available.

A qualified vendor with knowledge of the current market offerings can assist you in the choice of a system that will be both effective and profitable.

Incremental Change: Currently Automated, Looking For Increased Efficiencies

Advances in both robotics and communications technology have opened up new application opportunities for robotics systems in even the most sophisticated manufacturing plants. Global competition and razor thin margins drive the push for further speed and efficiency, yet with equal or better quality.

- High speed networks, improved computer processing and better digital interfaces allow the seamless flow of information across both the plant and office floor.
- Robotic systems are faster and more reliable than they were thirty years ago.
- Robotic systems may now be able to perform welds in positions or locations that were not possible when automation was first introduced.
- Robotic systems now have the ability to scan their environment with various sensors and then react and control conditions, to keep production running.
- There are efficiencies to be gained looking upstream from the weld: tooling, fixturing, cutting, forming etc.

A qualified consultant with knowledge of the latest technology can assist you in further optimization of your plant.

Building a Solid Foundation – Modeling and Design

Involve the Experts

- Involve experienced welders and managers from within the plant in the planning process for their first-hand, detailed knowledge of plant operations.
- Make an early decision as to the vendor/partner for your project and get them involved from the very beginning of the design phase. Consider the vendor's broad expertise in automated systems, robotic welding implementation and overall experience in metal fabrication. Use their knowledge base of best practices from other projects as a foundation for building your plan.
- Assess the impact of the installation on plant floor operations. Incorporating a robotic cell is a plug and play installation typically taking 7-10 days. A customized installation will require a longer planning and installation timeline. An experienced vendor can help to minimize the impact on your ongoing operations.
- Establish deadlines and budgets and clearly communicate them to the planning and implementation teams.

Process Flow

- Question your current thinking about the part, the assembly process, the weld and the flow through the plant. Can the process be made more efficient? Diagram the process flow from pre-assembly to post-weld Determine how long the current process takes as a baseline for your decision to upgrade.
- Consider alternate floor layouts to optimize space. Ensure that there is enough space to accommodate the robotic welding cell or system on the plant floor.
- Consider all the preliminary assembly steps that are taken before the actual welding operation. Is the process as streamlined as possible? Are there any bottlenecks or inefficiencies in the process?
- With a pre-assembled robotic cell, adequate space for the robotic arm and torch access and angle will be engineered into the design. With a customized system, space must be allowed for movement of the robotic arm and proper angle and access for the torch.

Upstream

- Are the cuts to the part as clean and accurate as possible? The cleaner and more accurate the cut, the better the quality of the weld.
- Could the automation of any upstream cutting or tooling improve efficiency?

The Part

- What are the potential issues in assembling the part? Are there basic welding issues that need to be addressed?
- How well do the parts fit together into the assembly? Are the tolerances as precise as they can be? Could additional upstream tooling contribute to a better result?
- Is the part made of coated steel or aluminum? Consider customized waveforms to ensure that welds have external strength, a good appearance and low internal porosity.
- Do you need a positioner and if so, what kind?
- Determine the robot's welding angle, the orientation of the part in space and the clamping method in order to calculate the robot's working zone. Is a long-reach robot arm necessary? Also, consider that a welded piece may be significantly larger and heavier than the entering piece or pieces. Parts should be able to be loaded and unloaded quickly.
- Design the weld joint for smooth torch access to minimize the possibility of damage to the robot arm, the torch or the part. This will also permit easier programming of the robot weld path.
- Project out "what if" scenarios: What if the current project ends? What if the specs of the part change? What if the materials of construction change?

The Robot Welder

- To determine the type and size of the robotic system needed, consider the tolerance of the parts, and the size and the weight of the part and the assembly. Consider whether a pre-engineered robotic cell will work, or whether a customized installation will work best.
- Consider the welding power source. Is it equipped with the power and flexibility needed to run efficiently to handle current production? Production changes?
- How large will the production lot be? How many parts can be welded with the same setup?
- Consider what impact human operator performance might have on the operation and flow.

The Environment

- What safety issues need to be resolved? The changeover to welding automation may be a good time to ensure that welding fume levels on the plant floor meet all safety standards. It is good practice to take measurements after installation and periodically during startup. Many full-service vendors also offer a complete line of welding safety equipment and fume control devices.

Put It In Writing

- Document the results of your study. The in-house team and the vendor should do a thorough review. Changes should be verified in a printed blueprint, electronic CAD drawing or via a software simulator.

Types of Welding Automation

Basic Elements of Robotic Welding

The Robotic Arm

- There are three types of motion for industrial welding robots:
  1. Jointed: The robot moves from point A to point B on all axes simultaneously
  2. Linear: All six axes move in a straight line from point A to point B, maintaining torch angles
  3. Circular: Three points can be programmed – start, middle and end – that can be joined together to produce a circular motion.

HMI/robot controller

- A Human-Machine Interface (HMI) is a graphic terminal that links the robot system to the human operator. It allows the operator to control, monitor, and collect data from the robot system and can be used to track, troubleshoot, and correct errors.

Tooling/part holding

- Tooling and fixtures, or any part that holds or supports a part during welding, are a critical part of any automation program and should be specified as part of the initial design planning. Robots expect the parts to be welded to be in the same place every time within ±0.005 inch. Well-designed fixtures can reduce fabrication time and improve quality.
- These devices can be used to hold individual pieces while they are being welded together or to hold together an assembly that has been pretacked. In either case, the parts or assembly must be held securely in a fixed position. The hold must be secure enough to withstand the actual robotic welding operation, strong enough not to be moved during the high positioner speeds that occur during loading and unloading, rigid enough to withstand any clamping necessary and so accurate that a consistent operation can be replicated for a long duration.

Positioner

- Robots can weld complicated parts with non-linear shapes or contours by fixturing the part on a rotating positioner. The movements of the positioner and the torch are synchronized by the system during the welding process.
- Enclosure
- With the inherent dangers involved in welding – sparks and fumes generated – any type of welding requires a safety zone around the welding area. Robotic welding adds another safety hazard to the mix with a moving robotic arm. Whether pre-engineered or customized, robotic welding areas are surrounded by an enclosure. The enclosure may or may not include a fume hood for additional safety. Where you might see a fence around a manual welding operation, robotic system enclosures are typically solid metal plates tall enough so that a person cannot reach inside.

Power supply

- The power supply to the automated welding system delivers the electricity, converted to heat, that melts the metal for the weld. Robotic power supplies are sophisticated machines, capable of digital communication with other industrial instruments to create an integrated system. They are flexible enough to produce multiple waveform platforms, in order to support optimal performance for a variety of welding applications.

Wire feeder

- Because process speeds in a robotic system are higher, special dispensing systems are used for automated welding systems that feed bulk packages of wire from a drum or a box to the robotic welding cell. Some of the processes available are wire dispensing arms, mechanical turntables, motorized dispensers and wire feed assists that exert positive pressure on the wire.

Safety considerations

1. Fume control

- There are federal standards in place for air quality in a welding environment. Fume hoods, properly positioned and maintained, can provide air filtration for both fumes and particulate material. Robust, high efficiency hoods are needed for automated welding systems.

2. Operator safeguards

- Safety light screens (also known as safety light curtains) are one type of device used to protect employees from potential harm by robotic welding systems. A safety light screen produces a wall of light that detects an intrusion into a defined welding area. When an object such as an arm or hand breaks the plane of the screen, it stops the machine operation. Safety light screens are reliable and fast to react, even when frequent stops are made. They can take the configuration of a flat plane or an L- or U-shaped configuration and can be programmed to ignore specified objects.
- Safety interlock switches monitor the position of a guard or gate, and they are used to shut off power, control personnel access, and prevent the machine from starting when the guard is open. They can be fixed, adjustable or interlocking. A control system typically indicates the open/closed status of the guard.
- Two-hand control systems are used to prevent accidental starting of the robotic welding system. They consist of two actuating buttons or hand controls and a safety module. When both buttons are actuated within a second, a signal is sent to initiate an action. Two-hand control systems can also be used as part of a system to keep an operator's hands away from the welding operations.
- A number of other controllers can be installed as part of the robotic welding system as safety devices or diagnostic devices to ensure worker safety.5

3. Fire safety

- Fire safety systems are essential in a welding facility and multiple welding robots working simultaneously compounds the need. Systems are available that prevent, detect and suppress fires in the welding, fume extraction and filtration areas.

The Robotic Welding Workflow

- The operator, outside of the active robotic welding zone, turns on the security system or systems, such as the light screen.
- The operator selects the intended work piece or process from the control panel. The first step is standby mode. The robotic arm, turntable and positioner are synchronized and assume positions ready to weld. The shielding gas is ready to flow.
- With standby mode activated, the system runs a check of the operator's input and the robot senses the readiness of the work area.
- With all systems checked, the arc is ignited and the welding process starts.
- During the welding process, the actions of the part and the robotic arm are continually monitored. Welding results are also monitored.
- The welding nozzle is cleaned at pre-determined intervals.
- In many automated systems, the operator removes the finished product from the work area, then installs a new piece and reactivates the system for a new cycle. In a fully automated system, the piece is moved down the line by other robotic parts.

Pre-Engineered Robotic Systems

A pre-engineered robotic cell consists of a table, a robot and torch, a welding power source and a safety enclosure. It is typically shipped as a single, self-contained unit, pre-assembled, with relatively short lead times and short training times. The units are ready to weld with the connection of the power source.

There are variations on the single cell configuration: robotic cells are available with up to 3 robots. There are also two-zone options where the robot welds on one side and an operator handles parts on the other. Other specifications specific to the weld can be modified to suit your application.

The pre-engineered cell is a cost-effective option for a plant automating for the first time, such as the small to mid-size fabricator. The compact, modular design of these cells makes them easy to fit into most smaller plant floors. For manufacturers who may be experiencing the current shortage of skilled welders in the marketplace, the robotic cell can help to bridge that gap. Application support and training is still available for these pre-engineered automated units from experienced firms.

There are also intermediate systems that are still considered pre-engineered, but offer more options. There are accommodations for parts of different sizes and weights, fixed table and turntable options and flexible positioning options to meet any fabrication need.

Custom Robotic Systems

Robotic system design is now customizable to meet the most unique client requirements in each industry sector. Automation systems have evolved, making advanced robotic integration possible for MIG, TIG or spot welding. The systems can flex to accommodate a range of fixturing and tooling, work piece positioning, robot positioning, welding processes, software and programming. Integrating automation into small batch production facilities is no longer an issue.

Here are some examples of customized robotic automation:

- For high speed or high deposition welds, a tandem, dual wire, high-speed GMAW welding process coordinating two separately generated arcs with a single torch
- To automate pipe welding, a one- or two-axis workstation providing shortened cycle times and superior weld quality
- A highly advanced robotic submerged arc welding (SAW) system

Other Mechanized Automation Systems For Welding

Mechanized automation in welding includes processes where mechanical devices are used to move or support the piece while the weld is executed. These mechanical devices can be turning rolls, welding positioners, pipe support stands or sliders. This type of welding is typically used on parts that are flat, large, generally thicker than the norm and/or difficult for a manual welder to reach. The mechanized equipment can be either fixed or programmable.

The economic benefits over manual welding are obvious — increased productivity and reduced costs for both labor and consumables. But there are also additional benefits, including more consistent weld quality and more predictable production rates.

Like robotic welding, mechanized welding requires more accurate part placement and orientation than manual welding, as well as more sophisticated arc movement and control devices.

A subset of mechanized welding is narrow gap welding for heavy wall fabrication. The industries that use narrow gap welding most frequently are the power industry, especially the nuclear power industry, the petrochemical industry and shipbuilding.

The following parameters typically apply to mechanized projects:

- Turning rolls capable of handling items ranging in weight from 1,500 to 30,000 pounds and pipe diameters of up to 15 feet
- Welding positioners capable of handling pieces from 350 to 4,500 pounds
- Pipe support stands capable of supporting up to 3,000 pounds
- Manual and power slides with load capacities up to 750 pounds and strokes of up to 10 inches
- Jaw chucks capable of holding from 1 inch up to 52 inches and over 700 pounds

Orbital Welding Systems

Orbital welding is a specialized welding technique used mainly for welding large pipes or tubes. The welding arc is mechanically rotated 360° around the fixed work piece in a continuous process. Orbital welding is almost always a TIG/GTAW process, and therefore produces a clean and consistent weld bead.

An orbital welding system incorporates all the elements needed to execute the weld -- a power source, welding head, water coolant system, head and track ring, control system and wire feeder. With the controller, the welder can program the weld parameters to the exact needs of the application.

Because orbital welding is automated, the quality of the weld is far superior to what can be achieved manually. Orbital welding can be performed where it would be difficult for a welder to access the back side of pipes.

Because the welder itself changes position during the welding process, a balance must be maintained between gravitational force and surface tension at every position of the torch.

Laser Welding Systems

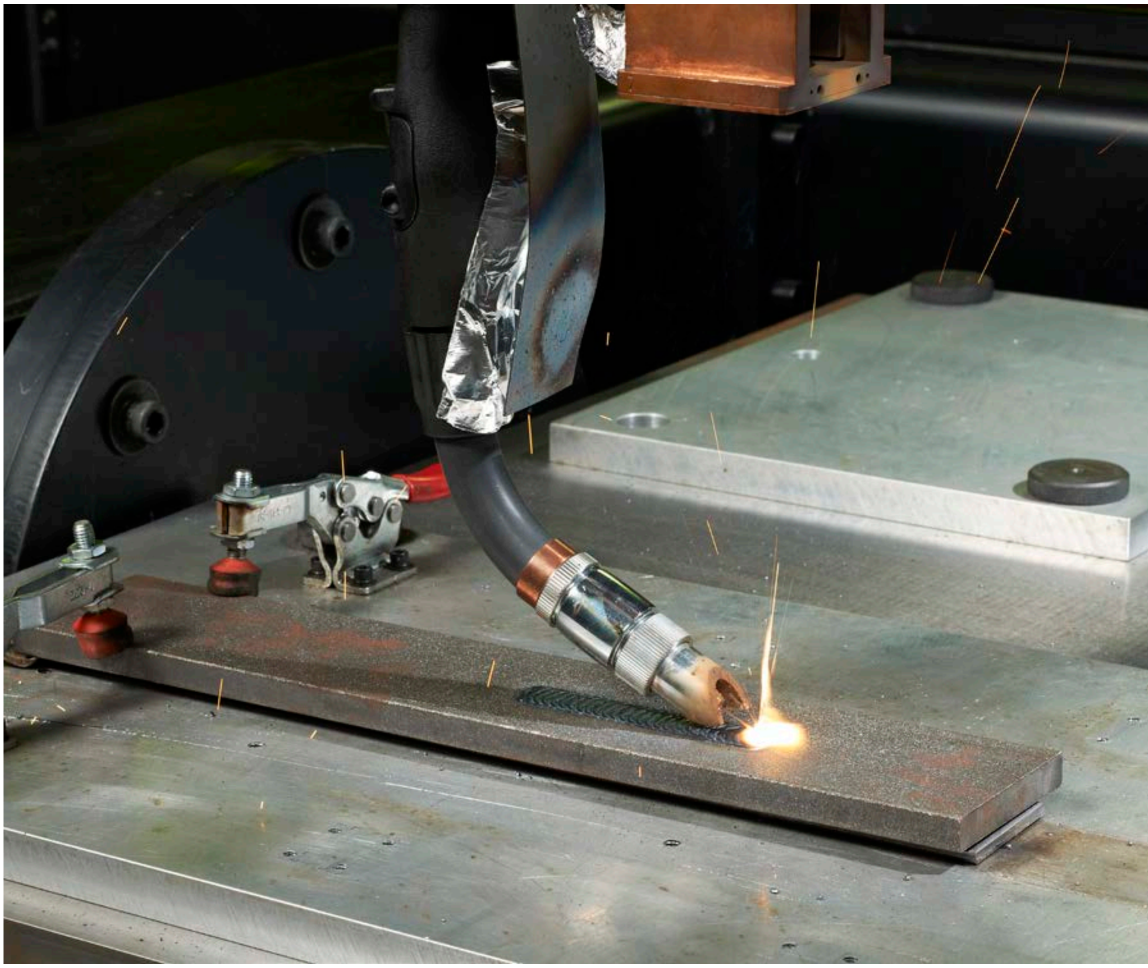
Though the laser welding process was first introduced in the 1980s, it has not been extensively commercialized until recently. Advances in laser power, focus and brightness and a reduction in equipment cost are now making robotic laser welding applications more feasible for industrial applications.

One use of lasers for automated welding is as a hybrid application with the GMAW process, called hybrid laser arc welding (HLAW). HLAW has the potential to be game-changing for industrial automated welding: it perfects the repeatable weld with low internal and external porosity, low spatter and ideal appearance while enabling high travel speeds. Weld penetration depth increases, making welds stronger, but the process is applicable to welding on both thin and thick materials. HLAW is often used for high volume applications or in applications where low heat is important. In some cases, you may be able to make a weld that was not possible because of limitations with the metal inert gas (MIG) process or tungsten inert gas (TIG) process.

There are also non-arc laser hybrid processes. Hybrid laser brazing combines a laser and resistance heating. Resistance raises the temperature of the wire, while the laser brings the brazing alloy to its melting temperature and also heats the substrate. Wetting occurs and the intermetallic bond is formed. This can occur at very high speeds (> 16 feet/minute) and results in joint quality that can be painted over. A number of auto companies are using this process for applications such as truck lids and roof ditch welds.

Another non-arc hybrid process is laser hot wire cladding. As with laser brazing, resistance heating is used in conjunction with a laser. The laser melts a preheated wire and deposits the metal on the surface of the piece. With relatively low heat input, the result is not a weld but a metallurgical bond, executed with high deposition at high travel speeds. The process is useful for corrosion protection, to create wear-resistant materials or for repairs.

Other laser processes used to prep the part for welding will be covered later in this article.



Product Quality: Manual Welding vs. Robotic Automation

Traditional Welding	Product Quality	Robotic Automation
—	Repeatable Weld Accuracy	↑
—	Stronger, more effective welds on all metals	↑
—	Welds with better appearance	↑
—	More consistent output over time	↑
—	Reduced rework and spatter removal	↑

Operational Efficiency: Manual Welding vs. Robotic Automation

Traditional Welding	Operational Efficiency	Robotic Automation
—	2-5x greater throughput	↑
—	Repeatability, to better meet ship dates	↑
—	Welding simultaneously on multiple axes shortens production time	↑
—	Faster changeover time/less downtime	↑
—	Process can be tracked for better accountability	↑

Improving Automation Efficiency Upstream – Product Prep and Shop Prep

The robotic welding line is often the primary focus and the ancillary processes an afterthought. In fact, high quality operations in the machining areas used to prep the part can be a key factor in achieving more productivity. Automation of the pre-production area is one key to staying competitive in your industry and the benefits are immediate and measurable. A technical integrator or manufacturer with experience in automated solutions for the entire factory floor can offer advice on state-of-the-art, pre-production technology and the best investments for your plant. They can also assist with eliminating bottlenecks and inefficiencies, propose alternative floor layouts and study timing to increase product throughput.

- Conversion to automation can ensure that pre-production quality and productivity remains high. Automation ensures consistent tooling over time.
- If your plant is considering shorter part runs than in the past, the conversion to automation can be a benefit. Automation software can be reprogrammed easily and in a short period of time, without the need for expert assistance.
- Human resources considerations favor conversion to automated processes. Issues of operator fatigue and safety come into play for many of the repetitive motions involved in these pre-production steps.
- When a process is upgraded to automation, more data is available for analysis. Installed software can identify bottlenecks, measure daily production rates and time tooling change outs so that the project team can use the reporting information to improve efficiency.

Tooling and Fixturing

Tooling refers to the various machining methods used to prepare a part for production. Fixturing is the holding or support device that keeps the part securely in a location or an orientation so that the next operation can be performed. Often a part also needs to be manipulated in some way as a preparation step.

If managed well, these first steps in the production process can make a significant contribution to overall productivity. To execute strong automated welds, the parts to be welded must be built to exacting specifications and positioned with close tolerances. And to execute those strong welds over and over and over again, the work pieces to be welded must remain in a stable position as they progress through the system.

Tooling and fixturing is customized to the job or production line. Just like with robotic automation, many steps put into place decades ago can now be made more efficient using more advanced machines. Tooling machines today utilize computers and tailored software and take instruction from engineering drawings. There are also multiple process machines that can streamline product prep.

High quality fixtures, such as clamping and holding devices, offer better durability and reliability over time and can prevent rework issues. Investment in the highest quality possible pre-production machinery can pay off in terms of precision results down the line.

Cutting Systems Plate, Pipe and Structural Steel

Metal enters the fabrication or assembly process as plate, pipe or a structural steel member and from there is subjected to machining steps to prepare the piece for welding and other finishing. One universal tooling process is cutting. The cutting process varies depending on the metal, and the size, shape and complexity of the finished piece. Today's advanced cutting methods include plasma cutting, oxy fuel cutting, laser cutting and all-in-one machine prep systems. Automated cutting machines can increase the power, speed and accuracy of your cutting operations.

CNC cutting for plate

Plasma cutting is generally used for cutting plate up to ¾ in. thick. The method can deliver high-definition and dross-free cuts. In plasma cutting, a gas such as oxygen is blown through a nozzle at high speed, while concurrently an electrical arc is generated from the nozzle to the surface of the piece. A portion of the gas is converted to a plasma that is hot enough to cut metal. Computer software controls the process for accuracy and control. Plasma cutters vary in size and amperage depending on the application. They can be packaged in a table configuration and other processes can be included with it, such as an oxy fuel torch or a torch height control system.

Oxygen-acetylene (and similar fuel) flame cutting, is commonly used for general cutting and edge preparation operations, such as coping, beveling and notching.

CNC pipe cutting for pipe or tube

Pipe and tube cutting machines cut using either plasma or oxy fuel. Machines are typically customized to an application, including adjustments for tube diameter and possible consolidation of both measuring and cutting. The cutting machines operate with servo-driven rollers that fully support and rotate the pipe during cutting. A lifter conveyor auto loads and unloads the part. Automatic adjustments are made for out of round parts. The cutting function can also be a robotic operation in a pre-production line. This type of system condenses the process of layout, material loading and cutting into one automated step.

Some of the industries where CNC pipe cutting can be useful are electric power generation, shipbuilding and offshore rigs, for such applications as pressure vessel manufacturing, process piping, structural construction and space frame fabrication.

CNC cutting of structural steel

Structural steel members require special heavy-duty cutting machines because of the size and weight of the pieces. The larger structural members are difficult to cut but may be even more difficult to move around the shop floor, especially when more than one type of cut or type of operation is needed.

Some robotic structural steel fabricating systems can perform cutting, drilling, punching, sawing and hand torching simultaneously, or in one pass or in quick succession on one machine. These plasma cutting systems use advanced software to direct the operations. This kind of multitasking machine can be particularly useful with large parts and can reduce the overall pre-production footprint, processing time and fabrication costs.

Hydroforming Automation, Pre-Hydroforming, Post-Hydroforming

Hydroforming is another widely used tooling operation. Hydroforming is an operation where hydraulic fluid under high pressure presses material into a die. It is particularly useful in forming complex shapes, such as automotive parts. Strong, high-quality parts can be produced, sometimes replacing multiple parts, and costs are reduced.

Automation is also available before and after the press. The automation that takes place prior to the part being placed in the hydroform press is called pre-hydroforming. This area typically includes part debundlers to cut apart bundled tubes, weld seam detectors, tube benders, pre-forming modules, lubrication modules, inspection devices, and a material handling system that moves parts from one module to another. There is also post-hydroforming automation to complete the process, such as shearing equipment to remove seal plugs necessary during hydroforming or to split connected, duplex parts. Mechanical or laser end forming equipment is used to contour cut the ends to ensure proper fit-up with other component parts. Punching, drilling or laser cutting can also be performed at this point in the process. Parts washers are used to remove hydroform fluid and debris. Vision systems throughout the process confirm the tooling steps.

The movement of parts through the stations that was once performed by an overhead transfer system is now being converted to robotic automation. The robotic system can be easily programmed when a part or process changes.

Tube Bending

Tube bending is the term for the processes used to form pipes or tubes. Tube bending is another common pre-production step. Robotic tube bending is available as part of the pre-production process.

Automated tube bending is flexible, permitting multiple bends in multiple directions at varying speeds. Robotic operation of this step is another way of streamlining the process in advance of the welding operation.

Press Automation

Press operations can also be adapted to an automated operation. Servo transfers and automated press systems can further optimize system capabilities and increase output. The servo-based transfer die automation is a modular component and is fully programmable.

Laser Processes: Welding, Cutting, Etching, Cladding, Marking

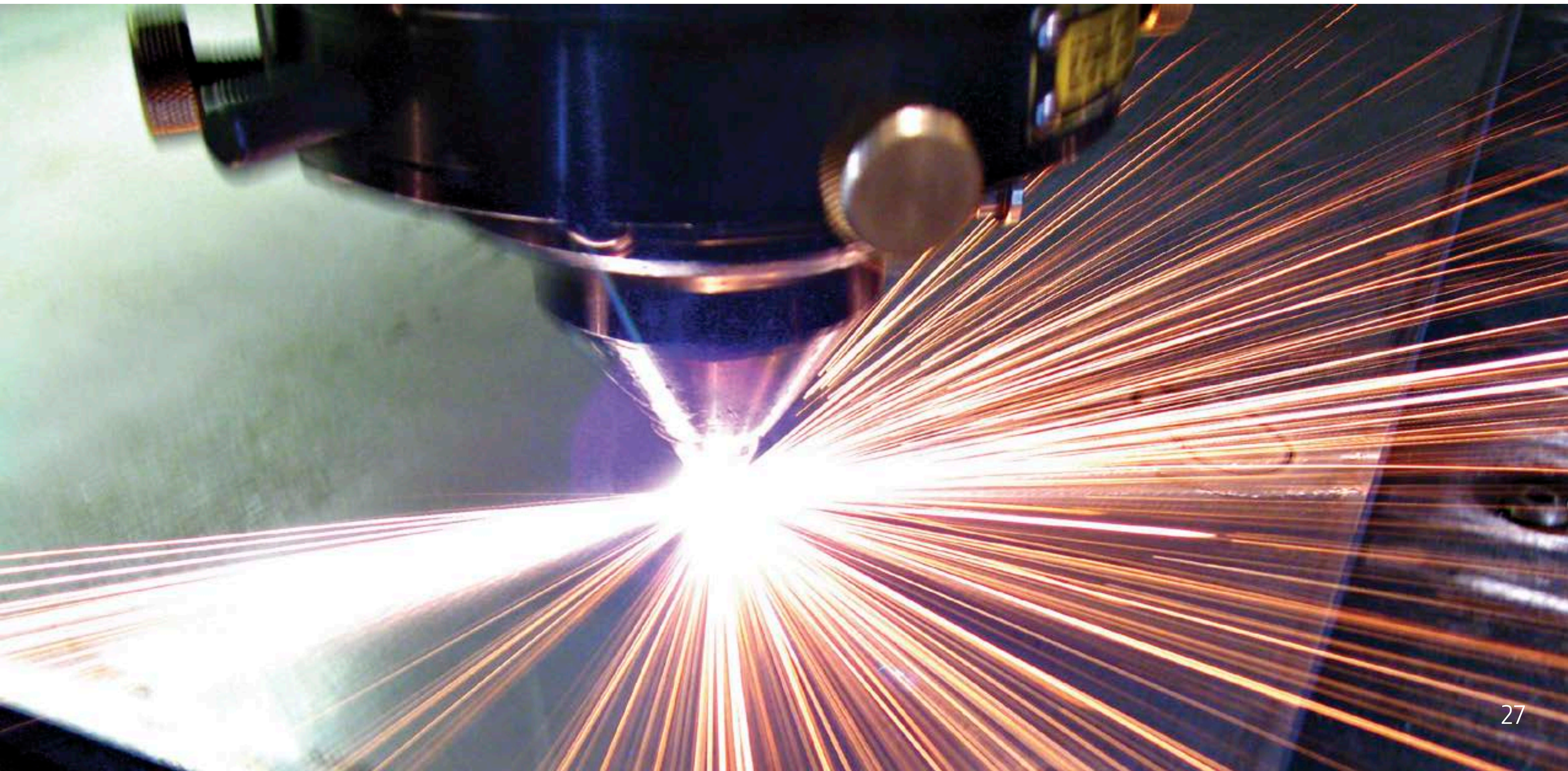
Pre-production industrial laser processes include cutting, etchng, cladding and marking. In these operations, laser optics and CNC are used to direct the output of a high-power laser. Laser cutters are used to cut flat-sheet material as well as piping and structural materials.

One of the greatest advantages to a laser cutter is that it can cut up to thirty times faster than standard sawing. Cutting rate is determined by the power and type of the laser, and the type and thickness of the material. Compared to plasma cutters, lasers are somewhat more precise, but for the thickest materials, lasers are typically not cost effective. Typical industrial laser systems will cut carbon steel metal from 0.51 – 13 mm in thickness.

There are also advantages to not having a hard cutting edge:

- Fixturing is easier as there will be no pressure on the piece from a cutting tool
- There is less likelihood of contamination
- Precision is greater over time as there is no wear to the laser as there would be to a cutting edge
- The material is less likely to warp since the area affected by heat is smaller

There are different types of industrial process lasers identified by the kind of gas used (CO_2, Nd, Nd/YAG) and the speed and type of gas flow. The best choice for your application will depend on the type of work being done and the materials used.



Plant Environment – Fume Control and Fire Detection

Welding and cutting metals are potentially hazardous activities that pose both safety and health risks for plant personnel. Fume control and fire prevention are essential components of a welding automation system.

Fume Control

The process of cutting and welding metals continuously generates airborne contaminants that are released into the plant environment. When heated to extremely high temperatures, welding consumables, base metals and coatings emit gases and particulates. Compounds of antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, lead, manganese, mercury, nickel, selenium, silver, and vanadium are produced. Some of the other gases liberated are carbon monoxide, nitrogen, ozone, phosgene oxides and decomposition products of chlorinated hydrocarbons. All of these fumes pose a health risk to plant personnel. Permissible exposure limits are set by OSHA and other safety organizations such as the American Conference of Government Industrial Hygienists (ACGIH). Thresholds for most contaminants are 1.0 mg/m3 or less.

Standard plant exhaust is typically not strong enough to clean the air to acceptable standards. Manual welding operations may have some fume extraction equipment in place but converting to a robotic welding operation will require additional protection to keep levels of these elements below prescribed limits. Smaller shops with fewer robotic welding cells can probably reach compliance with a less expensive portable fume extraction system. These systems can be moved close to the welding cell and the flexible arm directed toward the robot.

A larger operation with more robotic units using more current emits an even greater volume of hazardous fumes into the air. Larger robotic welding applications will generally employ a centralized fume extraction system. Fume extraction hoods are located over the welding cells and air is pulled through installed ductwork.

Different sizes and configurations of fume control equipment are available to meet the needs of all plants. A consultant or manufacturer can do a comprehensive plant audit, assessing whether the level of fume control currently in place on the plant floor is keeping welding fumes within acceptable limits, or make recommendations for upgrades. Worker exposure level should be checked upon installation and periodically thereafter to be certain it is within applicable limits. A plant screening should also be done when changes are made, such as changes in the metals being cut or welded, the plant layout or the throughput.

Weld fume control is available in models to fit any application, including portable, stationary and engineered units.

Portable

- Light duty, high vacuum systems typically extract 135 cfm
- Low vacuum systems move up to 765 cfm

Stationary

- Compact systems
- Workbench, downdraft systems
- Wall mounted systems
- Modular extraction hoods
- Flexible fume extraction arms

Engineered Systems

- Customized to meet cost and air filtration requirements in any manufacturing environment

Fire Prevention/Detection/Suppression

Welding fires on the floor can be caused by sparks, hot slag or flame from the torch. Any manual or automated welding operation observes basic fire safety such as removing all flammable and volatile material from the welding area and ensuring adequate ventilation. As you automate and increase the number of welding positions on the plant floor, the fume control system is another area where welding sparks and spatter can ignite, and those fires are less likely to be immediately detected. To reduce the risk of fire to its lowest possible level, a complete fire system is needed to prevent, detect and suppress fires in fume control systems.

Prevention: A fire system should be configured to prevent sparks, spatter and dust from reaching any combustible filter cartridge or dustbin debris.

Detection: Early detection is key in any fire system. You should ensure that a fire detection panel is in place that receives signals from temperature, spark and smoke sensors to activate the alarm and fire suppression system.

Suppression: In case of a fire, a fire suppression system should shut off the compressed air supply and release the air from the filter's compressed air tank.

Engineered Line Builds

In the planning phases of an automation project you will have worked with internal and external experts who can predict how it will look, how it will withstand the pre-production process, how the robotic welding line will move and how quickly, and how everything will fit together. It can be helpful to translate those predictions into a close simulation of the line.

There are companies who have the space and equipment to create an engineered line build, or a customized, full-size prototype of your proposed automation. Though typically not to speed, an engineered line build can demonstrate how the system will function and can produce a finished product similar to the result of actual, planned production.

A small investment in a line build while still in the development stages of the project can provide critical feedback to the project team at a time when there's very little cost to make a change. Smaller fabricators may use the line build as a test run or as part of building a business case to present to decision makers.

Choosing A Consultant

Choosing a consulting partner for your automation journey is, arguably, one of the most significant decisions of the process, next to the choice of your equipment supplier. You may find that the same company can fulfill both roles. It is important to work with a company that you can count on for support throughout the implementation of the equipment and for years thereafter.

Knowledge base

It is wise to evaluate both the knowledge base of the company you will be working with as well as that of the team of personnel you'll interact with during planning and implementation. There are some companies who have been a part of robotic welding manufacturing since it was introduced in the 70's who understand the potential of automation as well as the potential traps. A company on the forefront of welding automation can introduce you to the most advanced technology that will not fall into early obsolescence. There are new welding waveform technologies and innovative, new upstream machines that are unique to certain suppliers. Further, the people you will be working with from the vendor should be experienced. Not all companies thoroughly train and vet their field salespeople, who can share their knowledge of best practices in the industry as well as their knowledge of specific equipment.

Vertically integrated provider

There are welding providers in the industry who have become more vertically integrated, having acquired manufacturers of upstream machinery and welding consumables. Depending on what part of your system you are looking to upgrade, there may be value in working with a provider who supplies both upstream and robotic welding equipment. There's a good chance that the upstream and robotic project team will have worked with each other before, and that each knows the other's technology, minimizing the risk for miscommunication and technical errors. Speed of implementation is also a consideration, as the channels of communication will be simplified. There can also be cost considerations with a larger purchase.

Choosing an integrator

An integrator brings component subsystems together as a service offering and may or may not be a manufacturer of any part of the system in their own right. It is important to consider the track record of the integrator, including length and breadth of service with each of the components or in your industry, plus certifications and industry association ties. Just as with a manufacturer, there should be hands-on expertise to establish credibility with the technology. Their service commitment is critical and should be captured in the contract; if a smaller company, consider any other obligations they might have during the same time frame and how close in proximity the company is to your plant. Can they meet your targeted implementation timeline? Do they have the personnel to manage the implementation with minimal downtime? And make certain that the "extras" are in place – spare parts are readily available, training is scheduled for your personnel and safety standards are adhered to stringently. Finally, look to the financial strength and long-term stability of the integrator as a strategic partner.

Detailed System Analysis

Before any plans are drawn, an automation upgrade should begin by working with the vendor to prepare a flow chart of the current system and a detailed analysis of every component of the plant's manufacturing process. Efficiencies and inefficiencies should be clearly identified as well as what inefficiencies can be improved with automation. This may seem like a lengthy exercise but it will establish a baseline for improvements.

Building a Business Case

To prepare a compelling business case for a robotic welding system or automated pre-production process, you will need to examine and assign costs to each step or each part so that you can compare what currently exists vs. what is projected with an upgrade. A vendor, integrator or manufacturer can assist you with the study. They can also help you keep the big picture in mind as you work toward a more efficient overall process.

A thorough cost analysis will take into account a combination of hard costs and indirect costs. For example, material costs make up only 20% of welding fabrication costs. The remaining 80% is made up of associated costs like labor and overhead.

The following chart will assist you as you consider automation for the first time or an upgrade to your plant. Perform this cost analysis for each step of the process or part to be welded and project the total annual savings.

ANNUAL COSTS (PER STEP, PER PART ETC.)	CURRENT ($)	AUTOMATION/ AUTOMATION UPGRADE ($)	SAVINGS ($)
Cost of scrap, repair and rework			
Cost of welder training			
Cost of labor turnover			
Cost of shielding gas			
What is the cycle time (floor-to-floor)?			
What is the fully burdened labor cost?			
Cost of filler metals ($/lb.)			
Cost of floor space ($/sq.ft.)			
Cost of safety products			
Cost of fume removal/ventilation			
Cost of inspection			
Other			
		SAVINGS per STEP/PART	

Savings on Part A/Step A .... $____________

Savings on Part B/Step B .... $____________

Savings on Part C/Step C .... $____________

Savings on Part D/Step D .... $____________

TOTAL ANNUAL SAVINGS .... $____________

COST OF NEW INSTALLED AUTOMATION .... $____________

Payback Period = [Installed Automation System Cost ÷ Total Annual Savings] X 12 = _____months

Return on Investment = Total Annual Savings ÷ Installed Automation System Cost = _________ % [6]

Industries

Automotive/Transportation

The automotive industry has always been on the forefront of welding automation. Manufacturers are now upgrading to robotic systems that are more flexible and have more robust communication capabilities. Some in the industry are also converting to advanced welding waveforms and precision manufactured consumables optimized for robotic welding.

General Fabrication/Maintenance and Repair

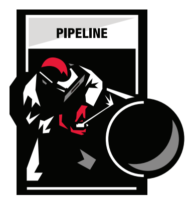
Smaller fabricating shops were not able to take advantage of automation when robotic technology was first introduced due to cost and complexity of operation, but that has changed. Customizable robotic systems, cells and engineered systems, are now available that are cost effective for lower-volume operations. Pre-production tooling that automates repetitive motion operations also makes sense for the smaller shop from the perspectives of both cost and personnel safety.

Heavy Fabrication

Robotic applications for the heavy fabrication industries include the synchronized tandem MIG process. This process coordinates two separate arcs to create a common weld pool, and is suited to heavy duty projects that require deposition of a large volume of metal.

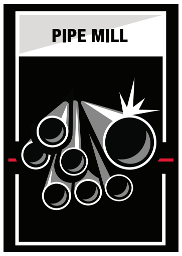
Energy/Offshore

Welding is essential to the construction, maintenance and repair of rigs, platforms, subsea fixtures and supply vessels for offshore drilling and production rigs. Submerged arc welding (SAW) is a robotic application used on rigs to maximize operational speed in challenging offshore environments.



Pipeline

There will always be robust demand for infrastructure repair and new construction in pipeline fabrication. Customized, mechanized pipe welding systems exist for root, fill and cap passes that provide superior results with shortened cycle times over manual operations.



Pipe Mill

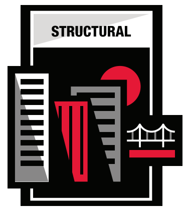
Automation for the pipe mill includes pipe and tube cutting machines via plasma and laser, for diameters of 1 through 12 inches and for one or two axes.

Shipbuilding

There are robotic applications available to the shipbuilding industries, such as narrow gap welding, that improve welding speed and weld effectiveness.

Power Generation

Welding has always been a critical piece of construction, maintenance and repair for all types of power generation – fossil fuel plants, nuclear plants, LNG facilities and wind power structures. Advanced automated techniques like tandem narrow groove SAW speed welding are used for storage tanks and pressure vessels.



Structural

Including robotic welding techniques in structural fabrication can dramatically improve speed of construction and weld quality, and meet even the most stringent seismic standards.

FAQs

Question: What if our product mix or product specs change?

Programming this generation of welding robots is no longer a long, tedious process and the instructions are now very user friendly. Reprogramming to adapt to changing conditions can typically be done in 1-2 hours.

Question: How important is the type of robot?

While it is important to choose a quality robot that meshes well with the rest of your process, the brand or type of robot is not the most critical element of a welding automation system. It is much more important that you work with a company who has expertise in designing and implementing similar systems.

Question: My part can't be welded by a robot – it's too complex.

Clamping requirements, access problems, specific positioning requirements or sheer number of pieces may make the use of robotic welding impossible or impractical, but those situations are now much more uncommon. Robot welding has evolved to the point where robot movement is flexible and robotic system components can accommodate complicated construction. If you haven't visited the issue of automation in 10 years or more, it may be worthwhile to schedule a system audit with a vendor.

Question: What if my plant produces parts of various metals?

Robotic welding systems are now flexible enough to produce quality welds at good travel speeds on parts of different metals. The robot can easily be reprogrammed and the welding system can supply a variety of waveforms to optimize the process.

Question: Where can I get additional information about the latest automation technologies?

Manufacturers will be able to share specific information about their products. Most will encourage a visit to their plant site to view the equipment in operation and to meet the experts.

Question: How long does the implementation process take?

If you choose a pre-engineered robotic welding cell or fabricating machine, time from order to start up can be very short, typically under a month. Custom engineered systems will take somewhat longer, but your manufacturer should be able to meet your implementation time lines.

Question: How do I train my people?

A full service integrator or manufacturer will conduct training for system operators and for supervisors and managers who will have access to system data.

Question: How do I train new operators after the system is in place?

Many manufacturers offer additional training sessions at your facility or at theirs. Training manuals should provide baseline instruction in system operation.

Footnotes

[1] "Industrial Robot Statistics," <http://www.ifr.org/industrial-robots/statistics/> (accessed November 2014).

[2] Cary, Howard B. and Scott C. Helzer, Modern Welding Technology. (Upper Saddle River, New Jersey: Pearson Education, 2005) 316.

[3] "Robotic Welding: Busting the Misconceptions behind This Vital Technology," <http://automation.lincolnelectric.com/robotic-welding-busting-misconceptions-vital-technology/> (accessed November 2014).

[4] Lincoln Electric – Automation Division, "Robotic Welding Keeps Ohio Manufacturer Competitive and Profitable in Tight Economic Times," <http://www.robotics.org/content-detail.cfm/Industrial-Robotics-Case-Studies/Robotic-Welding-Keeps-Ohio-Manufacturer-Competitive-and-Profitable-in-Tight-Economic-Times/content_id/1365> (accessed November 2014).

[5] Mike Carlson, "Safeguarding Against Robotic Welding Hazards," <http://www.thefabricator.com/article/safety/safeguarding-against-robotic-welding-hazards> (accessed November 2014).

[6] "Justifying the Cost of a Robotic Welding System," <http://www.lincolnelectric.com/en-us/support/process-and-theory/Documents/mc04179.pdf> (accessed November 2014).

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