# 4.3 WELDING PROCESSES

The design engineer is often asked to design automotive components that require welded assemblies. The choice of welding joint design, welding process, and the selection of welding procedures can substantially affect the cost and performance of the welded assembly.

This section covers several welding processes that are used for auto body and component manufacturing. A general process comparison chart is presented in Table 4.3-1.

**Table 4.3-1** Process Comparison Chart

| **Welding Process** | **RSW$^{(a)}$** | **RSEW$^{(b)}$** | **Projection Welding** | **Resistance Butt/Flash** | **LBW$^{\copyright}$** | **GMAW$^{(d)}$** | **FCAW$^{(e)}$** |
|---|---|---|---|---|---|---|---|
| Joint design | Overlap flange | Overlap flange | Lap, attachments | Butt | Butt, flange, overlap | Butt, plug, overlap, groove | Butt, fillet, overlap, groove |
| Part fit-up | Some tolerance | Some tolerance | Some tolerance | Wide tolerance | Critical | Wide tolerance | Wide tolerance |
| Filler possible | No | No | No | No | Yes | Yes | Required |
| Material | All steels with and without coatings | All steels with and without coatings | Most steels | Most steels | Most steels | All steels and alloys | Low carbon, alloy, some stainless |
| Thickness (mm) | Min = 0.25<br>Max ≈ 8.0 | Min = 0.25<br>Max ≈ 8.0 | Wide range | Min = 0.75 | All common body gauges | Min = 0.25 | Min = 0.25 |
| Cost of equipment | High | Low to moderate | Low to moderate | Moderate | High | Low | Low |
| Cost per weld | Low | Low | Low | Low | Moderate | Low | Low |
| Quality of weld | Good | Good | Good | Good | Very good | Good | Good |
| Distortion | Some | Moderate | Low | Generally NA | Low | Moderate | Moderate |
| Skill factor | Low | Low | Low | Low | Generally automatic | High | High |

Legend: (a) Resistance spot welding
(b) Resistance seam welding
(c) Laser beam welding
(d) Gas metal arc welding
(e) Flux-cored arc welding

## 4.3.1 RESISTANCE WELDING (RW)

### 4.3.1.1 Process Description

RW processes use the inherent resistance of the components to be attached, combined with very high current flows, to generate heat required for welding. The RW processes encompass a very wide range of technologies, the best known of which include RSW, RSEW, resistance projection welding, etc. All RW systems contain three essential components. These are:

- An electrical system for supplying the currents required for welding
- A force application system to bring the components together under the required pressures for welding
- A cooling system to localize heat within the workpiece and protect the electrode from thermally induced changes.

How the required currents, forces, and cooling are supplied largely defines the differences between these processes.

RW technologies are widely used in sheet metal fabrication industries, especially in the automotive industry. The primary reason is the relatively low cost of joining in high-volume applications. Though the capital costs of RW are high, processing speeds are typically very fast, there are no consumables, no shielding is required, and the processes tend to be extremely robust to the manufacturing environment. Therefore, in view of manufacturing costs, the RW technologies are generally quite advantageous.

#### 4.3.1.1.1 Resistance Spot Welding (RSW)

RSW is the most widely used RW process. The basic configuration for RSW is given in Figure 4.3.1.1.1-1. Typically, the parts to be joined are assembled in a lap-type configuration. Water-cooled electrodes are then brought into contact with the workpieces under high forces. These electrodes serve three functions. First, the electrodes conduct the current into the weld area, facilitating heating. Second, the electrodes apply high force to the welding area, both to stabilize contact resistance (allowing stable current flow and facilitating stable heat generation), and to constrain the growing weld nugget. Although it is not recommended, welding forces have the additional advantage of mitigating the effects of poor fit-up (realistic in auto body welding). Finally, the electrodes provide cooling to the growing weld. This feature thermally drives the growing weld to the center of the stackup, and facilitates proper attachment of the component sheets.

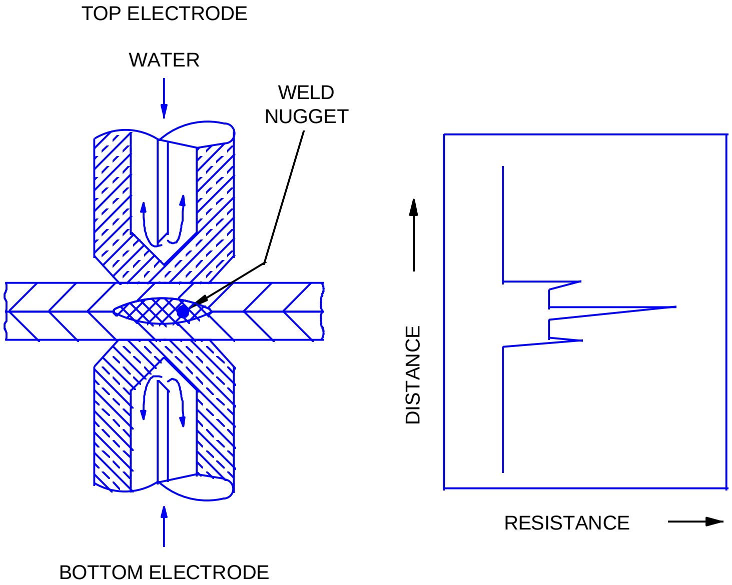

**Figure 4.3.1.1.1-1** Schematic RSW process

The distribution of heat during the spot welding process depends on the resistance elements [electrode/sheet contact resistance, bulk resistances, and sheet/sheet contact resistance(s)] in the stackup. A typical variation in resistances for a stackup of uncoated steels (before the initiation of welding current) is presented in Figure 4.3.1.1.1-1. Typically, the pre-current flow stackup shows high contact resistances at the sheet-sheet and electrode-sheet contact surfaces, with substantially lower resistances in the bulk. As the weld cycle begins, current flow through the contact resistances generates heat, causing contact asperities to collapse and contact resistance to drop. At the same time, bulk resistance increases and continues heating the components until a molten zone (nugget) is formed at the sheet-sheet interface. The temperature at the electrode-sheet interface is controlled by the cooling action of the water-cooled electrodes, effectively concentrating the heating at the sheet-sheet interface, where the nugget ultimately forms.

Numerous organizations and companies have published recommended practices or specifications for RW steels.(1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19) These specifications detail most of the critical requirements for RW, including the process conditions (forces, currents, weld times), electrode geometries, required flange widths, etc. In addition, these documents also detail some basic weld performance information, including weld sizes and mechanical strengths.

Most sheet steels can be welded using relatively simple welding conditions. A typical welding profile includes four time segments: squeeze, weld, hold, and off. The squeeze time is required to allow the mechanical system to supply the required force and come to mechanical equilibrium prior to initiating weld current. The weld time is simply the duration of current flow. The hold time is an allotted period to allow the weld nugget to re-solidify after welding. The off time allows the electrodes to return to home position, and allow any automation to index. Depending on the stackup configuration and equipment employed, RW can be done at rates ranging from 10-60 welds/min. Because optimum welding parameters are different for different substrates, sheet thicknesses, coatings and stackup combinations, they must be varied to suit the material(s) being welded. General guidelines are available through AWS, RWMA, other standards issuing bodies, and the automotive specifications.

When welding high-strength steel, higher heat is needed, dictating larger electrodes. Therefore the weld flanges must be wider than those with mild steels.

Applications for RW cover the myriad of sheet metal fabrication. In automotive applications, body fabrication and assembly accounts for as many as 6000 spot welds per vehicle. Frame and sub-component assemblies also extensively use RSW.

### 4.3.1.1.2 Resistance Seam (RSEW) and Mash Seam Welding (MSEW)

RSEW is a variant of RSW in which copper wheels, rather than single-point copper electrodes are used. RSEW is typically done with similar press-type equipment as used for RSW. The same types of electrical, mechanical, and force and cooling systems are required to accomplish RSEW. Components for joining are oriented in a similar lap configuration. The major difference between seam and spot welding is that current is fired continuously or pulsed through rolling wheels, rather than single-point electrodes.

RSEW is typically done by firing multiple pulses of current as the electrodes roll along the surface of the workpieces. Generally, the duration of the current pulse (typically less than 0.1 sec) is extremely fast relative to the motion of the electrode wheels, so an effective spot is made. The process proceeds, then, as a series of overlapping spots as the wheels move along the surface. Depending on the speed of the wheels and the rate of current pulsing, a number of joint types can be made, as shown schematically in Figure 4.3.1.1.2-1. If the delay between current pulses is relatively long compared with the speed of the welding wheels, the process will produce a series of discrete spots, virtually indistinguishable from a row of spots made with conventional spot welding. This is an extremely high-speed way of creating such rows of spots, and is used extensively where leak-tight joints are not required. An example of this is attachment of roofs onto automobile bodies. If the pulsation frequency is increased relative to the wheel speed, the individual spots will overlap. The use of such overlapping spots is a common way to achieve leak-tight RSEW. Typical applications for this variant of the RSEW process include automobile gasoline tanks and catalytic converters.

A major advantage when using pulsation RSEW for fabricating leak-type joints is that it is quite robust to a range of manufacturing variations. Most notably, minor changes in speed as well as changes in direction can be made while maintaining leak-tight integrity. General guidelines for RSEW are available in a number of the standard references.(4, 5, 8, 19, 20)

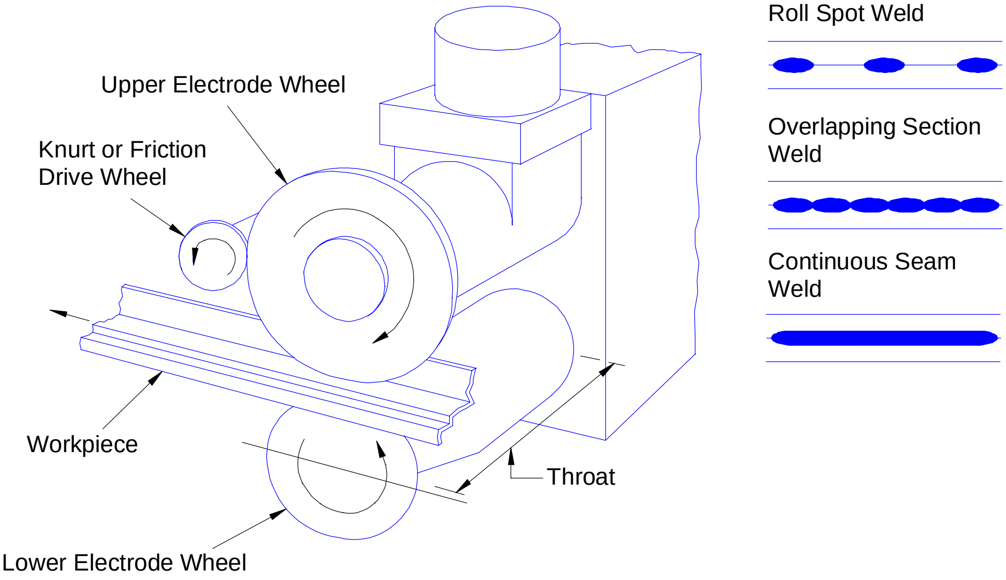

**Figure 4.3.1.1.2-1** Description of RSEW Process

Generally, RSEW operations are conducted with flood cooling, which allows heat to be maintained in a manner similar to RSW. Where water cannot be tolerated, internal cooling of the electrode wheels is also used. In no case, however, should RSEW be done without some cooling.

The mash seam electric welding (MSEW) Process is related to RSEW, and is used to make lap joints that are only slightly thicker than the unwelded sheet. The basic process is illustrated in Figure 4.3.1.1.2-2. Essentially, the parts are overlapped by 0.5 to 1.5 times material thickness. Seam welding wheels are then passed along the joint. The resulting heat allows the joint to collapse under the influence of the welding wheels, consolidating the joint. The resulting joints, if fabricated properly, are solid state in character, with minimal retained buildup in the joint area. Post planishing is sometimes used to make the resulting mashed joint of equal thickness with the base material. The process has been demonstrated to be effective for joining both similar and dissimilar thickness materials.

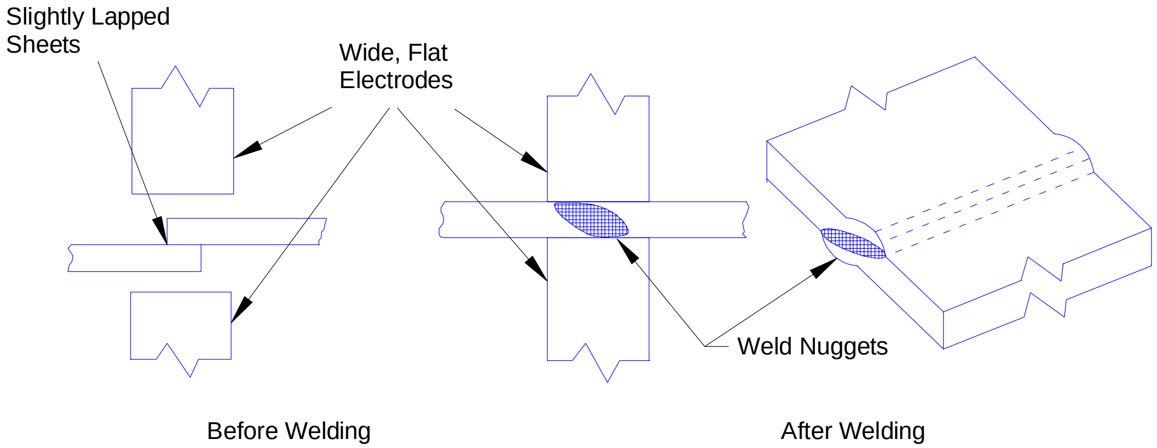

**Figure 4.3.1.1.2-2** Resistance MSEW Process

MSEW is used in a variety of sheet metal fabricating industries. Applications range from materials as thin as 0.1 mm (can applications) to as thick as 3 mm (steel drum and water heater applications). In automotive applications, MSEW is used for tailor-welded blanks. In addition to welding materials of different thicknesses, MSEW is used to weld materials of different strength levels and with different coating types into a single component, where it is very cost competitive. Unlike conventional seam welding, standard practices are not available.

A variant of RSEW, the "electrode wire seam welding" process (sometimes called Soudronic welding), employs an intermediate copper wire electrode between each wheel electrode and the workpiece (see Figure 4.3.1.1.2-3). Using a complex mechanical arrangement, the wire is continuously fed from a spool to a groove in the periphery of each welding wheel to provide a continually renewed electrode surface. This approach prevents the buildup of coating/paint residue from a coated or pre-painted sheet steel, and therefore is well suited to the welding of automotive fuel tanks[20].

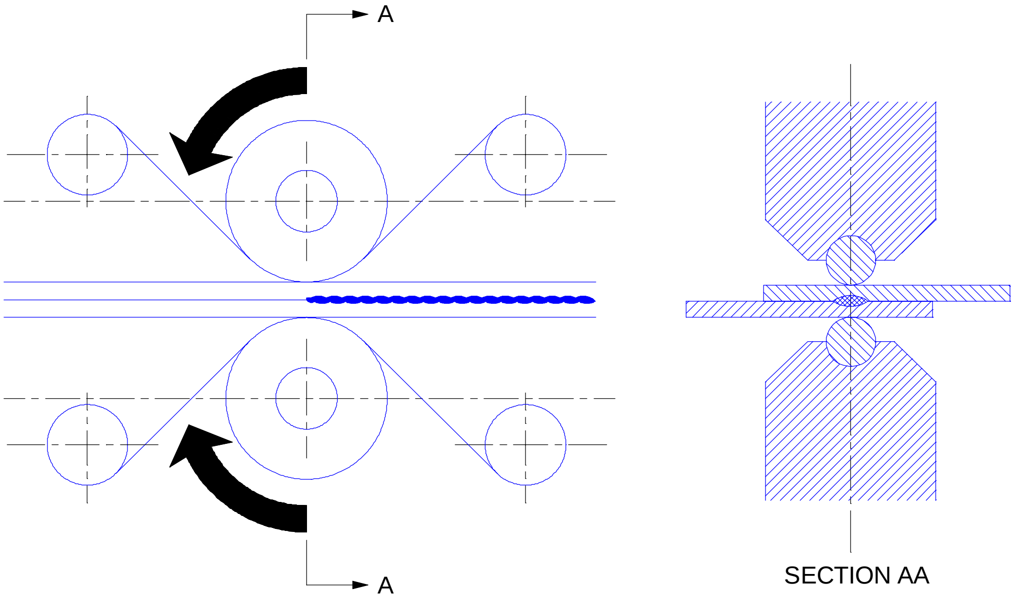

**Figure 4.3.1.1.2-3** Electrode Wire Seam Welding Process

### 4.3.1.1.3 Resistance Projection Welding

Resistance projection welding is another variant of RSW. It is typically used as an alternate process to attach sheet components in a lap configuration, irregular components to sheet, or irregular components to one another. The basic resistance projection welding process is illustrated in Figure 4.3.1.1.3-1. The figure illustrates the sheet-to-sheet or "embossed" projection welding process. A projection is first stamped onto one of the two sheets to be joined. The sheets are then positioned in a lap configuration for joining with standard RW equipment. Welding cycles are similar to those used for RSW. During welding, the projection serves as a point contact between the two sheets to be joined. This point contact acts to focus welding current, and therefore heating, at that location.

The weld development proceeds in two stages. Over the first few cycles, the projection collapses and some solid-state bonding results. With additional weld time, this hot region at the residual projection tip continues to heat, and a nugget similar to a resistance spot weld develops. Embossed projection welding is well described in the recommended practice documents. Recommended practices include projection designs, designs for the stamping tools, welding schedule information, minimum weld size and mechanical properties information.(4, 5, 8, 21, 22)

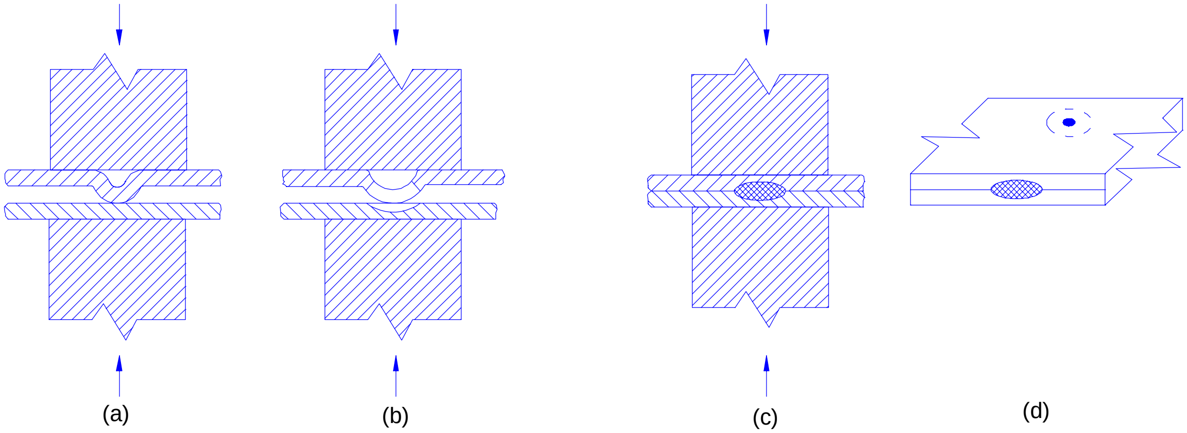

**Figure 4.3.1.1.3-1** Resistance Projection Welding Process

Solid projection welding is related to embossed projection welding. Solid projection welding is used in joining components to sheet metal. Applications range from annular projection welding to nut welding. In these applications, either a machined projection or a physical discontinuity acts as the projection for welding. Solid projection welding differs from embossed projection welding in that there is no surrounding sheet to constrain a growing weld nugget. As a result, the welds by necessity take advantage of only the solid-state part of the process. Surprisingly, there are also few guidelines for either projection designs or weld processing for solid projection-type welds. Most such information is derived empirically, on an application-to-application basis.

The ability of the projection(s) to locate current flow (and subsequent heating) provides projection welding with a number of advantages over conventional RSW. For the embossed variant of the process, these advantages include closer spot spacings, narrower flange widths, and the ability to accommodate a wide variety of stackup configurations. Of particular note is new technology using embossed projection welding which offers the potential of "mark-free" welding on one side. This technology takes advantage of current localization associated with the projection and very short weld times. The major advantage of solid projection welding is the ability to join a variety of shapes and configurations in a cost-effective way.

The major drawback of projection welding is in the manufacture of the projections themselves. Embossed projections often can be formed as part of ancillary stamping operations simply by modifying the die. Where this is not possible, or the component does not experience other forming operations, the projections must be stamped in a secondary operation, adding cost. Forming solid projections is typically much more difficult. For weld nuts and some embossments, forming the projections must be consistent with other cold heading operations. This restriction often limits obtainable projection geometries, and subsequent weld quality. Projections with more precision, particularly annular projections, are often machined at additional cost.

### 4.3.1.1.4 Resistance Upset (Butt) Welding

Resistance butt welding utilizes RW-type hardware (transformers, forcing systems, controls) to create solid-state joints. Resistance upset welding is used in a number of automotive applications, ranging from wheel rims to steering wheels. The basic configuration for welding is shown in Figure 4.3.1.1.4-1. Essentially, parts to be welded are loaded in a butt configuration under very high compressive stress, typically 75-150 MPa. On initiation of the welding current, material between the jaws softens and the parts are forged together under the applied stress. The resulting joints are solid state in character, with bonding completely across the joint interface. Joining is typically very rapid, usually less than 1-2 seconds, so production rates can be very high.

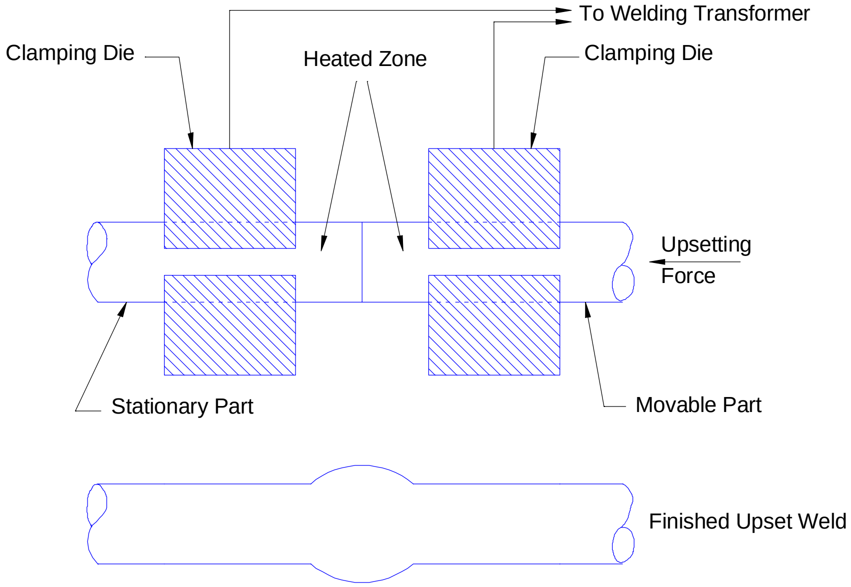

**Figure 4.3.1.1.4-1** Schematic of Resistance Upset (Butt) Welding

While resistance butt welding can be quite attractive for some applications, there are a number of restrictions that limit its use. Most notably, resistance butt welding is generally restricted to applications of relatively simple geometry. In order to accomplish balanced heating and forging, the workpieces must be of similar, uniform cross section and geometry. This generally restricts the process to bar and flat strip. In addition, given current distribution problems during welding, strip widths are generally restricted to about 500 mm. The applications of resistance butt welding are also limited by the current delivery capabilities of the equipment. Most resistance butt welding applications require about 80-120 A/mm$^2$ (50-75 kA/in.$^2$). The largest power supplies today are limited to about 200 kA, limiting welding cross sections to about 2500 mm$^2$ (4 in.$^2$). Finally, all resistance butt welds have some degree of extruded flash from the joint area, which must either be removed in an additional processing step or tolerated in the final product.

### 4.3.1.1.5 High-Frequency (HF) Welding

HF welding composes a group of welding technologies that utilize HF currents, typically greater than 10 kHz. The most common of these is HF tube welding, shown schematically in Figure 4.3.1.1.5-1. This variant of the process typically uses 100 kHz to 450 kHz current and a coil to induce current flow in flat stock that is being formed into a tube. Closure of the tube is accomplished by a set of pinch rolls at a location termed the “vee” of the configuration. Current flow in the tube occurs around the body of the tube, along the edges of the vee, and finally across the apex of the vee itself. The vee effectively acts as a current concentrator, localizing heating. Heating and forging conditions occur at the vee similar to those seen for resistance butt welding. The major advantage of HF welding is the relatively high welding speeds. In some applications, line speeds greater than 100 m/min can be obtained. Applications for HF welding have included exhaust pipe tubing, as well as tubing for sub- and full-frame structures.

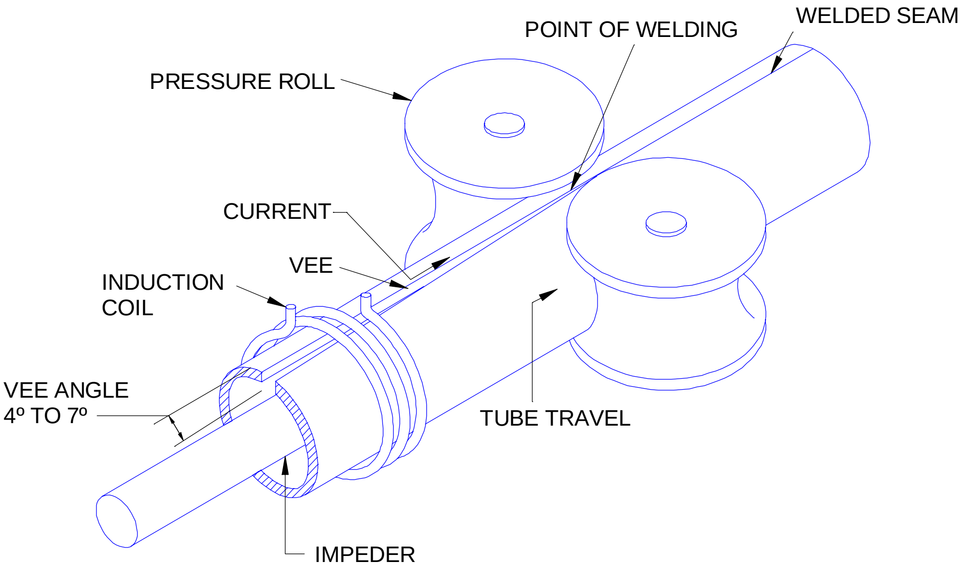

**Figure 4.3.1.1.5-1** Tube Seam Welding by HF Induction Welding

The major drawbacks to HF welding include limited weldable geometries, generally restricted to longitudinal seams, and quality control. In general, only the longitudinal seams on tubes are HF welded. A variant of HF welding is used in production, however, for manufacturing tailor-welded blanks. For tube fabrication, lack of quality control combined with high line speeds can be a problem. The concern here is that if weld quality lags, given the processing line speeds, considerable scrap will be generated in a short period of time.

### 4.3.1.2 Design Considerations

Successful weldment design requires understanding of both the weldability of the material and the weld joint placement. The process descriptions and cited references will provide the basis for design using a resistance welding process. However, consultation with each automotive company's welding design specifications is recommended.(21, 23, 24)

In all cases, resistance spot welding produces some local surface indentation or marking (if a solid backup is used on one side) in the area of the weld. This condition will be influenced by part fit-up, weld time and electrode force. For this reason, spot welds are not generally used in surface critical conditions.

### 4.3.1.3 Material Considerations

Many of the welding technologies described above are relatively mature, with most problems related to how these technologies apply to newer materials. With regard to sheet steels, the range of such products is extensive. These include bare steels, high-strength steels (HSS), and a range of coated steels. Nuances of resistance welding the various steel types are covered in the following sections. It is of note that most of the information provided here is for RSW. Much of this information is transferable to the other processes, keeping in mind the differences in the processes themselves.

#### 4.3.1.3.1 Uncoated/Mild Sheet Steel

Uncoated/mild sheet steels have been resistance welded in production for many decades. These steels typically have relatively high contact resistances, which break down readily as the weld current is applied. These materials can therefore be welded at relatively moderate currents. Materials typically exhibit very wide current ranges (>2000 A), and demonstrate electrode lives of many tens of thousands of welds. Sheet thicknesses ranging from less than 0.25 mm to greater than 10 mm have been readily resistance welded in production applications. These steels are equally amenable to all types of RW processes.

#### 4.3.1.3.2 Zinc-Coated Sheet Steels

A variety of coated sheet steels are now used in vehicle construction. The most common of these are the zinc-coated steels. Zinc-coated steels commonly fall under three classifications: hot-dipped galvanized (HDG) steels, electrogalvanized (EG) steels, and galvannealed steels. All are readily weldable by RW.

The resistance welding of these steels differs dramatically from their uncoated counterparts. The primary reason is the effect of the coatings on the various contact resistances. The zinc on the surface, in any of its forms, represents a relatively soft layer at the interfaces. Under the applied welding load, these surfaces preferentially deform, resulting in lower sheet-to-sheet and electrode-to-sheet contact resistances. Representative contact resistances for a variety of zinc-coated sheet steels, as well as uncoated sheet steel, are presented in Table 4.3.1.3.2-1. Clearly, the coated steels show order of magnitude reductions in contact resistance compared with bare steel. The lower contact resistances result in large increases in the required welding currents. Some comparable currents for welding different coated steels are presented in the table. The free zinc (HDG and EG) coated steels require roughly 50-100% more current than their bare counterparts. The coatings and higher welding current produce several effects. First, initiation of the weld nugget is delayed in the weld cycle because the initial heating melts the coating and causes much of the current to be shunted through the molten coating annulus formed at the faying surface. Second, the alloying of the electrode faces with the coating increases their resistance and causes a shift in the heat balance. These first two factors combine to result in much narrower current ranges with coated sheet steels. Finally, the surfaces of the electrodes experience much more heating, increasing alloying of the coating with the electrode and reducing electrode life.

**Table 4.3.1.3.2-1** Typical Weldability Data for 0.88-mm-Thick Mild Steel (2.2-kN Electrode Force and 6-mm Electrode Face Diameter)

| Coating Type | Contact Resistance ($\mu\Omega$) | Typical Welding Current (kA) | Typical Electrode Life (No. of Welds) |
|---|---|---|---|
| Uncoated | 1500-3000 | 7-9 | 20,000 |
| HDG | 50-150 | 11-13 | 1,000-3,000 |
| EG | 10-50 | 11-13 | 2,000-5,000 |
| Galvannealed | 300-500 | 8-10 | 3,000-8,000 |

The greater electrode heating is the primary source of the fundamental concern for RSW-coated sheet steels: accelerated electrode wear. Electrode wear has been a concern for galvanized steels for decades. Compared with uncoated steels, electrode lives for coated steel are appreciably shorter. Representative electrode lives for typical coated steel products are presented in the table. Recent work has shown that this reduction in electrode life is directly related to overheating of the electrodes. Essentially, overheating allows a substantial depth of copper to soften in the electrode face, allowing the copper to distort, resulting in mushrooming.(25, 26) The higher temperatures also result in accelerated alloying between coating and electrode, producing brittle layers of higher resistance on the surface. The alloying leads to wear by pitting of the electrode surfaces.

It is of note that generally electrogalvanized steels demonstrate substantially longer electrode lives than HDG steels. Recent work has demonstrated that the aluminum content of the coating plays a major role in electrode wear. Higher aluminum content in both HDG and galvannealed steels reduces electrode life.

### 4.3.1.3.3 Aluminum-Coated Steels

Aluminum-coated steels are used for a range of high-temperature applications, particularly exhaust systems, including exhaust pipes, brackets, heat shields, etc. Aluminum-coated steels are readily resistance weldable but, as with zinc-coated steels, the process is affected by electrode wear. Aluminum readily alloys with the copper electrodes, causing considerable wear. The problem is exacerbated by the relatively high contact resistance associated with aluminum oxide on the coating surface. The effect is to preferentially heat the surfaces, accelerating electrode wear. Typical electrode lives with Al-coated steels are less than 1000 welds.

### 4.3.1.3.4 Prepainted Steels

Weldable organic (or pre-painted) steels come in two configurations: single-side painted, and with conducting paints. Single-side painted steels can be welded to unpainted steel sheets using a series-type process. Series welding places the welding and shunt electrodes on the same side of the stackup. Joints can be made without damaging the paint on the back side when very short times are used. Also, the application of a projection onto the unpainted component also allows concentration of current, and welding with minimal damage to the paint. However, the possibility of dimpling, which is associated with the projection, may be a consideration. Steels with conducting paints, or “weldable primers” typically are coated with paints containing conducting pigments.(11) These pigments range from zinc particles to $Fe_2P$. During application of the welding force, the conducting pigment particles are compressed together, creating conducting paths. These paths allow current flow and local heating and subsequent softening of the paint. The softened paint is then extruded, allowing full conduction, and subsequent welding.

### 4.3.1.3.5 High-Strength Steel (HSS)

HSS offers a number challenges for RW.(7, 8, 9, 10, 27, 28) Most of these challenges have been grouped under the term “hold-time sensitivity”, which is defined by peel test behavior. A material that is considered hold-time sensitive will exhibit button-type failures of spot welds when short (0-5 cycles) hold times are used, but interfacial (or partial) failure when longer hold times (30-60 cycles) are used. Two classes of hold-time sensitivity have been defined, each corresponding to a different classification of HSS. Rephosphorized grades of steel demonstrate hold-time sensitivity due to solidification cracking related to phosphorus additions. Extensive empirical work has shown, however, that hold-time sensitivity in these grades of steels can be avoided if the phosphorus content is maintained below 0.06%. Dual-phase grades of steels, with higher carbon and manganese additions, exhibit hold-time sensitivity through the formation of relatively hard martensites. Similar empirical work has shown that hardness hold-time sensitivity can be avoided by maintaining carbon levels below 0.1%. Hold-time sensitivity is also a problem in plain carbon steel when carbon content is greater than approximately 0.08 to 0.09%.

Hold-time sensitivity is essentially a cooling rate-related phenomenon. As a result, factors that increase the cooling rate in the weld also increase hold-time sensitivity behavior. These include thinner sheet and smaller weld sizes. Using thicker sheets (and subsequently larger weld sizes) will mitigate some of the compositional effects described above.

It is of note that many of the dual-phase HSS (high carbon, manganese) will use compositions inherently hold-time sensitive. For these applications, more advanced weld schedules are required. The application of post-weld tempering has been found to be very effective in reducing weld hardnesses, and minimizing (or eliminating) hold-time sensitivity effects. These methods offer great potential as more hardenable grades of steels are applied in auto body construction.

## 4.3.2 ARC WELDING PROCESSES

Arc welding processes use electrical energy to melt or fuse metals to produce a joint between two or more parts. All processes are characterized by an electrical arc between an electrode and the workpieces. The processes of current use or interest are GMAW, FCAW, and plasma arc welding (PAW). AWS (American Welding Society) or company standards may be used to define required weld quality in automotive applications.(27, 29) These processes, their advantages and disadvantages, and their applications for autobody manufacturing are described in the following sections.

### 4.3.2.1 Gas Metal Arc Welding (GMAW) – Process Description

The GMAW process (also known as Metal Inert Gas, MIG, or MAG welding) is characterized by an arc that is formed between the end of a continuously fed electrode wire and the workpiece (see Figure 4.3.2.1-1). The solid wire is continuously fed through a contact tip in the torch, and melts to form the weld bead joining the base metals. The wire feed rate is balanced to the burnoff rate to maintain a stable arc. The wire type is selected to give the weld metal a matching (but typically overmatching) strength compared with the base metal. The weld area around the arc is protected by a shielding gas supplied from the torch.

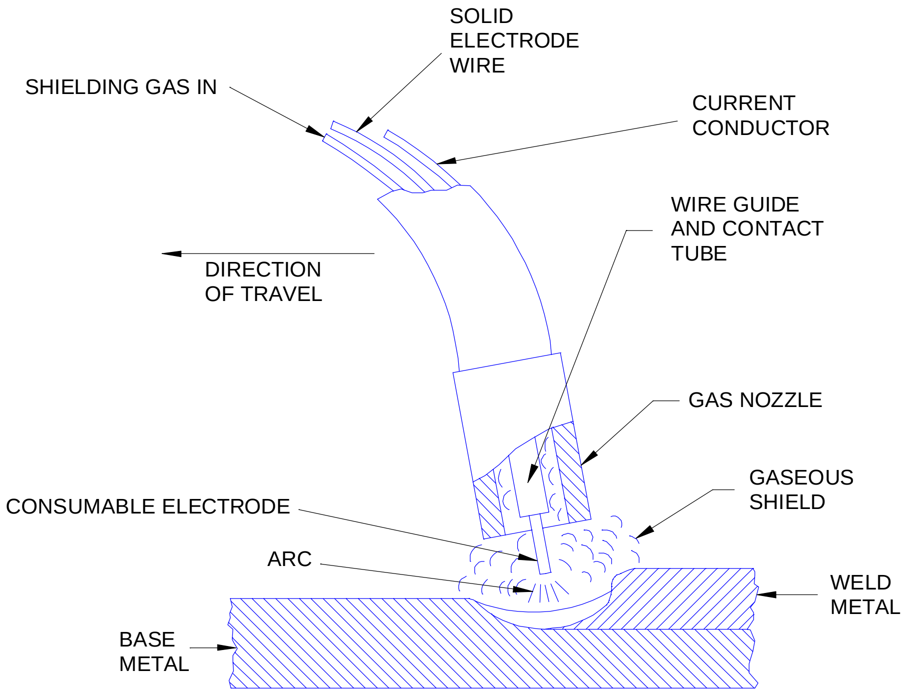

**Figure 4.3.2.1-1** GMAW Process

GMAW weldments can be made in all positions, especially using “short-circuit” transfer, or pulsed current, P-GMAW; thus the process is ideally suited to automation, especially through arc welding robots. Gap tolerance for GMAW is good, with joint gaps up to one sheet thickness (1T) being tolerable.

The welding parameters that must be controlled to produce acceptable welds include welding current, arc voltage, wire feed speed, torch travel speed, torch travel and work angles, and shielding gas flow rate. The joint gap should be minimized to achieve the best joint quality and productivity.

#### 4.3.2.1.1 GMAW – Advantages and Disadvantages

The major advantages of the GMAW process are its high productivity and reliability coupled with low cost. The process is suited for automation, and very little cleanup is required after welding. The equipment can be deployed on welding robots with relative ease, and single-side access only is required. In addition, the process is suitable for many different alloys including, among others, carbon and low-alloy steels, stainless steels and aluminum alloys.

The disadvantages of GMAW are the plant ventilation that is required to remove welding fumes, and the protection that is needed from strong drafts to avoid loss of shielding gas efficiency, which can lead to porosity. Welding of coated steels can cause porosity by volatilization of zinc-rich coatings. This can be mitigated by correct development and implementation of welding procedures.

### 4.3.2.1.2 GMAW – Applications

The GMAW process is suitable for a variety of alloys as noted above in butt, fillet, and lap joints. Joint fit-up is less critical than for Gas Tungsten Arc Welding (GTAW) and laser beam welding (LBW).

Typical applications on sheet metal body in white (BIW) are short welds of an inch or less, either in a lap-fillet configuration, or by spot or plug welding. Many attachment welds are made using GMAW, such as door hinges to door pillars. The process is suitable for welding vehicle frames, including tubular spaceframes. A sub-set of GMAW operations is GMA brazing, which uses silicon bronze filler wire to braze steel components such as roof-to-quarter panel components.

### 4.3.2.1.3 Variant GMAW Processes

Pulsed GMAW (P-GMAW) offers increased control of metal transfer compared with conventional constant-voltage GMAW. This gives the P-GMAW weld improved cosmetic appearance and reduction in spatter and cleanup considerations compared with constant-voltage GMAW.

Variable polarity (VP or AC) GMAW is a new variant of GMAW in which the balance of electrode polarity is adjustable to change the degree of penetration achieved during the weld. This variant of GMAW is designed to be even more tolerant to joint gaps (even up to 2× metal thickness) and to minimize distortion associated with the heat input of the process when welding sheet thicknesses. These two features make the process potentially attractive for sheet metal BIW fabrication. Commercial equipment is currently available from a limited number of sources for welding steel and aluminum alloys.

Twin-wire GMAW exploits the benefits of two torches and two arcs in a single weld pool to achieve productivity gains in excess of three times that of single-wire GMAW. The most suitable systems for robotic operation incorporate two wires in a single torch using two contact tips and sequencing the current pulsing to minimize arc interference. Several commercial systems are available and applications range from 1.6-mm sheet to thicker materials. Applications include frame manufacturing, such as in light trucks and SUVs, and a wide array of suspension and axle components.

## 4.3.2.2 Flux-Cored Arc Welding (FCAW)

The operation of the FCAW process is essentially similar to that of the GMAW process. The main difference is that FCAW uses a flux- or metal-cored consumable that consists of a tubular metal sheath wire, which contains either a flux or a powdered metal core. Some FCAW consumables operate without a supply of shielding gas, but most of those suitable for welding components relevant to the automotive industry employ a shielding gas, usually a mixture of argon and carbon dioxide.

#### 4.3.2.2.1 FCAW – Advantages and Disadvantages

Most of the advantages and disadvantages of FCAW are similar to those for GMAW. An additional consideration for FCAW is that the weld metal is partially protected by a slag coating which has to be removed after welding. This additional operation is a considerable disadvantage in a high-productivity welding environment. The wire must be handled with caution to minimize moisture pickup, which will affect hydrogen content and may cause subsequent cracking in low-alloy and higher strength steels.

Since metal-cored wire consumables do not contain fluxing agents, they do not produce a slag covering. The advantage of metal-cored wires is that they have higher melting efficiency than do solid wires, and thus present the opportunity for gains in productivity through increased welding speed or deposition rate.

#### 4.3.2.2.2 FCAW – Applications

The FCAW process, which utilizes flux- or metal-cored wires, is typically used for carbon, low alloy, and stainless steels. The metal-cored wire consumables have been used to considerable advantage on fabrication of exhaust components such as Type 409 stainless steels. Metal-cored wires are also available for carbon and low-alloy steels, and provide productivity advantages through increased melting efficiency compared with solid steel wires.

Both flux- and metal-cored wire consumables can be used to weld butt, fillet, and lap joints. The applications can be similar to GMAW with brackets, body panels, spaceframe welding, and component parts being suitable.

### 4.3.2.3 Plasma Arc Welding (PAW)

The PAW process is like GTAW (Gas Tungsten Arc Welding) except that a copper nozzle protects the tungsten electrode. The nozzle has an orifice that focuses the arc to produce an increased power density compared with the conical arc of GTAW. PAW should be considered and used as an arc welding process most similar to Laser Beam Welding (LBW). PAW can be used in the melt mode (conduction mode) or keyhole mode. The melt mode is similar to GTAW, but with increased tolerance to variation in torch-to-workpiece distance (because of the columnar arc shape) higher power density, and increased tolerance to electrode contamination which is important when welding coated steels. Melt mode PAW can be used with or without cold wire addition.

#### 4.3.2.3.1 PAW – Advantages and Disadvantages

The advantage of PAW is that it can be used with or without filler wire addition, and provides good control of heat input relative to wire addition. This can be used to advantage for a variety of joints where low distortion and good cosmetic appearance is important. The high penetration capability in the keyhole mode, allowing sheet stackups up to 8-mm thick to be welded without pilot holes, is a considerable advantage.

The main disadvantage to PAW for conventional joints is that good fit-up is required as the process is not very tolerant to joint gaps in the spot welding context, or in a lap-fillet joint configuration. For joints such as butt and lap-fillet joints this can be improved by adding filler wire. The equipment is also more expensive than that for GMAW.

#### 4.3.2.3.2 PAW – Applications

Applications of PAW are currently limited to some brazing operations for roof-to-quarter panel joints, and to hemming of door outers to inners. The potential applications are larger than those currently being exploited.

#### 4.3.2.3.3 PAW – Variant Processes

Plasma brazing is analogous to GMA brazing, but uses independent control of wire and heat through a separate heat source and external cold wire feed. This can be used to advantage to minimize spatter associated with arc starting in GMA brazing. The independent control of heat and wire enables better control of distortion, and also minimizes porosity compared with GMA brazing.

Plasma spot welding can be accomplished using the PAW process in the melt mode to produce a spot weld in multiple stackups, without addition of filler wire or the use of pilot holes. The ability to weld several sheet metal thicknesses, up to 8 mm in total thickness without pilot holes (such as are used in plug and slot welds for GMAW/FCAW) offers a considerable advantage. The equipment can be readily automated, or attached to a robot, and has good tolerance to variations in torch-to-workpiece distance because of the columnar nature of the arc.

## 4.3.3 LASER BEAM WELDING (LBW)

Laser processing is accomplished by a transfer of energy from a coherent beam of light to the material it is impacting. The power density and the interaction time of the light determine how the material is affected. Typical laser processes that can be achieved include heat treating, cladding, welding, cutting, and drilling. In all laser processing the energy is converted from light into thermal heating of the target material to achieve the desired result.

### 4.3.3.1 LBW -- Process Description

LBW requires a concentrated beam on a surface at a high enough level to melt the material (see Figure 4.3.3.1-1).(30) The critical concentration of energy is approximately $10^4$ W/cm$^2$ for most ferrous alloys. At this power density, the energy transfer from the laser beam into the part occurs in two dimensions, and the depth of the weld is determined by the flow of material in the molten pool. This type of weld is very similar in appearance to a GTAW weld with a low depth-to-width ratio and is called “conduction mode welding”. At higher power densities, >$10^6$ W/cm$^2$, the transfer of energy occurs in three dimensions. The three-dimensional heating is made possible by the high power density, which heats the molten material enough that it vaporizes. The pressure from the expansion of the substrate material causes the formation of a “keyhole”. Keyhole mode welding has the characteristic of a very high depth-to-width ratio.

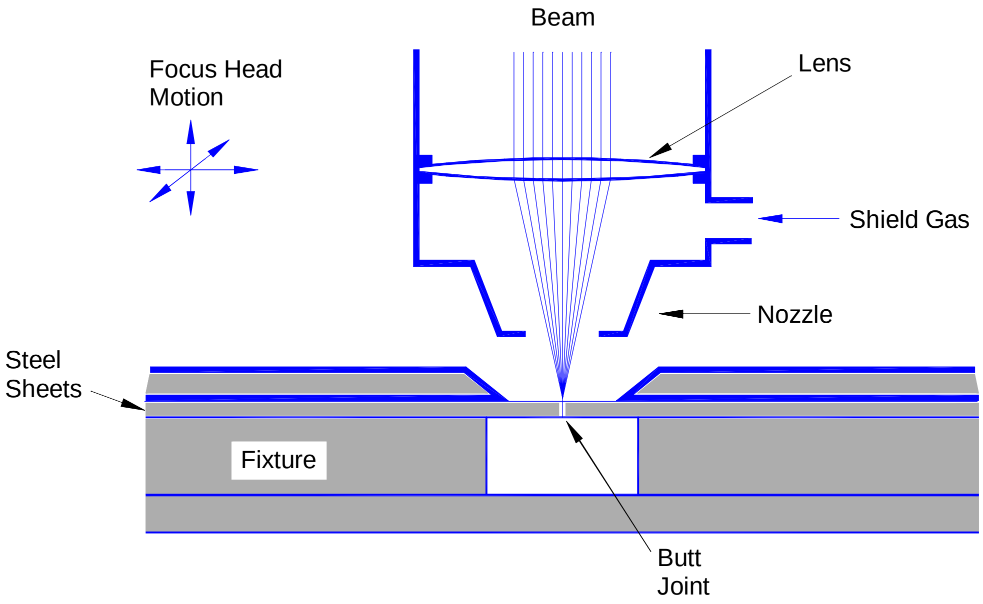

**Figure 4.3.3.1-1** Example of Laser Welding Arrangement that may be Used for Tailor Blank Welding (The laser beam can be either $CO_2$ or Nd:YAG.)

In addition to the power density, there are other factors that determine whether a weld will be conduction or keyhole mode.(30) The melting point of the material, the reflectivity of the material, the relative speed between the material and the beam, the wavelength of the laser, and the power density profile of the laser beam are all factors that determine the configuration of the weld.

While there are major differences in the conduction and keyhole-mode laser welding, there are some similarities. Both processes can be accomplished in air, unlike electron beam (another high power density process), which requires a vacuum. Both processes can be accomplished without filler material being added (autogenous). Filler material can be added as shim, wire, or powder to address fit-up problems, meet positive re-enforcement requirements, or to alter the chemistry of the weld metal. Gases are often used to increase the transfer of energy in the keyhole welding process and shielding gases are also used to decrease the oxidation of the molten material, insure weld integrity, and improve the visual appearance of the weld.

### 4.3.3.2 Types of Lasers ($CO_2$ vs. Nd:YAG)

There are two primary laser types used for automotive welding of steel alloys: $CO_2$, a gas laser, and the Nd:YAG laser, a solid-state laser. The $CO_2$ laser operates at 10.6-µm wavelength while the Nd:YAG operates at 1.06-µm wavelength. While both lasers can use mirrors and lenses to direct and focus the beam, the shorter wavelength of the Nd:YAG permits it to be delivered by glass fibers (200- to 1000-µm diameter). Fiber delivery enables the use of Nd:YAG lasers in standard robotic systems for delivery, while $CO_2$ lasers are restricted to specially designed workcells, gantries, or complex manipulators. These factors can impact the capital investment and operation costs.

Also related to the wavelength are the safety issues associated with the different lasers. Because the processing is performed in an automated fashion, most laser processing is accomplished in enclosures or at safe distance from workers. The only protection that is normally required in the area is for the eyes. For the $CO_2$ lasers, plastic safety glasses are sufficient, while the shorter wavelength of the Nd:YAG requires special glasses for eye protection.

Although there are system and safety issues, both types of laser are used in industrial facilities. The only concerns may be controlling the temperature of certain components and vapors or moisture in any beam-delivery system.

### 4.3.3.3 Typical Applications

The use of lasers in the fabrication of automotive components is growing rapidly.(30) Laser welding has permitted a number of major innovations such as tailor-welded blanks and three-dimensional cutting and welding of hydroformed parts.

The two major classes of laser welding applications are thin gauge and thick gauge. Thin gauges, typically less than 3 mm, can either be conduction or keyhole-mode welded. The mode will depend on the joint configuration (lap or butt joint) and the properties desired from the welded joint. To maximize production, higher processing speeds can be achieved with keyhole-mode welding, but welds are narrower. Narrower welds may potentially impact joint fit-up requirements. Poor fit-up can result in undercut which reduces the strength of lap joints. Conduction mode welding is slower but can reduce fit-up requirements and produces larger interfaces in lap joint welds.

Thick gauges, typically 3 mm and greater, normally require keyhole welding. The high depth-to-width ratio of the keyhole mode welding permits very deep welds to be made with minimal heat input. With these parameters there is less heat, and therefore little or no distortion, potentially minimizing post-weld processing or the impact on surrounding material.

#### 4.3.3.3.1 Body Applications (Tailor Blanking)

One of the largest current applications of lasers in the automotive industry is in fabricating tailored blanks, where sheets of steel in various thicknesses, grades and coatings are welded prior to stamping to maximize performance and reduce waste. Examples include door rings, inner door panels, floor panels, and shock towers. For a fuller discussion, please refer to Section 3.9.1, Tailor Welded Blanks.

#### 4.3.3.3.2 Other Components

Lasers are also used to weld a number of other automotive components, such as:

1. Engine, transmissions, and suspension components
2. Exhaust manifolds, catalytic converters, mufflers
3. Temperature and pressure sensors, ABS sensors, electronic packages
4. Air bag igniters and inflators

### 4.3.3.4 Advantages/Disadvantages

The advantages and disadvantages of laser welding determine the best application of the process. Often the advantages and disadvantages occur in manufacturing steps before or after the laser welding process.

Laser welding has many advantages over other welding techniques. It is a very low heat input process less than 10% of the heat of arc processes. This means that there is little distortion of the workpiece or modification to the properties of the material in the vicinity of the weld. This may reduce or eliminate secondary processes or allow for welding to occur very late in the assembly process. Also, because high depth-to-width ratios are possible, lap joints can be accomplished in very thick materials. Other advantages of the process include:

1. Improved visual appearance
2. Little or no distortion or waviness
3. Capability to weld through multiple layers
4. Single-sided access

Laser welding may additionally offer mass reduction by decreasing or eliminating flanges normally required for spot welding. The use of continuous weld beads may also increase the stiffness of the structure compared with a spot-welded structure.

While laser welding has a number of advantages it also has disadvantages. One disadvantage is that laser welding is a “line-of-sight” process meaning that the weld joint must be visible for the weld to be made. Laser welding is a “thermal process” which means that there will be some distortion due to differential heating of the part during welding.
Some of the general disadvantages are:

1. Sensitivity to part fit-up
2. Sensitivity to the surface condition
3. Potentially poor weld quality when lap welding coated sheet steels due to trapped gases in the metal
4. High cost of equipment, which can be offset by productivity

### 4.3.3.5 Materials

Laser welding can be performed on a wide range of ferrous and non-ferrous alloys. Most steel alloys are very weldable either in the conduction or keyhole modes. The alloy composition and post-weld processing must be considered when selecting the welding parameters due to the high cooling rates associated with laser welding. High cooling rates can induce high hardness, high yield strength, low ductility, or low toughness in the weld metal or in the heat-affected zone (HAZ) of the weld. Despite this fact, laser welded tailored blanks have readily formable joints. The degradation of properties is of special concern for high-alloyed steels where martensite may form in the weld metal or HAZ.(30,31)

Any coating on the steel may be a concern. The relatively low boiling point of zinc can make the laser weld unstable causing “blow holes” and porosity in the weld. This is a major problem for lap joints and less of a problem for butt welds. To prevent this problem in lap joints a gap may be established between the plates to allow for the zinc vapors to escape.

### 4.3.3.6 Design Considerations

If laser welding is considered in the design of a component, some major advantages can be utilized. The ability to adjust the stiffness of a joint by variations in the weld length or configuration allows for “fine tuning” of the structural performance of a joint.

The ability to make continuous welds with very low distortion has a number of advantages. The elimination of post-process grinding or straightening decreases production costs or can eliminate the need for sealers or other measures to take up irregularities in the joint.

## 4.3.4 OTHER WELDING PROCESSES

In the last few decades, a number of new, so-called single-shot solid-state processes have come into limited use in the automotive industry. The most common of these is friction welding, which uses relative motion of the workpieces to generate heat for bonding. Metallurgically, this process is quite similar to resistance butt welding described above with the exception that friction heating, rather than resistance heating, is used to achieve temperatures for forging.

Two variants of friction welding are used in automotive manufacture today: direct-drive friction welding and inertia welding. The primary differences between these two processes are the energy sources for friction heating. Direct-drive friction welding uses a continuously driving motor to achieve rotational velocities for friction heating. Friction heating is then done at a constant speed for a fixed time prior to forging. Inertia welding first stores energy in a rotating flywheel prior to welding. On contact of the workpieces, the energy of the flywheel is dissipated as friction heat (in the workpieces). Both variants of the process yield exceptional quality welds. Typical applications for friction welding in the automotive industry include engine valves and axle spindles. Friction welding has an implied advantage over resistance butt welding in that the amount of heat generated is based only on the motor or flywheel size. Therefore, sections of several tens of thousands of square millimeters can be welded.

Friction welding, however, suffers many of the drawbacks of resistance butt welding, including high equipment costs, the need for flash removal and part geometry restrictions. Since parts must be round, friction welding is limited to a relatively few automotive applications, and currently no body applications.

Magnetically impelled arc butt welding (MIAB) has also seen limited use in the automotive industry. MIAB welding allows joining of relatively thin-walled tube sections in relatively short times. The parts are positioned in a butt configuration similar to resistance butt or friction welding. The welding equipment uses relatively high-voltage DC power applied across the parts, a forging system for upsetting the parts, and magnetic coils around the parts. On welding, the parts are gapped, and an arc is established locally across the gap. Under the influence of the magnetic coils, the arc is driven around the periphery of the parts, generating uniform heat along the bond line. After sufficient heat is generated, the parts are upset together. The process is capable of short cycle times, similar to that for resistance butt and friction welding. In addition, non-round sections and very thin-wall tubing can be welded. The process has seen extensive use for applications such as prop shafts and spindles in Europe; however, the technology has not been used in North America.

The process has similar drawbacks to resistance butt and friction welding in that equipment costs are high, and flash removal may be a concern. An additional concern with MIAB welding is that joinable wall thicknesses are relatively limited. Generally, the process is not recommended for parts with wall thicknesses greater than 3 mm.

## REFERENCES FOR SECTION 4.3

1. American Motors Corporation, Criteria for Evaluation of Resistance Spot Welds (Mild and HSLA Steels), Manufacturing Engineering Standard 76-8.

2. American Welding Society D8.7-78, Specification for Automotive Weld Quality – Resistance Spot Welding (1978).

3. American Welding Society D8.6-77, Standard for Automotive Resistance Spot Welding Electrodes (1977).

4. American Welding Society C1.3-70, Recommended Practice for Resistance Welding Coated Low Carbon Steels (1970).

5. American Welding Society C1.1-66, Recommended Practice for Resistance Welding (1966).

6. Auto/Steel Partnership Report AZ-017-02 997 1.0C EG, “Weld Quality Test Method Manual” (Oct. 31, 1997).

7. Chrysler Corporation, Resistance Spot Welding – High Strength Steel Structural Components, Process Standard PS-6328 (Aug. 31, 1978).

8. DelVecchio, E. J., Resistance Welding Manual, 4th Edition, Resistance Welder Manufacturers’ Association, Philadelphia, PA (1989).

9. Dickinson, D. W., Welding in the Automotive Industry, Report SG 81-5, American Iron and Steel Institute (Aug. 1981).

10. Ford Motor Company Specification BA 13-4, Resistance Spot Weldability Test for High Strength Low Alloy (HSLA) Steel (Sept. 26, 1980).

11. Ford Motor Company Specification BA13-3, Welding Acceptance Test for ZINCROMETAL (Nov. 25, 1972).

12. Ford Motor Company Specification BA13-1, Welding Acceptance Test for Galvanized Steel (June 8, 1971).

13. Ford Motor Company, Resistance Welding Cap Electrodes, Manufacturing Standard WC-1 (July 1971).

14. General Motors Corporation, CPC Group, Specifications and Procedure for Determining the Weldability of Zinc Preprimed Sheet Steel, Specification MDS-246 (revision of July 16, 1985).

15. General Motors Corporation, Automotive Weld Quality – Resistance Spot Welding Low Carbon Steel, Engineering Standard GM 4488P (Apr. 1985).

16. General Motors Corporation, CPC Group, Specification MDS-247, Specifications and Procedure for Determining the Weldability of Body Steel Materials (revision of July 18, 1984).

17. Howe, P., “Spot Weld Spacing Effects on Weld Button Size,” Paper C3, Proceedings of AWS Sheet Metal Conference VI (Oct. 1994).

18. IIW, Recommended Practice for Spotwelding Zinc-Coated Sheets, Document III/399/71 (May 1971).

19. Welding Resistance: Spot and Seam, Military Specification MIL-W-6858D (Oct. 20, 1964).

20. Vol. 2, Welding Handbook, 8th Ed, American Welding Society, Miami, FL, 1991, p.555

21. “Welding and Brazing,” Metals Handbook, Vol. 6, ASM, pp. 401-484 (1971).

22. Welding, Resistance, Spot and Projection for Fabricating Assemblies of Carbon Steel Sheet, Military Specification MIL-W-46154(MR) (Oct. 20, 1970).

23. American Iron and Steel Institute Report SG 85-2, “Solutions to Manufacturing Problems Using Galvanized Steel,” W. J. Riffe ed. (second printing June 1986).

24. American Welding Society D8.4-61, Recommended Practice for Automotive Welding Design (1961).

25. Auto/Steel Partnership Report ZSP7060 0997 1C EWI, “Resistance Spot Welding Electrode Wear on Galvannealed Steels” (Sept. 1997).

26. Auto/Steel Partnership Report AZ019 01 694 2.5C EWI, “Mechanisms of Electrode Wear During Resistance Spot Welding Hot-Dipped Galvanized Steel” (June 1994).

27. Chrysler Corporation, Resistance Weldability Test for Uncoated High Strength Steels, Laboratory Procedure LP461K-167 (revision of Sept. 4, 1981).

28. Chrysler Corporation, Resistance Weldability Test for Galvanized High Strength Steels, Laboratory Procedure LP461K-167 (revision of Nov. 25, 1981).

29. American Welding Society D19.0-72, Welding Zinc-Coated Steel (1972).

30. Steen, W. M., Laser Material Processing, Springer-Verlag, 1991.

31. Belforte, D. and Levitt, M., The Industrial Laser Annual Handbook, 1990 Edition, Pennwell Books (1990).

## **BIBLIOGRAPHY FOR SECTION 4.3**

1. American Iron and Steel Institute Report SG-936 282-10M-RI, “Spot Welding Sheet Steel.”

2. American Welding Society Specification D8-8, Specification for Automotive and Light Truck Components Weld Quality – Arc Welding (1997).

3. American Welding Society D8.5-66, Recommended Practice for Automotive Portable Gun Resistance – Spot Welding (1966).

4. Chrysler Corporation, Resistance Weldability Test for Galvanized and Galvannealed Low Carbon Hot and Cold Rolled Steel Sheet, Process Procedure LP461K-170 (revision of Jan. 26, 1984).

5. Chrysler Corporation, Resistance Spot and Arc Welding Automotive Components, Process Standard PS-1682 (Aug. 30, 1983).

6. Resistance Welding Equipment Standards, Resistance Welder Manufacturers' Association, Bulletin 16.