

We all know that there are special requirements for MIG welding (formally known as GMAW) in Section IX. Also, many of us have experienced problems with MIG during welding, particularly when welding thick sections. The following provides some background that anyone who uses MIG welding should understand.

The Gas Metal Arc Welding (GMAW) is characterized by a variety of modes in which the metal can be transferred from the electrode to the work piece. These transfer modes are

- 1) short circuiting transfer (GHAW-S),
- 2) spray transfer (GMAW-SP),
- 3) globular transfer (GMAW-G)
- 4) pulsed transfer (GMAW-P)
- 5) flux cored welding (GMAW-FC)

Among these, the short-circuiting transfer mode (GMAW-S) is the most troublesome, and has special requirements. Let's review the easy ones first.

### **Magnetic Fields and Current Flow**

Current flowing through the welding electrode beyond the contact tip sets up a magnetic field that encircles the wire. This magnetic force is known as the Lorentz force. See Figure 1. Anyone who studied electricity and magnetism in school may recall the "right-hand rule" which describes the relationship between the current flow and the direction of the associated magnetic field – that magnetic field is the Lorentz force.

### **Spray, Globular and Pulsed Transfer**

In spray transfer, the voltage is high (26 volts and up) current levels are high (230 amps and up) resulting in a strong magnetic field wrapped around the electrode. This strong magnetic field causes the liquid that forms on the end of the wire to be pinched by the Lorentz force; this results in formation of small droplets that are shot across the arc by the Lorentz force in a steady and regular fashion. See Figure 2.

If the current levels (and corresponding Lorentz force) are not high enough to pinch off the liquid on the end of the wire, a large droplet forms and stays attached for a brief period. Eventually, its size becomes so large that it detaches and falls across the arc into the weld pool. This is called globular transfer. See Figure 3. The

transfer of droplets in globular transfer is irregular and erratic. More than 20% CO<sub>2</sub> in the shielding gas will also prevent spray transfer except at very high current levels (above 450 amps).

Both spray and globular transfer modes run hot and provide consistent penetration into the base metal. Both do well in the flat position and when making horizontal fillet welds, Because of the large weld pool, neither works well in the vertical or overhead positions except when welding aluminum (due to aluminum's high thermal conductivity). Further, welding must be done on backing (i.e. a fillet weld or a groove weld made on a backing ring or a root pass put in by GMAW-S or another process,). The primary difference between spray and globular transfer is that globular results in a lot of spatter, whereas spray transfer is smooth and steady with little spatter. Both transfer modes have high deposition rates and are among the least expensive processes to use, although globular transfer requires more cleaning time.

GMAW-P, the pulse transfer mode, utilizes a special current-controlling power supply. In ordinary GMAW, the voltage is preset at the power supply and the current is proportional to the wire feed speed. In GMAW-P, the power supply controls the current so that it pulses from a background current level in the globular transfer range into the spray transfer range. When this happens, a droplet is transferred across the arc, then the current is reduced to the globular transfer range. The transfer mode is spray-like, but the arc energy is reduced from that characteristic of spray so that the weld pool is much smaller. With a smaller weld pool, welding can be done vertically, horizontally and overhead. Because the heat input is lower and the weld pool is smaller, pulse welding is effective for reducing cracking on crack-sensitive metals like some nickel alloys and Alloy 20.

In GMAW-FC, also known as flux cored welding (FCAW), the transfer mode is spray or globular, depending on the manufacturer of the wire, wire size, shielding gas, voltage and current. Flux cored wires do not exhibit short circuiting transfer. Although GMAW-FC transfer mode is spray or globular, small-diameter wires (0.035, 0.045 in.) can be used in all positions with deposition rates 50% higher than one can obtain using solid wire GMAW-S. This is largely due increased wetting of the base metal by the flux and the greater viscosity of the flux which helps to hold the pool in place.

### **GMAW Short Circuiting Transfer**

In GMAW-S, metal is transferred when the wire makes momentary and rapidly repeating contact with the work piece. When this happens, a short circuit occurs and the arc is momentarily extinguished.

During arcing and immediately before short circuiting occurs, a droplet of metal

forms on the on the end of the electrode. During the short-circuit, this molten droplet is drawn into the weld pool by surface cohesion forces (similar to capillary attraction). As the molten tip is drawn off the wire, the liquid bridge necks down and separates from the wire. When this happens, the arc is reignited and stays on until the wire again makes contact with the work piece and another short circuit occurs. See Figure 4.

### **Identifying Short Circuiting Transfer Mode**

Short circuiting occurs 50 to 200 times per second, so one cannot see it except with high-speed photography. It is characterized by low voltage (16 to 19 for steel) and can be identified by a steady buzzing sound in the background of snapping, crackling and popping that is the normal sound in GMAW. The frequency of that buzz is the frequency at which short-circuiting transfers occurs. If the welder can make an open root weld with specific power source settings, the transfer mode is short-circuiting. This is true for both ordinary power sources and for waveform controlled power sources such as Miller's RMD, Lincoln's STT and Fronius's CMT.

Because the arc is off part of the time with GMAW-S, the weld pool stays small and is easy to control; however, because the arc is off part of the time, it is easy for lack-of-fusion to occur. Lack-of-fusion occurs when the weld pool washes over the base metal rather than penetrating into it. In other transfer modes, the force of the arc is so strong that it pushes the weld pool aside and burns into the base metal; a welder can see this with spray transfer and with flux cored welding, but not with GMAW-S. With GMAW-S, the arc force is much weaker, and if the welder tries to make passes that are too thick on sections over 1/4 inch in thickness, the arc will not penetrate into the base metal; rather, penetration becomes dependent on superheating of the weld pool.

Superheat is the heat energy that raises the temperature of the molten pool above the material's melting temperature. That is, a steel weld pool may reach 4,000°F – well above the 2,750°F melting point of steel. This superheat will melt into (penetrate) the base material even if the arc is not penetrating into the base metal -- provided the thermal mass (heat sink) of the part is not too great. The simplest way to understand heat sink effect is to consider the paths available for heat to flow from the weld pool. Figure 5. The more heat paths there are, the less effective superheat is in achieving penetration. The heat sink effect is so effective with aluminum that GMAW-S does not work except on aluminum less than 0.1 inches thick; almost all aluminum GMAW is done using spray transfer.

GMAW-S is used throughout the world with great success in a wide variety of applications. There is no problem welding thick base metal provided the welder is trained to follow certain techniques.

Foremost among the welding techniques is the need to control travel speed; high travel speed is necessary to keep the arc at the leading edge of the weld pool. If the travel speed is too slow, the pool will flow beneath the arc, and all the arc forces will be absorbed by the liquid pool, making penetration difficult to achieve.. Note that staying at the leading edge of the weld pool does not preclude weaving.

A second significant factor which affects the penetration is the angle of the welding gun relative to the direction of travel. A dragging angle (Figure 6.) produces the deepest penetration at about 20 degrees. A more upright angle produces less penetration. A pushing angle produces even less penetration

A third factor is welding position and the effect that gravity has on the weld pool. Gravity pulls the weld pool towards the earth, and, as in all other processes, this pull is opposed by surface tension forces which hold the weld pool in place.

In the flat position, it is easy for the welder to allow the weld pool to become large because it is contained by the side walls of the bevel and the metal underneath. In the overhead and horizontal positions this tendency is reduced because the pool can only become so large before runs out of control. In the vertical position when using uphill progression, gravity pulls the weld pool downward away from the arc, increasing penetration (see Figure 7); however, there is a tendency for the welder to use a pushing torch angle in this position due to the natural angle of the gun. This tends to reduce penetration in upward progression. When welding using the correct torch angle, fill passes made using uphill progression more consistently and reliably penetrates the base metal than those made using downhill welding, particularly on thick materials.

On the other hand, a dragging torch angle is natural for the vertical position when using downhill progression. In downhill progression, it is necessary for the welder to pay particular attention to staying ahead of the pool , since it travels fast due to gravity

Because of the limited penetration of GMAW-S, the limited heat sink effect of an open root weld and the fact that only the root face has to be melted (Figure 8), downhill progression is a fast and highly effective way to put in root passes on pipe butt welds. If the root face and root opening are correct, incomplete penetration of downhill root passes does not occur. Although downhill can be used for fill and cover passes on groove and fillet welds, uphill progression is more reliable because uphill progression exhibits more consistent and reliable penetration.

Finally, because there is no extra heat or a flux with GMAW-S, GMAW-S is much more sensitive to dirt, rust and oxides. In order to avoid weld flaws, cleaning the surfaces to be welded is more important with GMAW-S than with other transfer modes and other processes.

## Code Issues

There are two areas where ASME Section IX has special rules for welders who will use GMAW-S.

- For GMAW transfer modes other than short circuiting and for other arc welding processes, a welder is qualified for two times the thickness of weld metal that he deposits in his test coupon (2t); with GMAW-S he is qualified for 1.1t.
- For GMAW transfer modes other than short circuiting and for other arc welding processes, a welder's test coupon may be examined by bend test or radiography. For GMAW-S, only bend tests or ultrasonic examination are permitted since lack-of-fusion flaws are not readily seen on radiographs.
- If the welder is using a power source that is waveform controlled (e.g., Miller RMD, Lincoln STT, Fronius CMT.) to put in a root pass, the transfer mode is short circuiting.
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It is not unusual for Engineer's specifications to limit the maximum weld metal thickness or even prohibit the use of GMAW-S due to the potential for lack of fusion. Other transfer modes, including GMAW-FC, are no more likely to produce lack of fusion than SMAW and such restrictions only increase the cost of welding without any positive value.

## Summary

- Use GMAW-SP (spray transfer) when welding for flat and horizontal fillet welds and for flat position welds on backing.
- Use GMAW-FC (flux core) for fillet welds and fill passes of groove welds when welding in all positions.
- Use GMAW-S (short circuiting) for root pass welding on piping using downhill progression for the root and uphill for the fill passes. Switch to GMAW-FC or GMAW-SP for fill passes when thickness to be welded exceeds 3/8 in (8 mm) or the pipe is over NPS 8.
- GMAW-S requires a special training to ensure sound welds; be sure your welders have had it.
- Section IX imposes two special limitations on GMAW-S – welders are only qualified for 1.1 times the thickness of weld metal they deposit in their test coupon, and if any part of the weld was made using GMAW-S, only bend testing and ultrasonic examination of the test coupon are permitted – radiographis examination is not permitted.

# Figure 1

## The Lorentz Force

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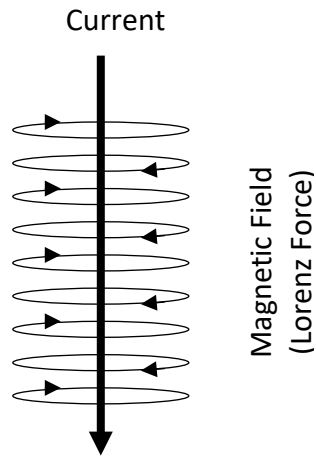
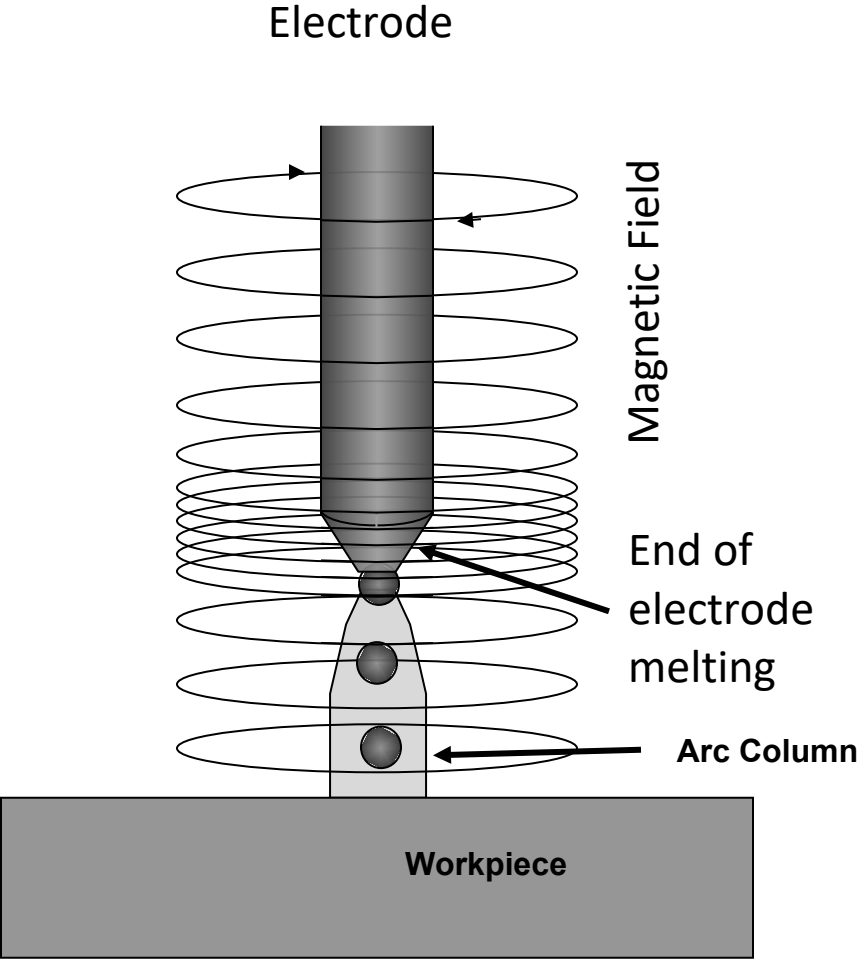


Figure 2

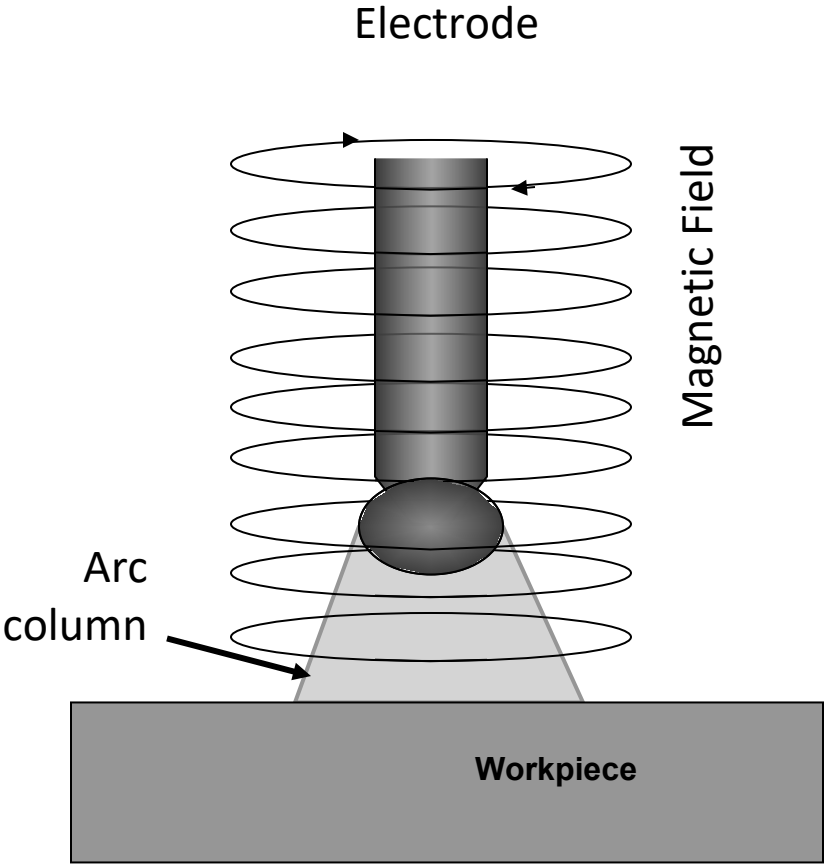
Spray Transfer



Droplets fly across the arc

Figure 3

Globular Transfer



Big drop forms and falls into weld pool creating spatter.

Figure 5

Heat Sink Effect  
Arrows Show Heat Flow Paths

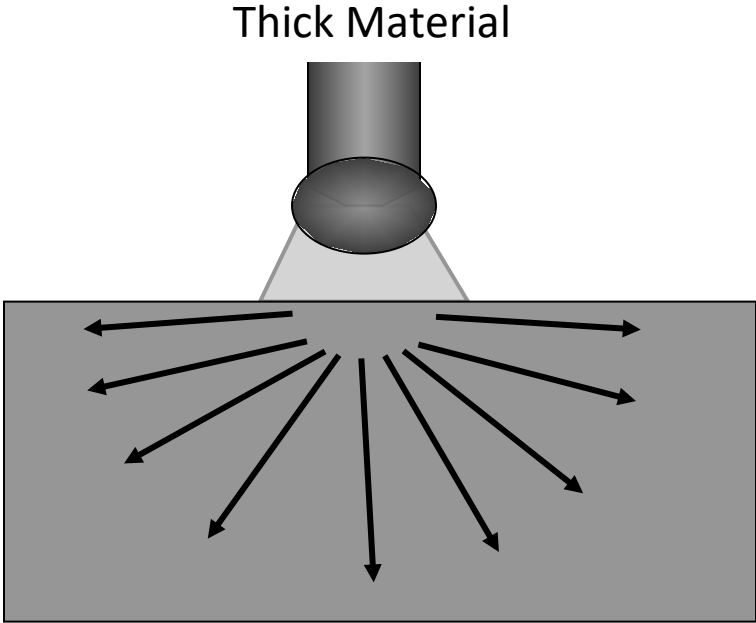
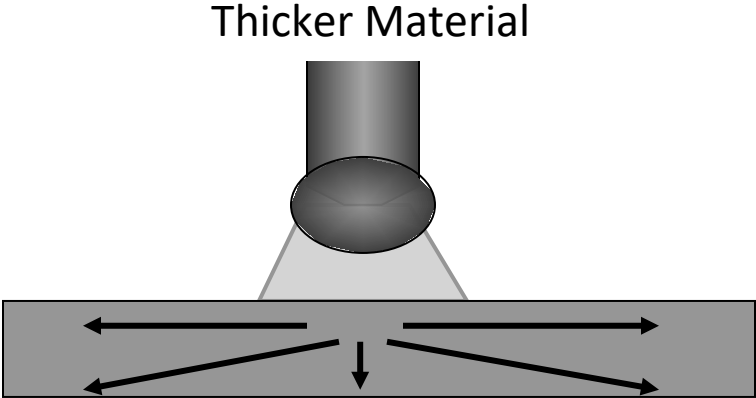
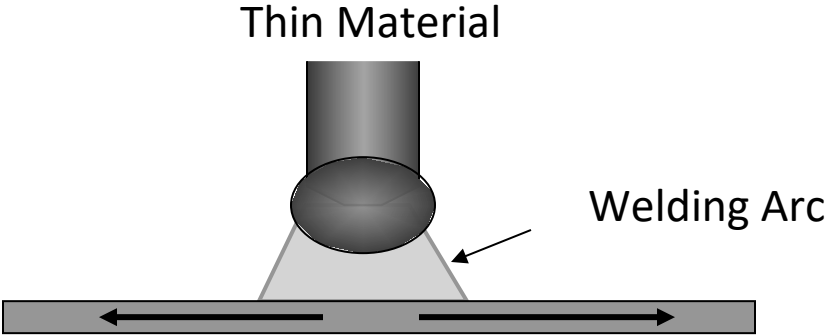
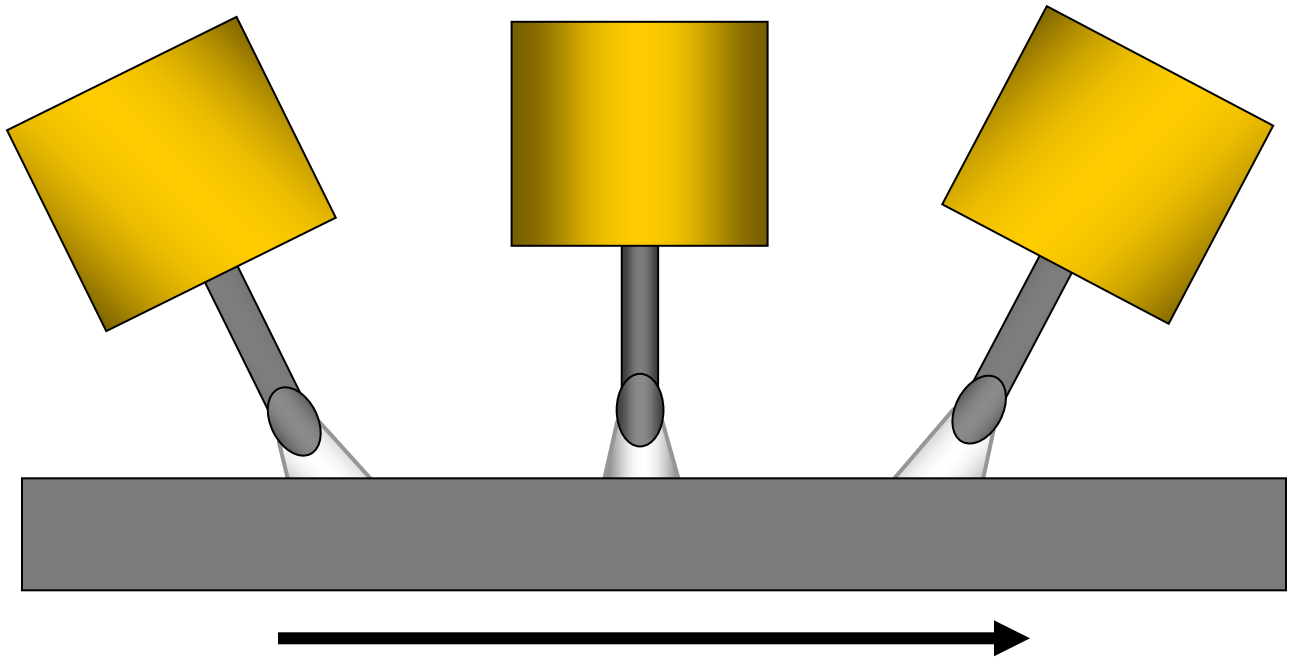


Figure 6  
Torch Angle

Pushing Angle

Upright (90°) Angle

Dragging Angle



Direction of Travel

Figure 7

Weld Pool Behavior in Vertical Position

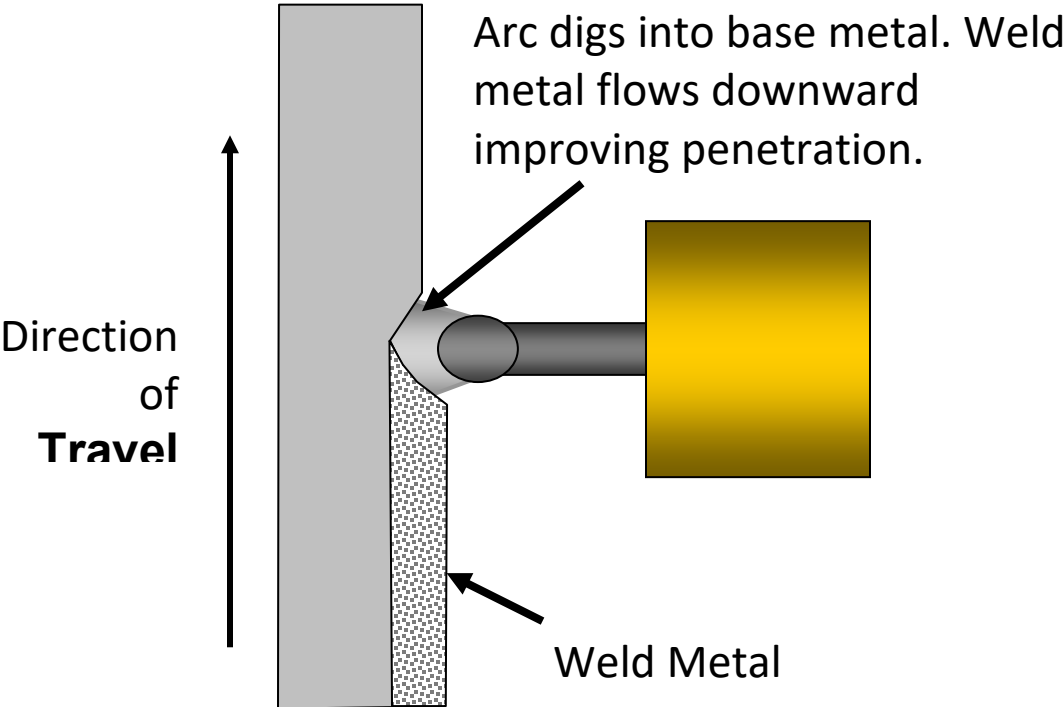
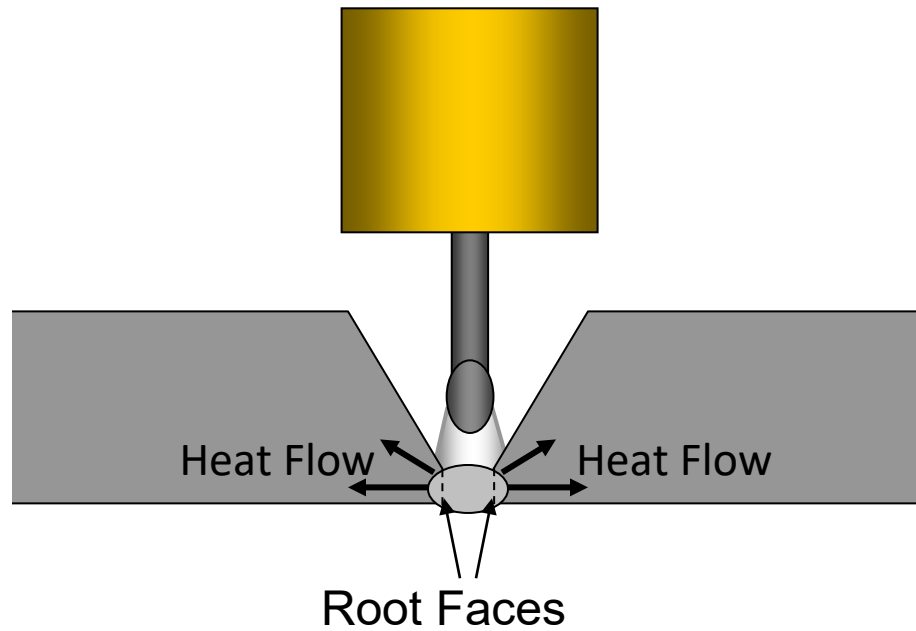


Figure 8

Heat Flow in Groove Weld Root Pass



All that needs to be melted  
is the small root face.

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