

ME 3370 Manufacturing Processes Laboratory

Lab No. 3: Welding Processes

1.1. Background information:

This lab will cover the different welding processes, such as welding by laser beam, friction stir welding, variable polarity plasma arc welding, gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW). The students will be having the chance to work with the GMAW and GTAW processes as well as on preparation of samples for the metallographic studies of weld, cross-section using an optical microscope and micro-hardness testing.

1.2. Process 1: Gas metal arc welding (GMAW)

1.2.1. Principle of operation

Gas-metal arc welding (GMAW) is a process that melts and joins metals by melting them with an arc established between a continuously fed wire and metal, as shown in Fig. 1. Shielding of the arc and the molten pool can be provided by using inert gases such as argon (Ar) and helium (He). More often to improve smooth metal transfer with low spatter loss and good weld penetration non-inert gas, particularly CO is mixed with Ar especially for aluminum alloys.

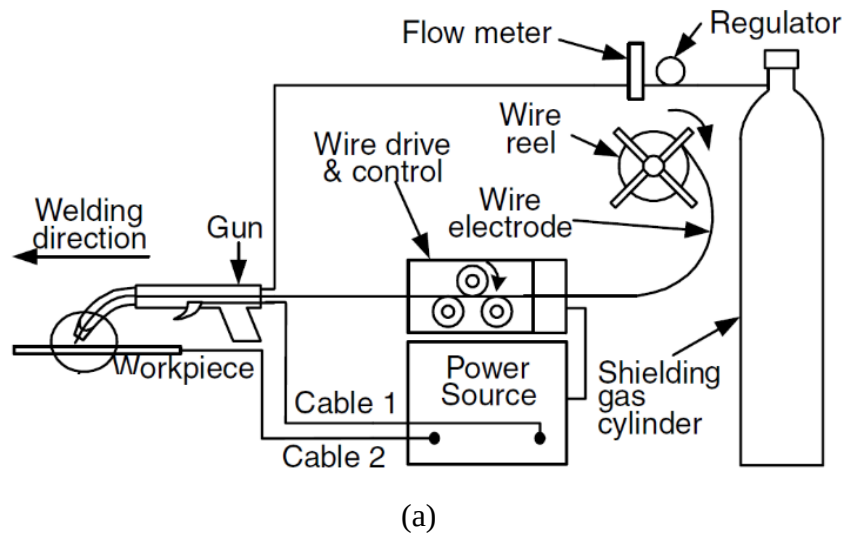


Fig. 1. Schematic of the (a) gas-metal arc welding (GMAW) [1].

Fig. 2 shows as the power density of the heat source increases, the heat input to the workpiece that is required for welding decreases. The portion of the workpiece material exposed to a gas flame heats up so slowly that, before any melting occurs, a large amount of heat is already conducted away into the bulk of the workpiece. Excessive heating can cause damage to the workpiece, including weakening and distortion. On the contrary, the same material exposed to a sharply focused electron or laser beam can melt or even vaporize to form a deep keyhole instantaneously, and before much heat is conducted away into the bulk of the workpiece, welding is completed [1].

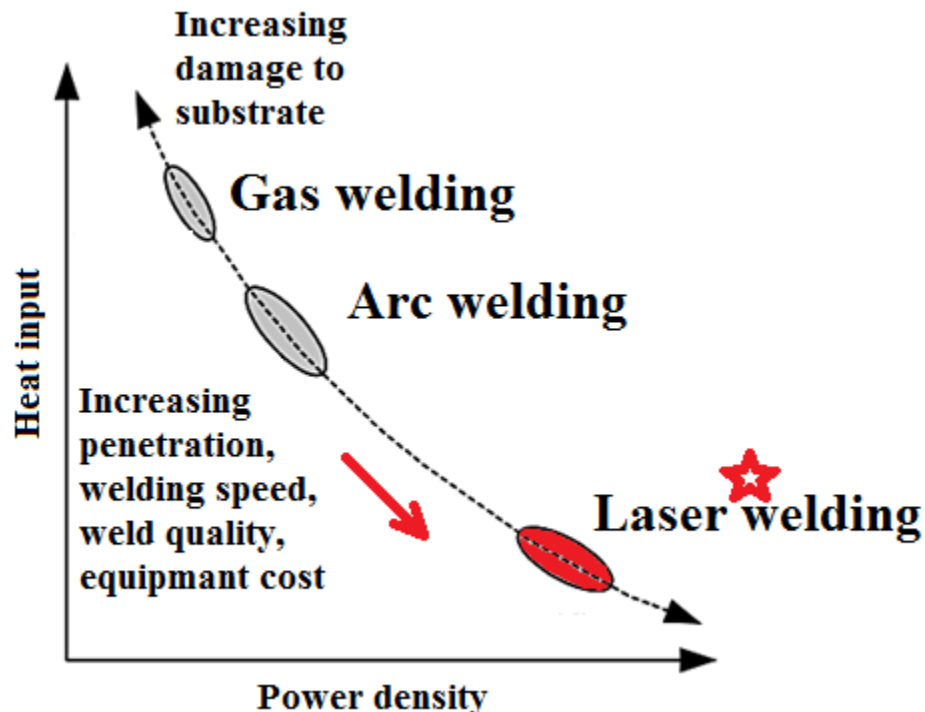


Fig. 2. Variation of heat input to the workpiece with high power density of the heat source [1].

Fig. 3 shows the manual Miller MIG machine in Lyle School of Engineering, SMU for the welding of materials. Table 1 also indicates the components of the machine. The students will perform the welding by MIG under supervision of the instructor. This will help them to learn about the positioning of the torch and influence of the process parameters.

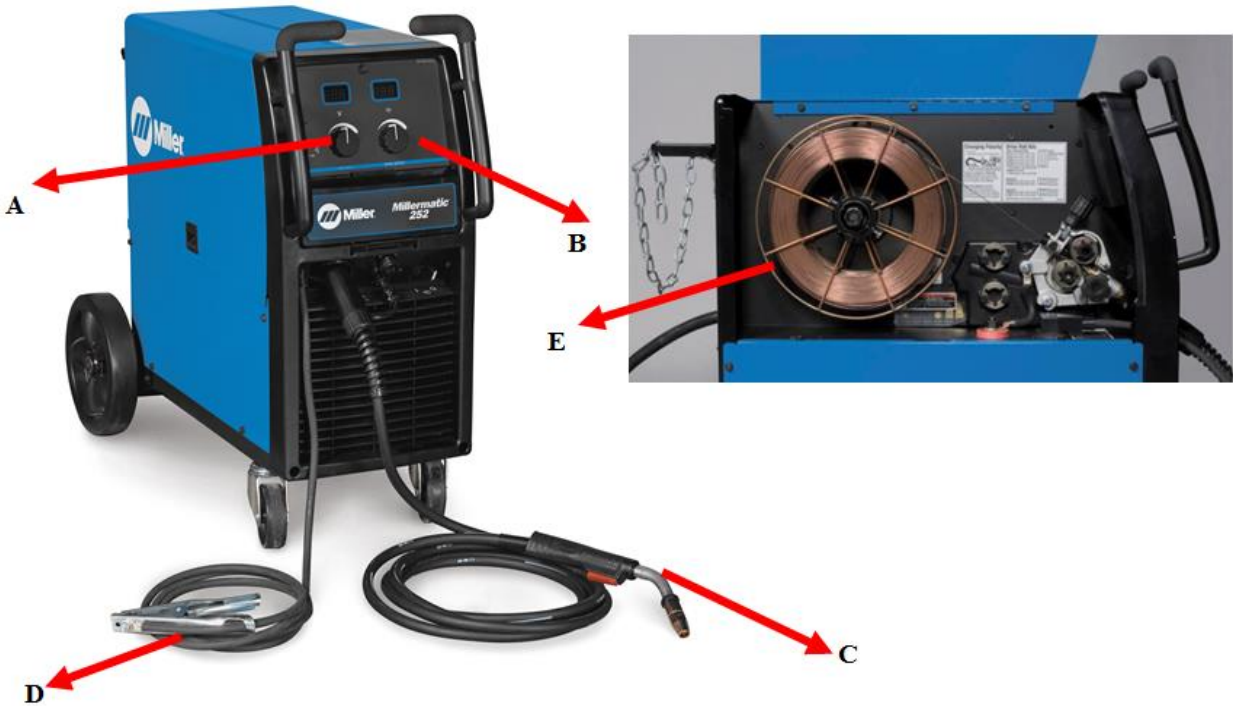


Fig. 3. Miller MIG welding machine.

Table 1. Millermatic GMAW components.

Item	A	B	C	D	E
Component name	Voltage control	Wire speed control	Gun conduit cable	Work cable	wire spool

1.3. Process 2: Gas tungsten arc welding (GTAW)

Gas-tungsten arc-welding (GTAW) is a process that join the metals by melting them with an arc established between a non-consumable tungsten electrode and the metals, as shown in Fig. 4. The torch holding the tungsten electrode is connected to a shielding gas cylinder as well as one terminal of power source.

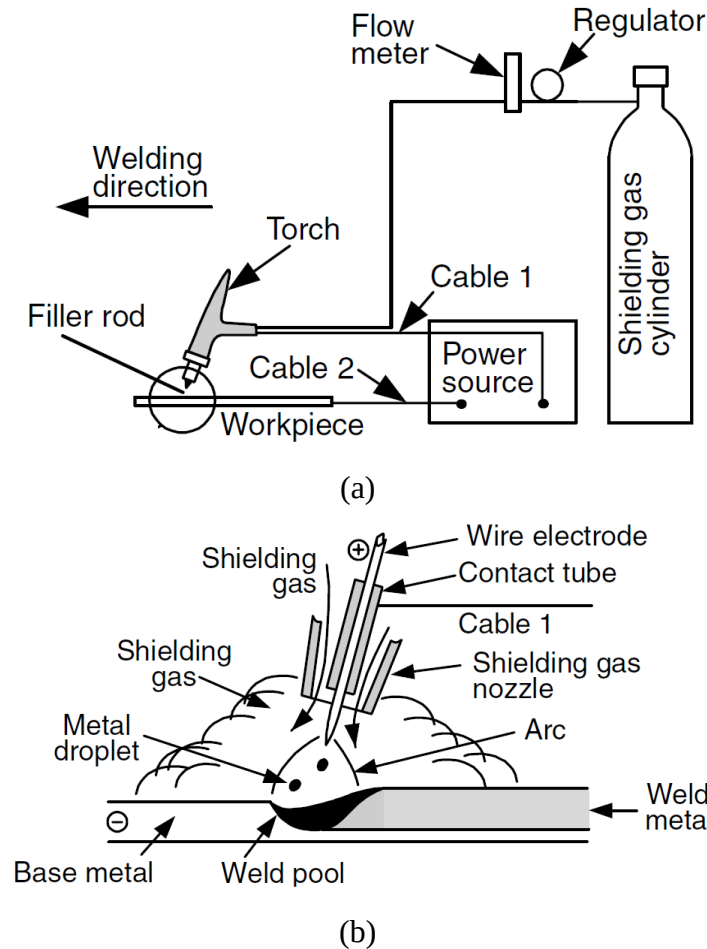


Fig. 4. Schematic of the (a) GTAW, and (b) welding area [1].

The tungsten electrode is usually in contact with a water-cooled copper tube. This allows both the welding current from the power source to enter the electrode and the electrode to be cooled to prevent overheating. The shielding gas goes through the torch body and is directed by a nozzle toward the weld pool to protect it from air. Polarity, one of the most important parameter, can be set in three different types:

- 1- Direct-current electrode negative (DCEN) is the most common polarity in GTAW. The electrode is connected to negative terminal of the power supply. In this case, electrons are emitted from tungsten electrode and more power (about two-thirds) is located at the work end of the arc and less (about one-third) at the electrode end. Thus, this polarity is suitable for deeper penetration.

- 2- Direct-current electrode positive (DCEP) is also called reverse polarity. The electrode is connected to the positive terminal of the power source. In contrast to previous case, the heating effect of electrons is now at the tungsten electrode. In this case, the positive ions of the shielding gas bombard the workpiece, as shown in Fig. knocking off oxide films and producing a clean weld surface. Therefore, DCEP can be used for welding thin sheets of strong oxide-forming metals such as aluminum and magnesium, where deep penetration is not required.

Figs. 5 shows a GTAW Millermatic equipment in the Lyle school of engineering machine shops with its components. Table 2 also shows the names of the components of the GTAW machine.

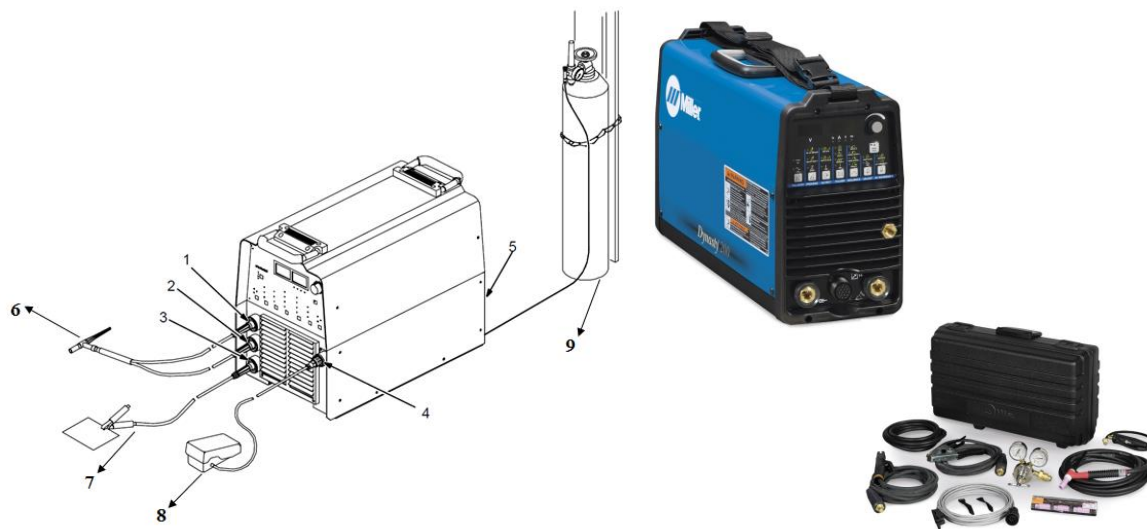


Fig. 5. Miller GTAW machine.

Table 2. Miller GTAW components.

	1	2	3	4	5	6	7	8	9
Component name	Negative weld output terminal	Gas output connection	Positive weld output terminal	Work cable	wire spool	TIG torch	Work cable	Remote receptacle	Shielding gas container

Table 3 indicates the advantages and disadvantages of the GTAW and GMAW over each other.

Table 3. Advantage and disadvantages of GTAW and GMAW.

	Advantages	Disadvantages
GTAW	• Very clean process when using an inert shielding gas • Higher deposition rate which allows thicker workpieces to be welded at higher welding speeds • The skill to maintain a very short and stable arc in GTAW is not required	• Bulky and difficult-to-reach small areas or corners • Large heat input and formation of wide HAZ compared by advanced welding process like Laser welding.
GMAW	• Suitable for joining thin sections due to its limited heat inputs • Very clean welding process to weld reactive metals such as titanium, zirconium, aluminum and magnesium	• Low deposition rate • Excessive welding currents can cause melting of tungsten electrode and results brittle tungsten inclusions in the weld metal

1.4. Process 3: Friction stir welding

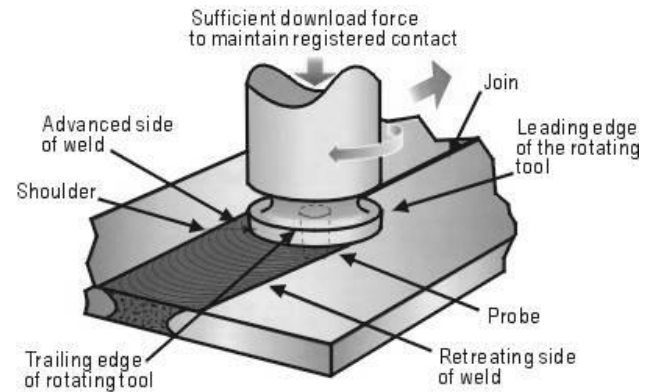
1.4.1. Principle of operation

Friction stir welding (FSW), invented at the Welding Institute (TWI) in 1991, is arguably the most significant development in solid-phase welding in the last decade. The basic concept of FSW is relatively simple. A rotating tool with a pin and shoulder is inserted in the material to be joined. The pin traverses along the joint line while the shoulder is in contact with the top surface. The workpieces have to be clamped onto a backing plate and secured against vertical, longitudinal and lateral movements. Rotary motion of the shoulder generates frictional heat that creates a softened and plasticized region around the pin and contacting surface. The shoulder prevents plasticized material from being expelled. A weld joint is produced by the extrusion of plasticized

material from the leading side to the trailing side of the tool (see Fig. 6). Table 4 shows the advantages and disadvantages of the FSW.



(a)



(b)

Fig. 3. Friction stir welding (a) machine and (b) its principle.

Table 4. Advantages and disadvantages of FSW for joining different materials.

Advantages	Disadvantages
• Ability to join materials which are difficult to fusion weld • Low distortion, even in long welds • Excellent mechanical properties • No fume, no porosity • Energy efficient • Non-consumable tool • No filler wire • No gas shielding required • No welder certification • Some tolerance of imperfect weld preparation (thin oxide layers can be accepted)	• Welding speeds are moderately slower than those of some fusion welding processes • Workpiece must be rigidly clamped • Backing bar required • Keyhole at the end of each weld

1.4.2. Applications

Friction stir welding is a very attractive technology because of its simplicity and applicability to a wide range of alloys. It offers a variety of new design and production welding opportunities, and is of particular interest to the shipbuilding, aerospace, and automotive industries. Table 5 shows the details of some of the applications of the FSW in different industries.

Table 5. Details of some of the applications of the FSW in different industries.

Shipbuilding and marine industries	• Panels for decks, sides, bulkheads, and floors • Aluminum extrusions
Aerospace Industry	• Wings • Aviation fuel tanks • External throw-away tanks for military aircraft • Military and scientific rockets
Railway industry	• High speed trains • Rolling stock of railways, underground carriages, trams • Container bodies
Land transportation	• Engine and chassis cradles • Wheel rims • Truck bodies • Fuel tankers

1.4.3. Materials and thicknesses

As a solid phase process, FSW operates below the melting point of the workpiece material. This process can join many types of materials. All aluminum alloys can be welded, including those that cannot normally be connected by conventional fusion welding techniques, such as the 2XXX and 7XXX series. Even welds of dissimilar aluminum alloys, such as 5053 to 6061 and 2024 to 7075, have been successfully performed. Friction stir welding successfully welds wrought and extruded alloys. Moreover, cast-to-cast, and cast-to-extruded combinations in similar and

dissimilar aluminum alloys are equally possible. Recent research reports confirm that welds can be successfully produced in copper and its alloys, lead, titanium and its alloys, magnesium alloys, zinc, and plastic. Preliminary investigations have established that the FSW technique can be applied to a wide range of material thicknesses. Single pass butt joints with aluminum alloys have been made in thicknesses ranging from 1.2mm to 50mm without the need for a weld preparation. Aluminum alloy 6082 in thicknesses up to 10mm has been welded using two passes, one from each side. The parameters for butt welding of most aluminum alloys have been optimized in a thickness range from 1.6mm to 10mm. Special lap joining tools have also been developed for aluminum with thickness of 1.2mm to 6.4mm.

1.4.4. Microstructure Classification

The examination of many friction stir welds in aluminum alloys has determined that there are four major microstructural zones, as indicated in Fig. 4.

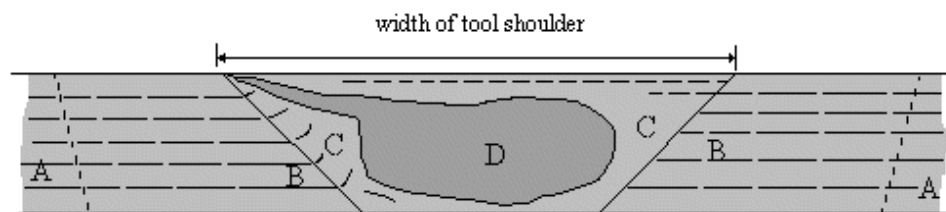


Fig. 4. Representation of microstructural regions in FSW.

- A. **Unaffected material** or parent material has not been deformed and may have experienced a thermal cycle from the weld but has not been affected by the heat in terms of microstructure or mechanical properties.
- B. **Heat affected zone (HAZ)** lies closer to the weld center. The material has experienced a thermal cycle, and modifications in the mechanical properties and microstructure are noticed. However, no plastic deformation occurs in this zone
- C. **Thermo-mechanically affected zone** has been plastically deformed by the friction stir welding tool, and the heat from the process will also have exerted some influence on the material.
- D. **Weld nugget** represents the recrystallized area in the TMAZ in aluminum alloys and has traditionally been called the nugget. It has been suggested that the area immediately below

the tool shoulder should be given a separate category, as the grain structure is often different here.

Typical microstructural features of all of the different zones of the friction stir butt welds of 6061-T6 Al-alloy are shown in Fig. 5. The microstructure of the weld is complex and highly dependent of the position within the welded zone. The fine grains in the nugget zone contrast with the TMAZ and HAZ where coarsened grains are observed.

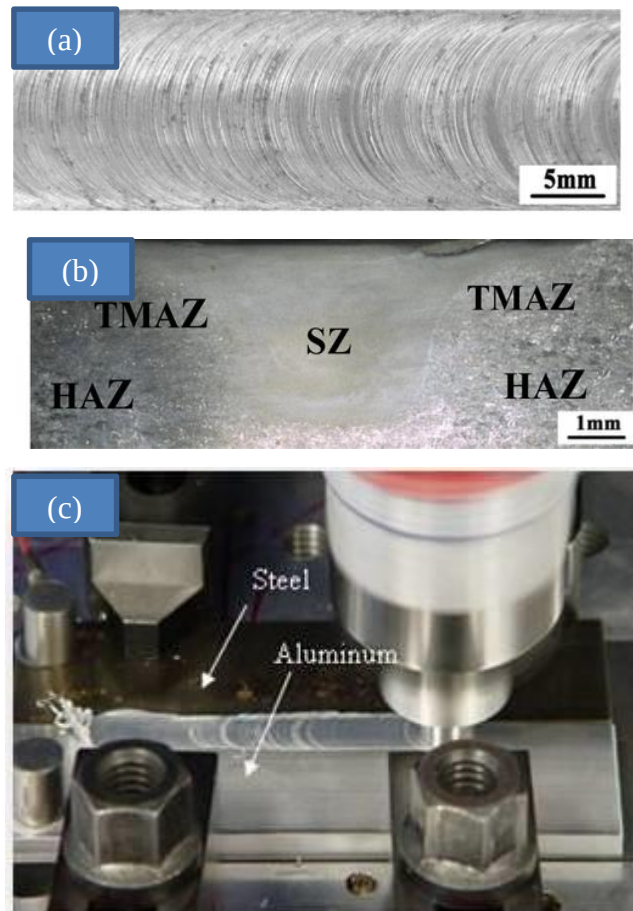


Fig. 5. Typical features of all different zones in a weld cross-section of 6061-Al alloy, (a) weld appearance, (b) cross-section, (c) FSW for welding dissimilar materials.

1.4.5. Friction stir welding tool

This technique uses a non-consumable steel welding tool to generate frictional heat at the point of welding and to produce the gross plastic deformation of the workpiece material while the material is in the solid phase, resulting in complex mixing across the joint. The tool, which consists of the shank, shoulder and pin, is rotating along the longitudinal axis in a conventional milling machine. The pin is equipped with a thread that assures that the plastically deformed material is fully distributed around the pin. High-quality welds can be produced using profiled pins (Fig. 6).

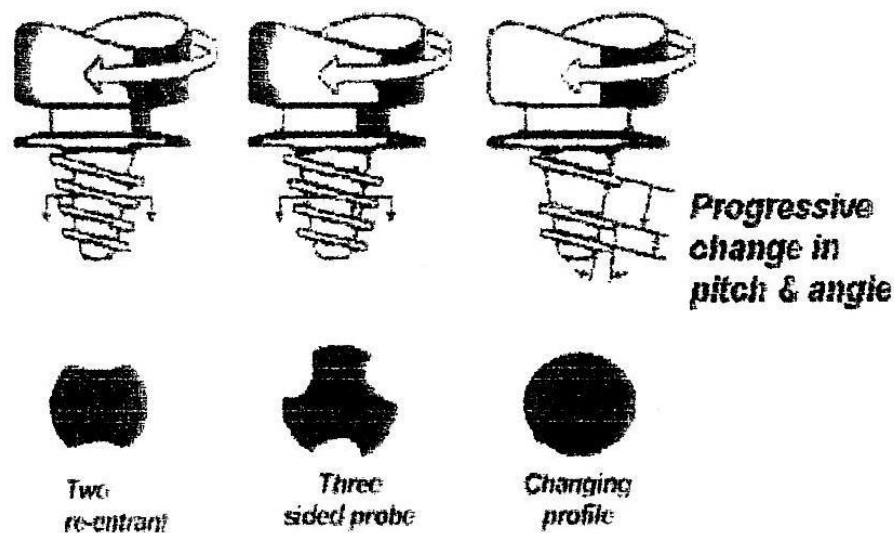


Fig. 6. The FSW pin structures for different applications.

For butt joining, the length of the pin is dictated by the thickness of the workpiece. It is necessary for the pin to pass very close to the backing plate, since only a limited amount of plastic deformation occurs below the pin. Modern pin designs include a conical shape, a non circular cross section, and conical spirals that allow the joining of 25-40mm thick plates of aluminum alloys by single-sided welding and up to 75mm thick plates by double sided welding. The main advantage of these new designs is that the tool pin provides an easier plastic flow of material. A more effective flow of the plasticized material around the tool is further achieved when the distance between each helical ridge is greater than the thickness of the ridge itself. The stirring effect of the tool is clearly visible in transverse microsections of the weld of dissimilar materials. The shoulder of the new generation of tools has sophisticated profiles. The shoulder profiles are designed to provide better coupling between the tool shoulder and the workpiece. Improved coupling is achieved by

entrapping plasticized material within special profiles, such as scoops, spirals and concentric grooves. The shoulder profiles with concentric grooves provide improved movement of the top surface layers of the plasticized workpiece material. Combined rotational travel speeds reproduced these concentric grooves as a series of continuous cycloidal paths on the weld track.

1.5. Process 4: Laser-based welding processes

1.5.1. Autogenous-laser welding

Laser beam welding (LBW) is a process that melts and joins metals and non-metals by fusing them with a laser beam. The laser beam can be produced in different ways, however, solid-state laser or a gas laser are the most common laser producers. To achieve high power densities, the laser beam needs to be focused through different optical means. In a solid-state laser, a single crystal is doped with small concentrations of transition elements or rare earth elements. For instance, in a YAG laser the crystal of yttrium-aluminum-garnet (YAG) is doped with neodymium. The power level of solid-state lasers has improved significantly, and continuous YAG lasers of 3 or even 5kW have been developed. Higher laser power can be achieved by CO₂ laser than s solid-state laser, for instance, 15kW.

The schematic of laser welding is shown in Fig. 7 welding speed and laser power are known as two important parameters that can affect the weld bead quality. The lab instructors will perform demonstration to show how the proceeding parameters has to set and will influence of the joints.

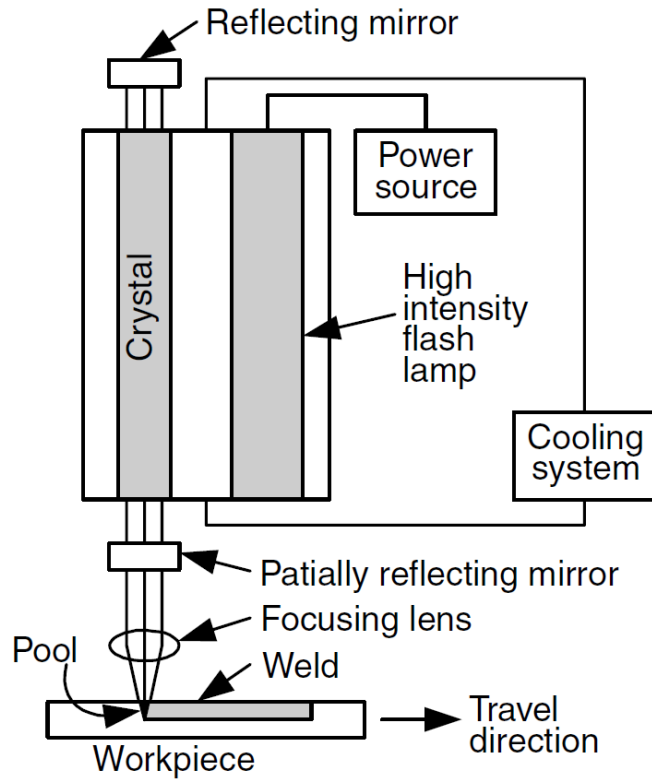


Fig. 7. Laser beam welding process.

Fig. 8 shows the keyhole formation and mechanism of the laser beam welding and cross section of a weld made by this method.

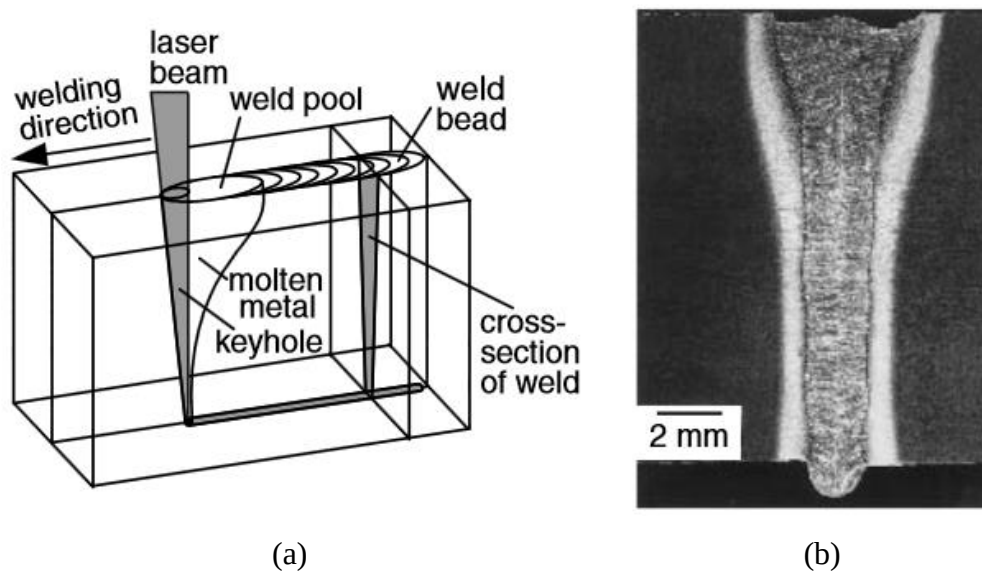
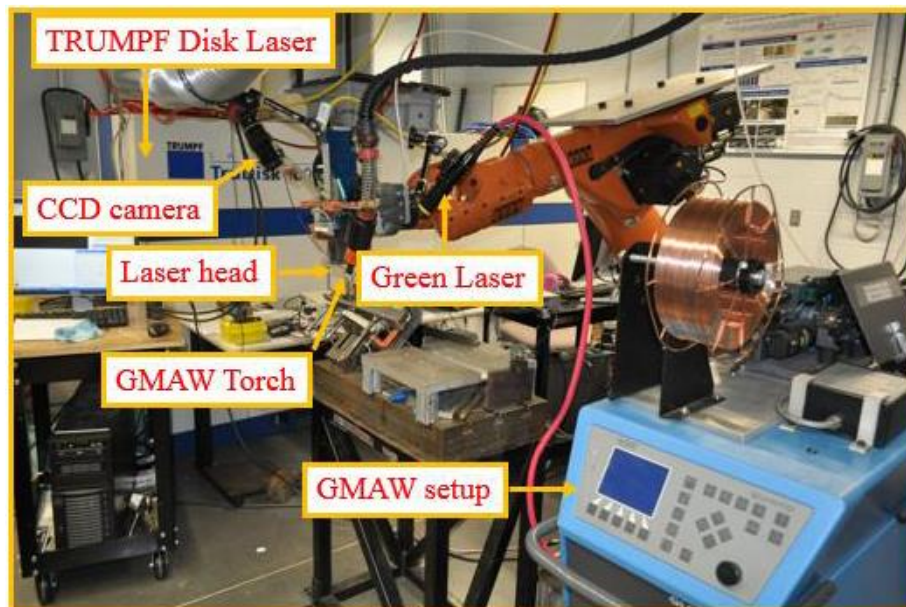


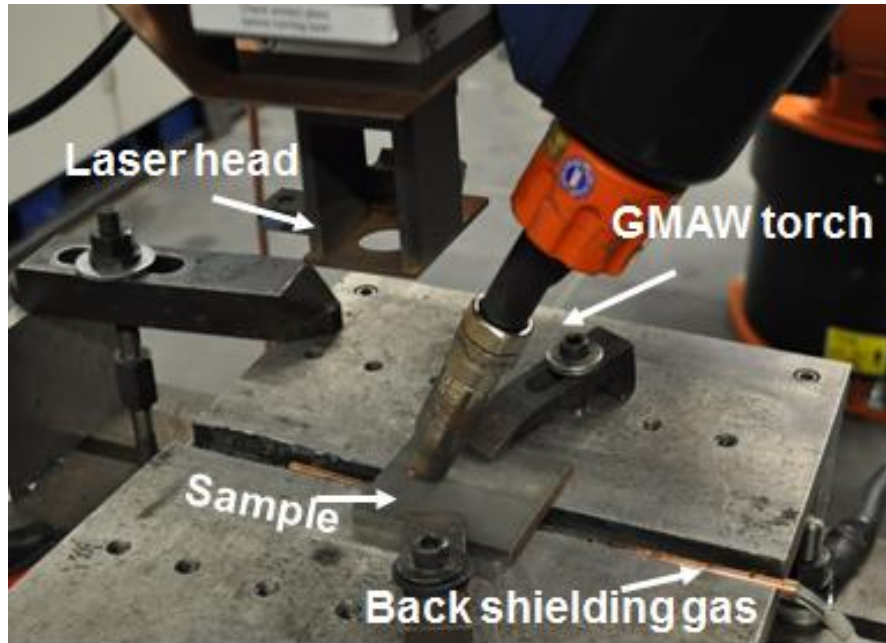
Fig. 8. Laser beam welding (a) keyhole formation and (b) cross-section [1].

1.5.2. Hybrid laser arc welding (HLAW)

By combination of laser and arc heat source, significantly greater penetration can be obtained than the conventional GMAW and LBW. In addition to direct heating, the laser beam acts to focus the arc by heating its path through the arc (Fig. 9). This increases ionization and hence the conductivity of the arc along the beam path and help focus the arc energy along the path. One of the most applications of the HLAW is its capability to weld dissimilar metals and heavy thick sections [3]. The interest for using HLAW is to achieve higher production rates for materials such as HY-80 steel for submarine fabrication as well as for the welding of high strength materials for cross country pipelines. Without the laser, it will take 10 passes to weld a one-inch-thick steel. With the laser assisted with arc a narrow groove could be generated in just one pass. Deep penetration, high speed, narrow weld bead and HAZ, high quality welds, suppression of humping, reduction of porosities in the weld, possibility to add filler materials, good tolerance to joint fit-up are the main capabilities of the HLAW process [4].



(a)



(b)

Fig. 9. Hybrid laser/arc welding (a) set-up, and (b) close-up of the positioning laser and arc.

The laser's small spot size creates a very high energy density and actually helps stabilize the arc. The laser penetrates deep into the joint, produces a narrow heat-affected zone, and enables a high welding speed. All this helps dramatically lower heat input (see Fig. 10).

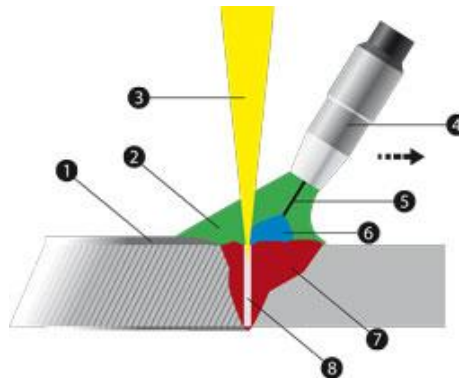


Fig. 10. Hybrid laser-arc welding (HLAW) uses a wire arc welding process with a laser beam. The laser provides concentrated energy for high penetration, while the arc helps overcome fit-up challenges. Process elements include: (1) newly formed weld bead; (2) inert shielding gas; (3) focused laser beam; (4) GMAW gun; (5) wire electrode; (6) electric arc; (7) molten pool; and (8) the keyhole.

Table 6 indicates the advantages and disadvantages of LBW and HLAW processes.

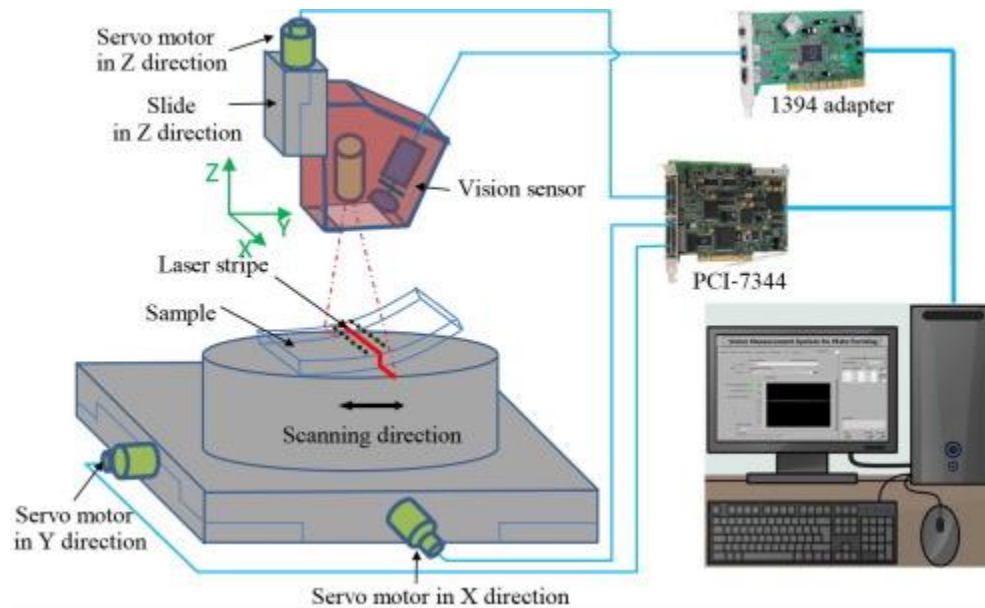
Table 6. Advantages and disadvantages of LBW and HLAW processes.

Process	Advantages	Disadvantages
LBW	• Production of deep and narrow welds at high welding speed • Narrow heat affected zone • Little distortion of the workpiece	• Very high reflectivity of laser beam especially for aluminum • High capital cost of laser equipment • Requirement of precise joint fit-up and seam tracking devices • Limitation of high penetration for thick parts.
HLAW	• Suitable for joining thick sections due to its limited heat inputs • Reduction in laser power requirement	• Requirement of precise adjustment of high number of operating parameters • Larger heat affect zone compared with laser alone

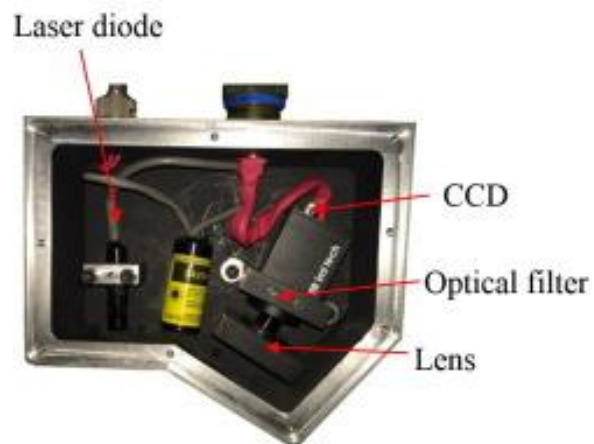
1.5.3. Seam tracking feed-back control

The laser-based vision measurement system (seam tracking) includes three major modules: a laser-based vision sensor module, an image-processing module, and a multi-axis motion control module. A laser stripe was projected perpendicularly at the measured surface. The height information of the stripe can be determined by processing the image of the laser stripe captured by the vision sensor module. The vision sensor is installed at the vertical axis of a multi-axis liner positioning system (Fig. 11). The worktable could move along the scanning direction (Y direction) so that the vision sensor could scan the full length of the target surface. During the scanning process, the physical Y position of the stripes could be recorded by the servomotor. The 3D profile data of the entire surface then could be reconstructed by the image-processing module. As a standard yet flexible off-the-shelf development platform, LabVIEW is used to develop the image-

processing module, the multi-axis motion control module, and the end-user interface. A fire wire 1394 adapter is adopted into the system to capture the frames. A National Instrument (NI) 4-axis motion controller PCI-7344 is also used to control the three servomotors [5].



(a)



(b)

Fig. 11. (a) Schematic of the measurement system, (b) laser-based vision sensor [5].

1.6. Microhardness Testing

In order to study the effect of welding process on mechanical properties and softening behavior of the joint and base metal, it is necessary to evaluate the hardness of the transvers cross-

section of the weld joint. Hardness change through the weld, HAZ and base metal is dependent on the width of fusion zone and HAZ area. Generally for welding processes involved in this lab the width of those zones are less than 20 mm. To increase the accuracy, micro-hardness test is the best way to get the hardness profile through the weld cross section. Clark Micro-hardness tester is digital-equipment used to collect hardness measurements (Fig. 12). The details of how to operate this apparatus will be given by the instructor. Also, the prepared video on BLACKBOARD can be useful to learn the steps of working with Micro-hardness. The students will be given the chance to perform the Microhardness test for the welded samples to see the influence of the processing parameters on the variations in the hardness.

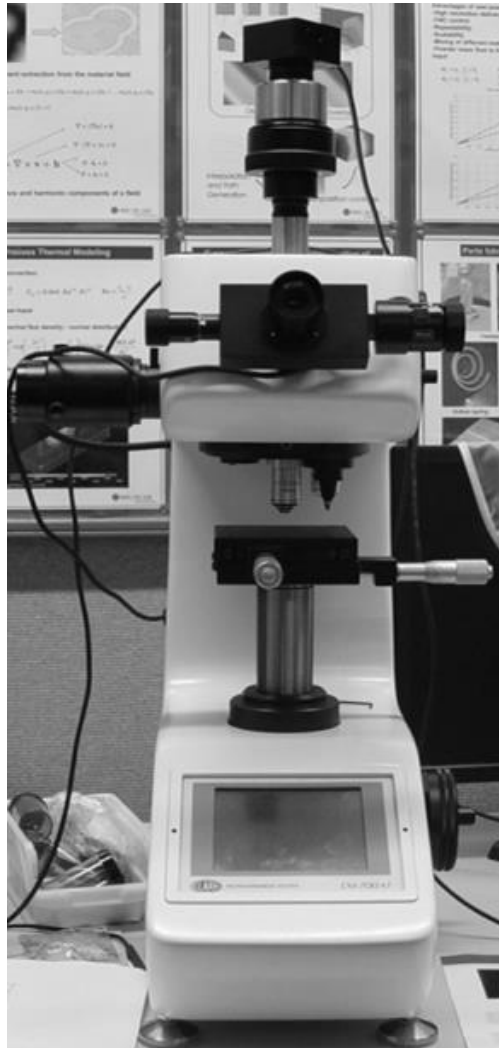


Fig. 12. Clark Micro-hardness setup in RCAM.

References

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