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Laser-TIG hybrid welding process

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ABSTRACT

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Joining processes and techniques need to meet the trend of new applications and the development of new materials. The application in connection with thick and thin plates in industrial fields is wide and the joining technology is in very urgent need. The laser-TIG hybrid welding technology can play the respective advantages of both of them. One major advantage of the hybrid laser-TIG welding technology is its efficient use of laser energy. Additionally, it can develop into a high and new advanced welding technology and become a hot spot in both the application and research area.

This thesis investigated laser –TIG hybrid welding with the aim of enlightening the reader on its advantages, disadvantages and future areas of improvement.

The main objective is to investigate laser-TIG hybrid on the welding of various metals (steels, magnesium, aluminium etc.). In addition, it elaborates on various possible combinations on hybrid laser-TIG welding technology and their benefits. The possibility of using laser-TIG hybrid in welding of thick materials was investigated. The method applied in carrying out this research is by using literature review. The results showed that hybrid laser-TIG is applicable to almost all weldable metals. Also it proves to be effective in welding refractive metals. The possibility of welding with or without filler materials is of economic advantage especially in welding of materials with no filler material. Thick plate's hybrid laser-TIG welding is showing great prospects although it normally finds its used in welding thin materials in the range of 0.4 to 0.8 mm. The findings show that laser-TIG hybrid welding can be a versatile welding process and therefore will be increasingly used industrially due to its numerous advantages and the development of new TIG arc that enhances its capabilities.

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SYMBOLS AND ABBREVIATIONS

AC	Alternating current
Al	Aluminum
BPP	Beam parameter products
CCS	China Classification Society
CO_2	Carbon Dioxide
Cr_2O_3	chromium (III) oxide
CW	Cold Wire
DC	Direct Current
DCEN	Direct- Current Electrode Negative
DCEP	Direct -Current Electrode Positive
DL_A	Distance between laser and arc
D/W	Depth to width
H	Hydrogen
He	Helium
HPDL	High Power Diode Laser
HW	Hot wire
Hz	Hertz
K	Kelvin
LATIG	hybrid laser-TIG
M^2	Beam Propagation Ratio
MAG	Metal Active Gas
Mg	Magnesium
Nd:YAG	Neodymium-Doped Yttrium Aluminum Garnet
N	Nitrogen
Ni	Nickel
PCTIG	Pulsed current Tungsten Inert gas
PW	Pulsing Wave
Si	Silicon
SiO_2	Silicon Oxide
Ti	Titanium
TIG	Tungsten Inert Gas
TiO_2	Titanium Oxide

X-ray	X radiation

1. INTRODUCTION

Laser welding technology has become an integral part of modern welding due to its unique fabrication opportunities. Although, the invention dates back to the 1970s, the practical application of its technology is still relatively new. The utilization of laser techniques is increasing due to the high efficiency of lasers and the development of laser applications such as laser welding, laser gladding, laser cutting. Laser welding has some disadvantages, such as high metallic surface reflection, depth penetration restriction ($\leq$ 25mm) and strict tolerances for groove preparation. Specifically for the welding of large thick plates, laser welding does not only needs expensive equipment with high power and high beam quality, but also has a great aspect ratio, that makes it difficult for the gas in the molten pool to rise and escape during welding[1]. As a result, the tendency of pore formation increases and the mechanical properties of the welded joint may considerably deteriorate. These challenges have led to the development of modified welding process called hybrid laser welding.

Hybrid laser welding is a welding technique which combines laser welding process and an arc welding so that both heat sources are incident on a single weldpool [2-4]. Hybrid laser welding have received much attention due to high speed processing, high efficiency and high quality, which results from its ability to compensate for drawbacks of the individual welding processes [5-7]. The most common hybrid systems are laser-MAG and hybrid laser-TIG. In addition to overall efficiency improvements, other advantages have been reported, including increase in groove gap tolerance, porosity reduction and greater arc stability [5, 7-9]. The ease of groove preparation and use of secondary energy source enables weld property modification by adjusting the heat input or by adding alloying elements to the weld through the application of filler material, are further advantages.

Steen and Eboo combined CO_2 laser and TIG arc and found that the electric arc is rooted to the point where the laser interacts[10]. Subsequently, laser-TIG hybrid (LATIG), has several advantages such as improvement in heat efficiency, increase in penetration and arc stability when welding Al alloys [11, 12]. In addition, accurate prediction of weld pool shape by neural network modeling, which indicates that the penetration is a sensitive function of the laser power [13]. In addition to these advantages, Gao et al.[14] showed that laser-TIG hybrid welding process can be applied successfully to welding of ultra-fine grained steel and that the process permits the use of higher welding speed while obtaining sound welds with sound mechanical performance. The development different laser sources(disc, fiber and fiber-delivered high-power diode lasers) and heat sources in hybrid welding is of great interest and has led further need for investigation of LATIG. The last decade has seen the development of different TIG process (TIPTIG, TOPTIG, Hot wire TIG) with aim of improving productivity.

Joining of thick plates is an important industrial process with wide a range of applications. Comprehensive knowledge of effective joining technologies is thus essential. Considering the advantages in combining laser and TIG arc, there is a considerable interest in the prospects of LATIG.

The purpose of this paper therefore is to review recent research on hybrid laser-TIG process for non-ferrous and ferrous materials. In addition, the work presents laser sources available for possible combination to TIG arc, allowing enhanced efficiency of hybrid laser-TIG welding.

1.1 The objectives of the work

The objective of this research is to;

1. Investigate the prospects of laser-TIG hybrid welding process
2. Elaborate on various possible combinations on hybrid laser-TIG welding and their benefits in welding of various metals.
3. Investigate the possibilities of using hybrid laser-TIG welding of thick metals in the near future

1.2 Research Methodology

The research objective as stated previously addresses new solutions to existing challenges in the welding industry. In order to achieve the objectives, a comprehensive literature review approach is use to serve as a basis for the new suggestions and proposals. In this regard, handbooks, journals, articles and conference papers were studied, evaluated, discussed and presented in this paper.

2 LASER TYPES USED IN HYBRID WELDING

There are different types of lasers used in materials processing even though many lasers have being in existence since 1960 [15]. Generally laser has an effect on the process, being it keyhole condition or conduction. In most laser welding, keyhole is prefered except welding of thin materials. Nevertheless conduction can be applied also in some circumstances for larger components [16]. Keyhole welding is extensively used because it produces welds with high aspect ratios and narrow heat affected zones, nevertheless keyhole welding can be unstable, as the keyhole oscillates and closes intermittently. The intermittent closure causes porosity due to the gas set up. Conduction welding, on the other hand, is more stable since vaporisation is minimal and hence there is no further absorption below the surface of the material [17]. Various laser types exist in hybrid laser welding which can be classified into micro processing and machine shop processing as shown in Figure 1.

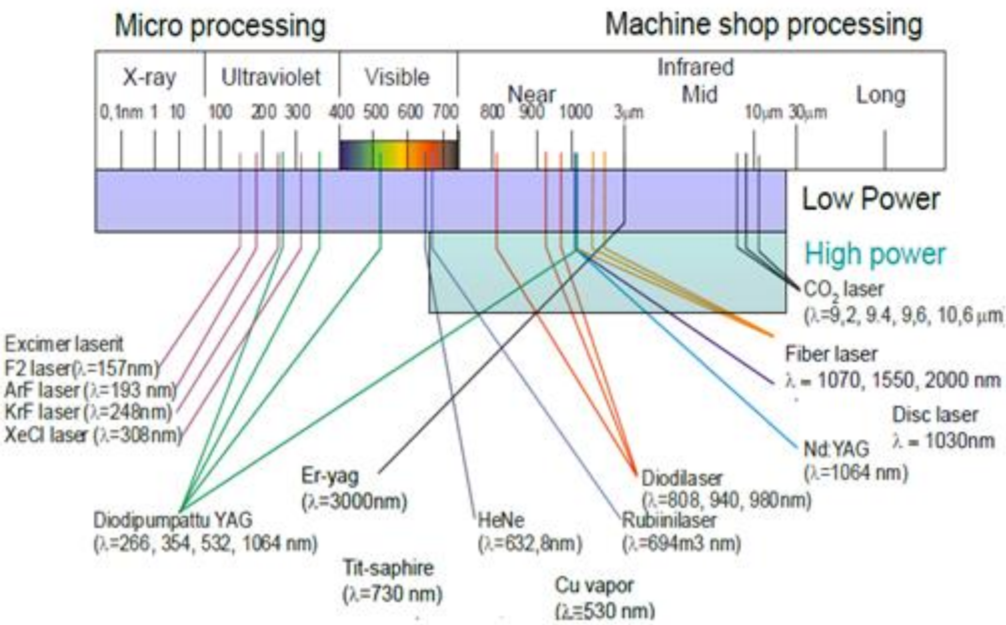


Figure 1. Types of lasers used in welding [18].

The major laser types used in welding are Nd:YAG, solid state and CO_2 gaseous state laser. Lately Yb:YAG , disc and Fiber lasers which has high output power as well as high beam quality are existing and are increasingly been used. [19]. The high-power diode laser was in the past preferred for conduction mode welding processes due to characteristics such as; emitted wavelength of the used lasing medium, the maximum output power available, the theoretical beam and the power conversion efficiency. The mobility of the laser system and characteristics maintenance interval is presented in Table 1.

Table 1. Illustrating feature comparison for typical materials processing laser sources [20].

	Nd:YAG laser (Lamped- pump)	Nd:YAG laser (Diode- pumped)	Disc laser	Fiber laser	CO_2 laser	Diode laser (fiber-coupled)
Laser medium	Crystalline rod	Crystalline rod	Crystalline disc	Doped fiber	Gas mixture	Semiconductor
Emitted wavelength (µm)	1.06	1.06	1.03	1.07	10.6	0.808–0.98
Power efficiency (%)	1–3	10-30	10-20	20–30	10–15	35–55
Maximum output power (kW)	6	6	8	50	20	8
BPP at 4 kW (mm rad)	25	12	2	0.35	4	44
M^2 at 4 kW	75	35	6	1.1	1.2	150
Fiber beam delivery	Yes	Yes	Yes	Yes	No	Yes
Typical fiber diameter at 4 kW (mm)	0.6	0.4	0.1-0.2	0.03–0.1	-	0.4
Mobility	Low	Low	Low	high	Low	High
Pump source	High Power Xenon flash lamps	High Power Xenon flash lamps			Electric discharge	

The main difference in these laser types are with their wavelength. The lower the wavelength the more possible the material will be able to absorb more laser light. The shorter wavelength is more useful in the welding of reflective materials such as aluminum, magnesium; titanium etc. Figure 2 shows typical values of BPP as a characteristics measure of the beam quality and a function of laser power in the range up to 10kW.

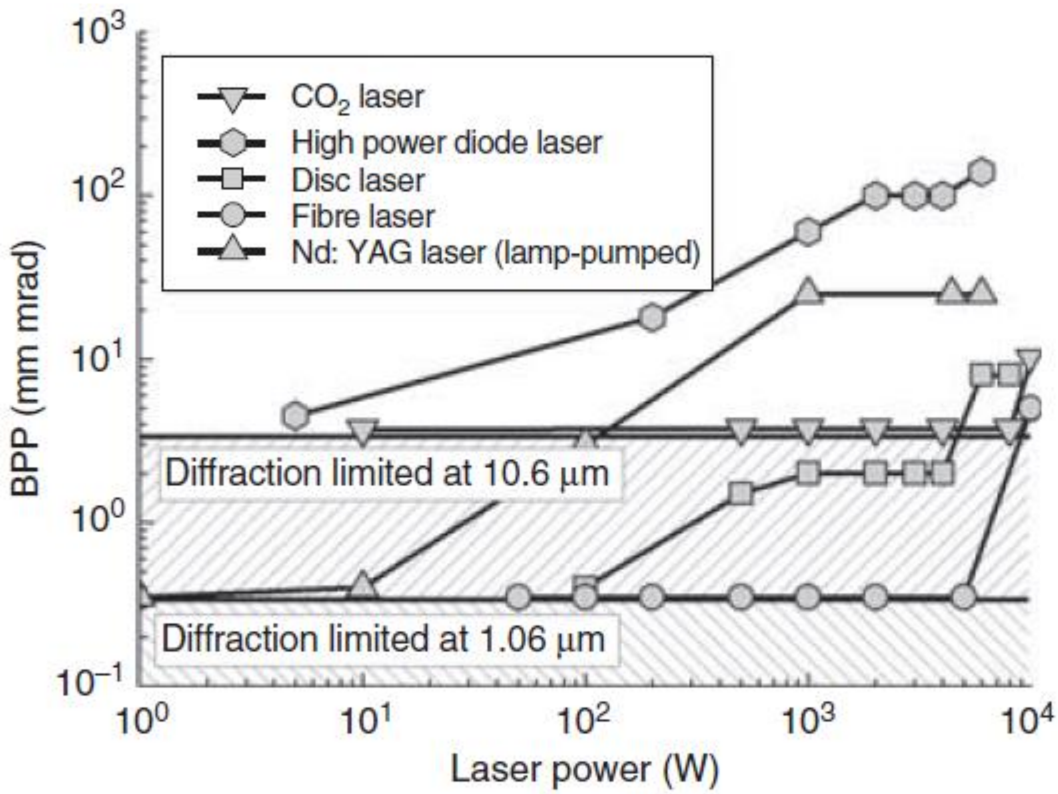


Figure 2. Characteristic of beam parameter products vs. laser power for different laser types [20].

There has been various development with laser sources since 1970s as illustrated Figure 3. The various types of laser used in welding are discussed in details in subsequent chapters.

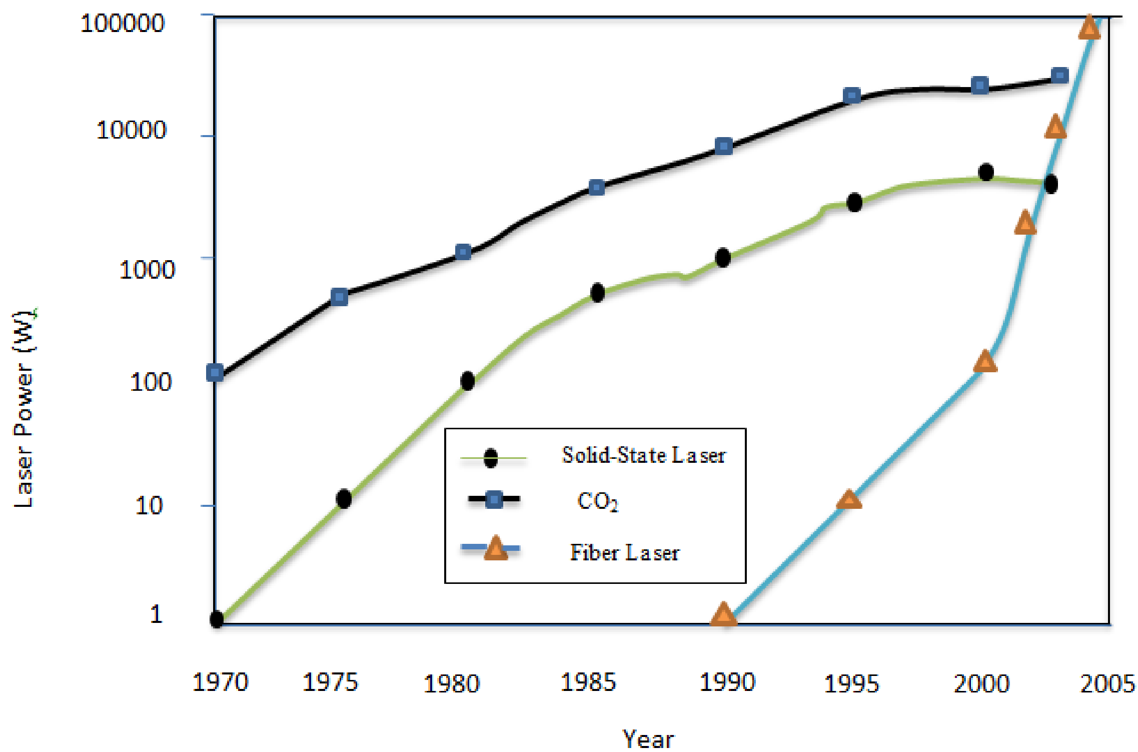


Figure 3. Development of Available Laser Sources [15].

2.1 CO_2 lasers

The CO_2 laser has been in existence for longer period and it is the most commonly used laser in material processing. A mixture of CO_2, N_2 and He in different amounts are used as the lasing meduim, depending on the laser resonator design, the operating pressure and the operating mode been it continuous or pulsed. The excitation of the CO_2 molecules is realised by means of an electric discharge through the gas mixture. Characteristically, conversion efficiencies of the CO_2 lasers lie in the range of 12 to 14%. The CO_2 lasers have been the highest countinuous wave (CW) power sources available for quite some time now. The maximum power output of current commercial systems amounts 20 kW. The wavelength of CO_2 laser is 10.6 µm whereas that of Nd: YAG laser is 1.06 µm, as illustrated in Figure 4. The smaller wavelength of Nd: YAG laser makes it more effective in the welding of reflective materials [19]. As mention in the previous chapter the keyhole formation which plays a major role in the welding of various matearials is dependent on the irridation intensity. CO_2 laser which has twice the irridation intensity than that of Nd:YAG laser makes it more efficient in keyhole formation [16]. During welding, CO_2 laser having longer wavelength beam is largely absorbed in great proportion by plasma created by the keyhole [21]. This intend causes the CO_2 laser beam to be partially blocked by the plasma. The absorption of the beam by the palsma can be reduced by the use of high potential ionization gases, for example helium although this has been tried with limited success [22-24]. Some disadavantages have been reported in conjunction with its long wavelength, that is most materials that are transparent within the visible range of the electromagnetic spectrum for example glass are reported to be opaque for CO_2 laser radiation. Consequently, required transmission elements of the laser resonator and the beam guidance must be manufactured from special materials such as zinc selenide and beam deflection and focusing must be realised by means of reflective optics such as gold-coated or multilayer coated copper substrates [20].

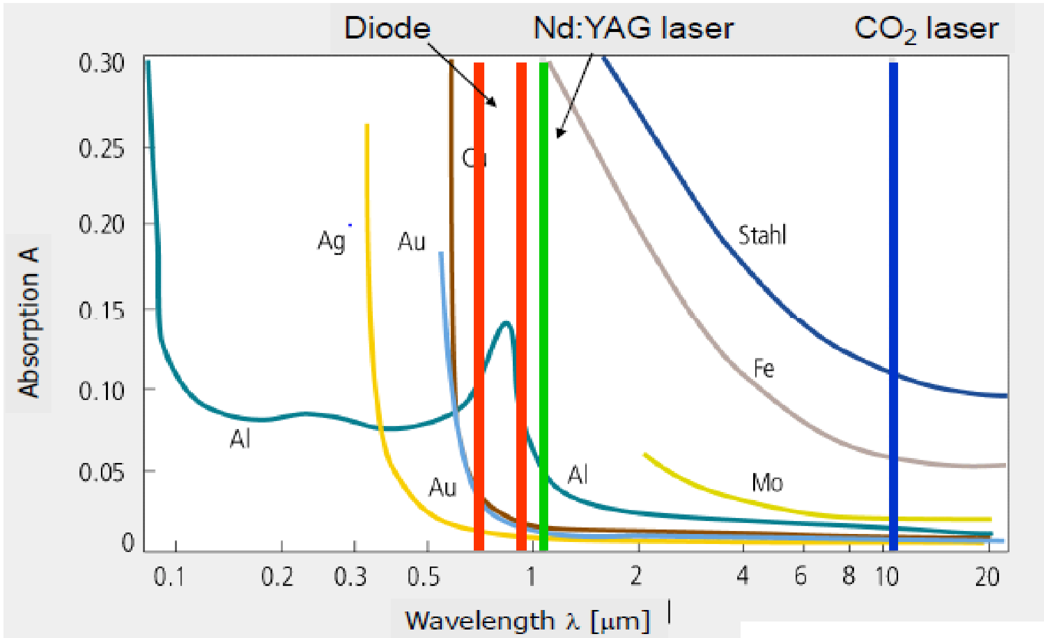


Figure 4. Wavelength dependent Absorption of Various Materials [25].

2.2 Nd: YAG lasers

Although Nd: YAG laser has been the most used solid state laser in hybrid welding for quite sometime now and has gain a lots of sucesss in welding of various metals, CO_2 was the first laser used in hybrid welding [26-33]. Nd:YAG laser is more dominant in various fields due to its possibility of delivery by glass fiber as well as its high output power and the improvement of beam quality. Excitation of electrons in neodymium is done with high-power xenon flash lamps between the ranges of 1-4 kV as represented schematically in Figure 5.

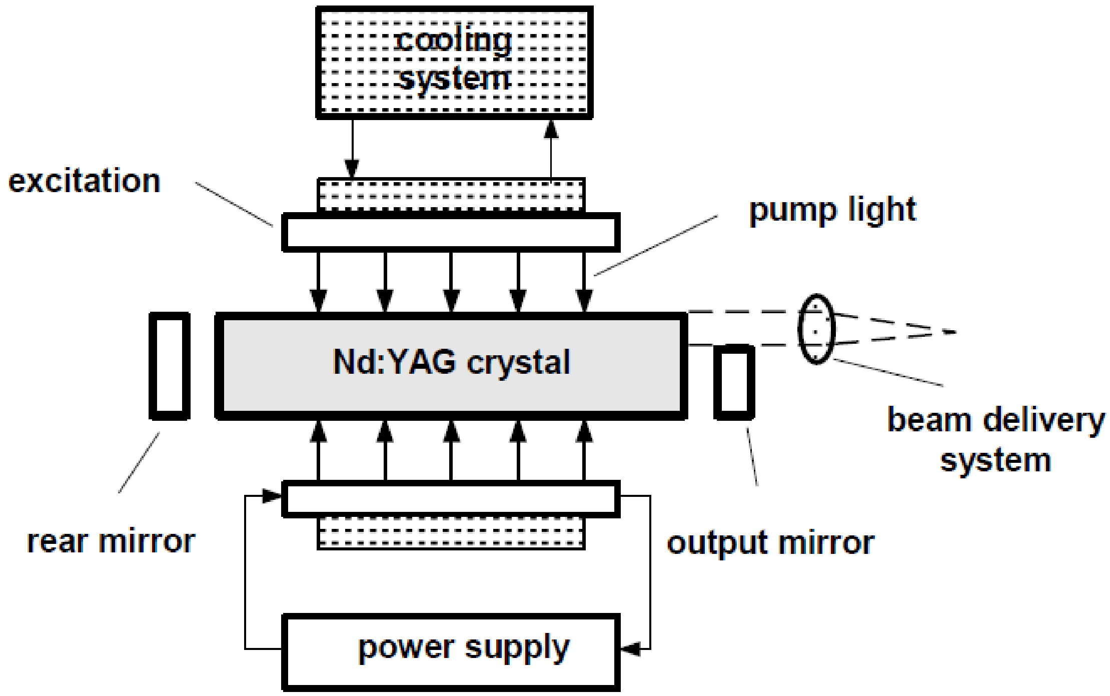


Figure 5. Schematic representation of a Nd: YAG laser system [34].

The weldability of magnesium alloys and aluminum alloys was reported to be considerably better with the Nd:YAG laser due to its shorter wavelength of 1.06 µm, which helps to reduce the threshold irradiance required for keyhole mode welding and aids in producing a more stable weld pool [35-37]. The Nd:YAG laser beams has a higher welding efficiency as compared to the CO_2 laser [36, 38, 39]. For example, it has been reported that for a 1.5 kW laser beam with a similar spot diameter and a welding speed of 5 m/min, a penetration depth of 2 mm was achieved for a Nd:YAG laser as compared to only 0.7 mm for the CO_2 laser [40-42]. Sanders et al. [38, 39], who also compared the weldability of a 1.8 mm wrought AZ31B-H24 alloy using a 2 kW pulsing wave (PW) Nd:YAG and 6 kW continuous wave (CW) CO_2 lasers came out with similar findings. It has been reported that very good welds were obtained with a Nd:YAG laser at a power of 0.8 kW with 5 m/s pulse width, 120 Hz frequency and a travel speed of 3 cm/s, on the other hand for a CO_2 laser comprehensive penetration welds were only produced at 2.5 kW and 12.7 cm/s. Additionally, it was possible to use shear cut edges in the Nd:YAG case whereas milled edges were essential for CO_2 laser [36, 41]. Nd: YAG laser has been reported to account for 80% of solid state lasers which in turn accounted for 32% of a $1.4 billion laser market [43].

The advantages of the Nd: YAG laser includes the following;

- Possibility of transferring laser beam via flexible laser light cable.
- Possibility to connect one laser source with up to 6 handling system and to add the radiation of two or three laser source into laser light cable.
- Possibility of achieving 12 kW power at the workpiece
- More stable beam quality
- Plasma does not absorb much of laser energy when YAG laser used, hence most of the energy is transferred to the sheets

2.3 Disc and fibre laser

Disc and fiber laser systems are special types of diode-pumped solid state lasers which have been used in recent years. Its laser active medium is made up of both disc and fiber respectively. The following advantages have been reported by the use of disc and fiber laser;

- high optical output powers
- high beam qualities and a short emission wavelength around 1μm
- high conversion efficiencies

In addition to the already mentioned advantages, the disc and fiber laser has the possibility of beam delivery through optical fibers. It can also boost of permitting a strong focusing of the laser radiation to a remarkably smaller focus radii if compared with typical focus dimensions reached with the well-known CO_2 laser as well as the Nd:YAG laser due to their wavelength of 10.6 μm and thermal effects in the rod-shaped laser-active crystal respectively. Recent research has shown that continuous-wave disc lasers are commercially available with output powers up to 8 kW [44]. At this power, the BPP amounts to 8 mm/mrad. Most used diode-pumped laser-active medium is Yb:YAG with a laser wavelength of 1.03 µm. It is possible for fibre laser systems to deliver even higher powers up to 50 kW in the multimode system. In addition, Single-mode fiber lasers with nearly diffraction-limited (Gaussian) beams (M_2 < 1.1) are currently available with up to 5 kW power. Various Authors have reported of continuous application of disc and fiber lasers for several welding purposes [45-55]. Figure 6 illustrates the principle of Disc and fiber laser.

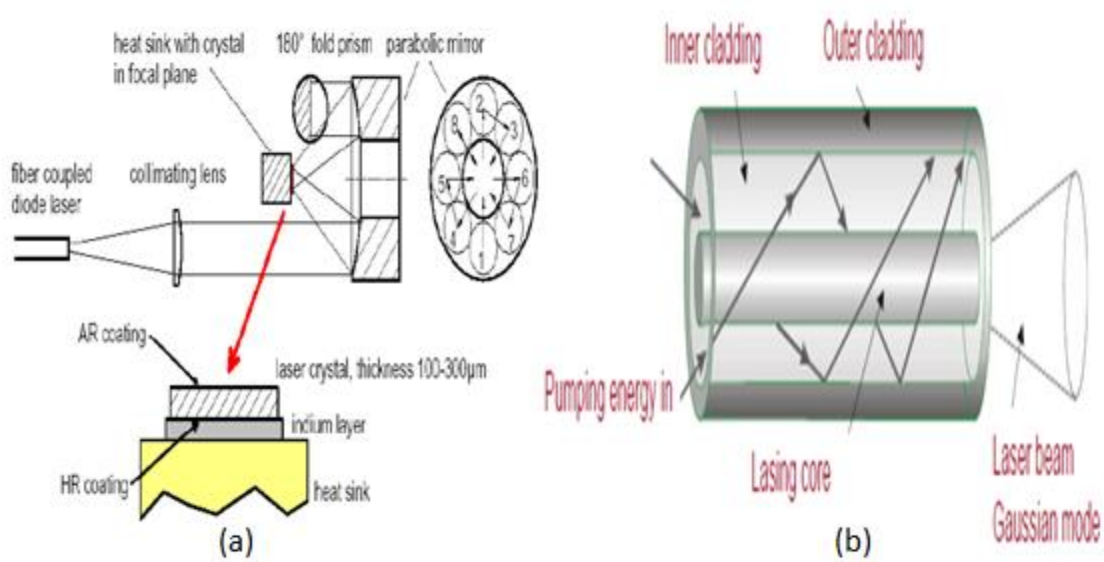


Figure 6. Schmatic illustrations: a) Disc laser principle; b) Fiber laser principle

2.5 Diode laser

High power diode laser (HPDL) systems have been limited to low output powers and low beam qualities for quite some time now. Its resultant focal intensities only permitted welding applications in the heat conduction mode. Nevertheless, the constant improvement in the laser beam power as well as the beam quality has led to the possibility for deep penetration in various welding processes has reported by [56, 57]. It has been reported that HPDLs with output powers up to 10 kW and fibre-optic-coupled HPDLs with output powers up to 8 kW are available currently. Also beam quality similar to that of Nd: YAG lasers can be achieved. The emitted wavelength of HPDLs depends on the temperature, the driving current and material properties of the semiconductor [56]. Typical values lie between 0.8 and 1 μm. One significant advantage of HPDL systems is their compatibility and low weight which makes them mainly suitable for use in conjunction with robotic control. HPDL are applied to the welding and brazing at high speed of carbon and stainless steels and aluminum alloys, as well as cladding operations. Thickness of welded components is limited by the power of the laser. They are becoming increasingly used in welding of thermoplastic materials, where they are replacing traditional techniques such as ultrasonic welding [58].

3 ARC TIG TYPES AND PARAMETERS

Tungsten inert gas (TIG) welding is an arc welding process which uses a non-consumable tungsten electrode and an inert gas for arc shielding to coalescene metals together, is an extremely important arc welding process. It is commonly used for welding hard-to-weld metals such as stainless steel and Al-Mg-alloys [59]. Figure 7 shows the schematic diagram of TIG welding process. In TIG arc welding, electrical energy is transformed into heat, which melts and partially vaporizes the material being welded. A shielding gas flow acts as a medium for the formation of the arc and shields the weld pool and hot electrode tip from atmospheric contamination. Arc is defined as a discharge of electricity in a partially ionized gas, and it is formed between the negative and positive terminal namely (cathode and anode respectively). A typical ionization degree in the gas is in the order of few percent. The arc which closes the welding current circuit ensures a continuous flow of electrically charged particles (electrons and ions) between the terminals [60, 61].

Current type and polarity, the shielding gas composition, the shape and size of the electrode, chemical composition of the material to be welded as well as the arc length as an effect on the heat input of TIG arc into the workpiece [20].

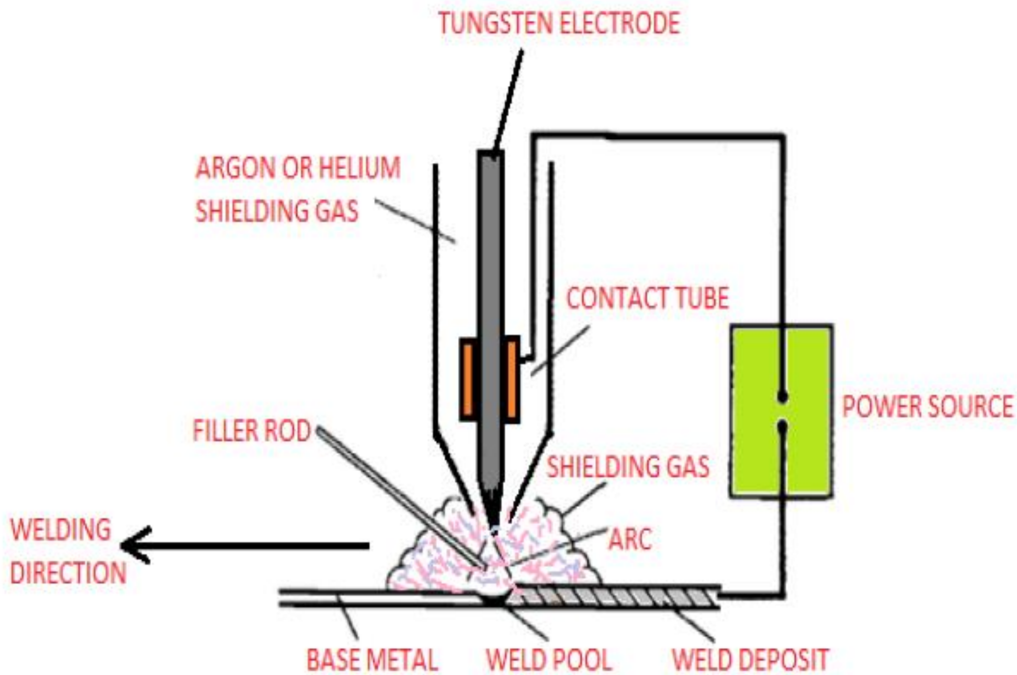


Figure 7. Schematic diagram of TIG welding incorporated with filler rod [62].

In TIG arc, the welding arc can be divided in five regions which are shown in Figure 8 that is the cathode and anode regions, the cathode and anode spots and the arc column. The cathode region is a thin region on the negative terminal. The electrons are released from the cathode spot as a result of thermionic emission and a strong positive charge above the cathode surface. The anode region is a very thin sheath covering the positive terminal. Electrons released from the cathode spot bombard the anode spot, which is heated up to the melting point [62].

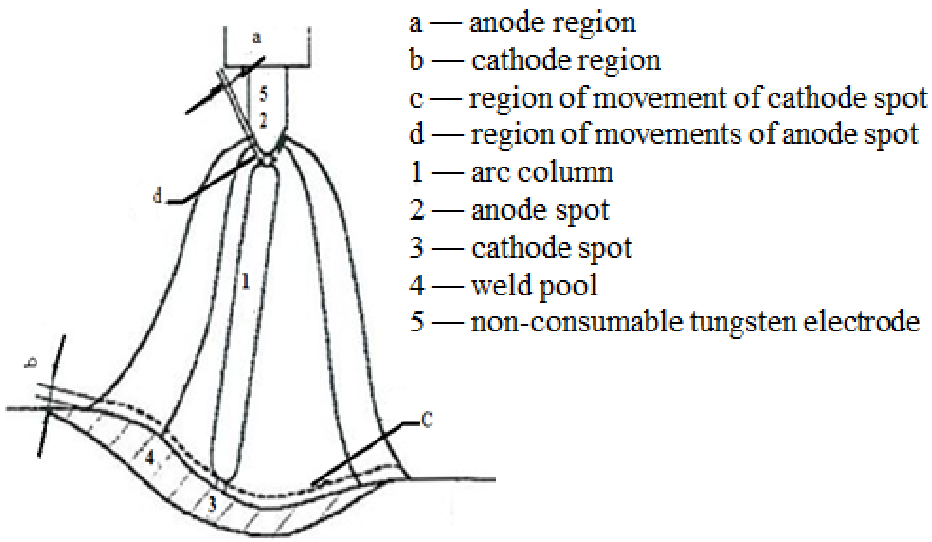


Figure 8. Schematic illustration of a free burning welding arc with a non-consumable electrode in a positive terminal [63]

The arc column is located between the cathode and anode regions. Current density, electrical field intensity and the cross section of the arc column depend on the degree of ionization in the arc plasma. The high temperature of the arc column is maintained by electrical resistance and dissociation of atoms and molecules. The electrical resistance of the arc also depends on current density, the setting of the current source and the degree of the ionization of the arc plasma [62]. It must be noted that ionization of gas containing vaporized metallic components requires less energy compared to pure argon or helium atmosphere. On the other hand, arc burns at notably lower temperatures, typically from 5000 to 7000 K, in welding processes with consumable electrode because of the great extent of metal vapor present in the process zone. Correspondingly, temperature in processes with non-consumable electrode, e.g. TIG welding, is considerably higher, characteristically from 15000 to 20000 K [2]. The degree of ionization may be influenced by external factors, such as laser beam in hybrid laser-arc welding, as mention previously.

TIG weld quality is strongly characterized by the weld pool geometry. This is due to the fact that the weld pool geometry plays an important role in determining the mechanical properties of the weld. Hence, it is very important to select the welding process parameters for obtaining an optimal weld pool geometry [64-66]. It has been reported that the TIG arc cannot transfer a lot of filler metal to the process when used with if filler wire because part of the heat of the arc is used to melt the filler wire [67].

There are different types of TIG processes, namely; alternating current and direct **(AC/DC) TIG, Dual shielded TIG, TOPTIG, TIPTIG, MIX TIG, Pulsed TIG, micro –TIG,TIG- hot wire, Narrow gap TIG and activated flux TIG (ATIG).** The most common TIG welding process variant is AC/DC, DC is divided into constant DC and Pulsed DC whereas AC is didved into Sine wave AC, square wave AC and Advanced wave AC. Figure 9 Ilustrates common TIG welding process variants used in welding various metals.

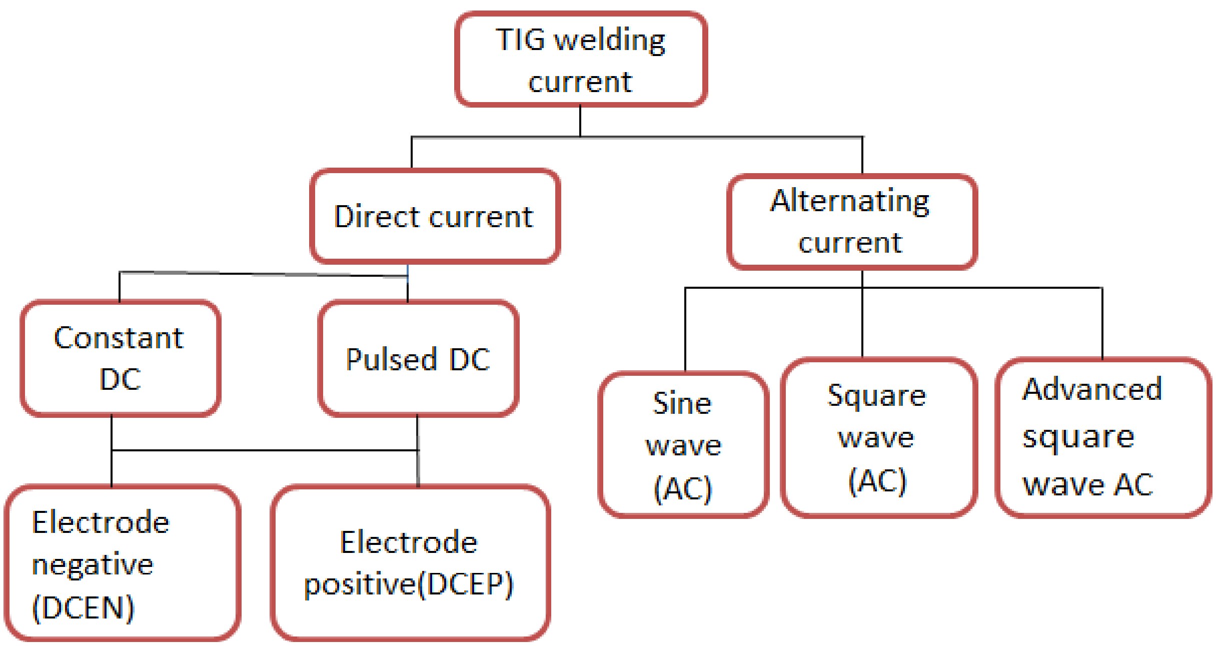


Figure 9. Schematic presentation of the common TIG welding process variants [60].

These TIG processes and their parameters will be describe in this section. According to the welding current used TIG process can either be AC TIG and DC TIG for alternating current and direct current respectively. As mentioned earlier, variety of metals are welded using the DC welding. AC usually is used in welding of aluminium and its alloys [68]. Nevertheless a combination of both alternating current and direct current can be used in TIG welding, this method is called MIX TIG weldig. MIX TIG is very useful in welding aluminuim materials of different thickness together.

3.1 Pulsed TIG

Weld fusion zone characteristically exhibits uneven columnar grains due to the prevailing thermal conditions during weld metal solidification. This result in poor resistance to hot cracking and poorer weld mechanical properties [69]. However, it is important that necessary measures are put in place to control solidification structure in welds. It is often difficult to control these problems due to higher thermal temperatures and gradients. Several methods such as inoculation with heterogeneous nucleants have been tried in the past without much success [70]. In order to solve the above mentioned problems associated with welding, pulsed current tungsten inert gas welding (PCTIG) was developed. PCTIG which was developed in 1950 is a modification of TIG welding which involves cycling of the welding current from a high level to a low one at selected frequency [69]. Current pulsing have gained wide attractiveness due to their striking promise and the relative ease with which these techniques can be applied to actual industrial situations with only minor modifications of existing welding equipment [71]. Pulsed TIG periodically changes the output current level in a square waveform which implies that the current level jumps between a maximum and a minimum value without change of the current polarity. Most pulsed TIG welding is done in a frequency range of 0.5 to 20 Hz pulses per second with the reason to reduce the heat input [60]. During Pulsed TIG welding, the direct current which acts as the welding current is fed sporadically in the form of pulses.

Also, the pulsed current alternates between low background level and a peak level [72]. Pulsed arc welding conditions are controlled by a range of parameters, namely peak current, base current and pulse on time pulse frequency. Figure 10 shows various parameters for pulsed TIG welding process. These parameters have an influence on bead geometry, fusion zone refinement and pitting corrosion. This was also confirmed in the welding of AA6061 aluminium alloy by Kumar et al. came out with the following conclusion; pitting corrosion resistance increases with increase in peak current as well as increase in frequency. However pitting corrosion decreases with an increase in base current [73].

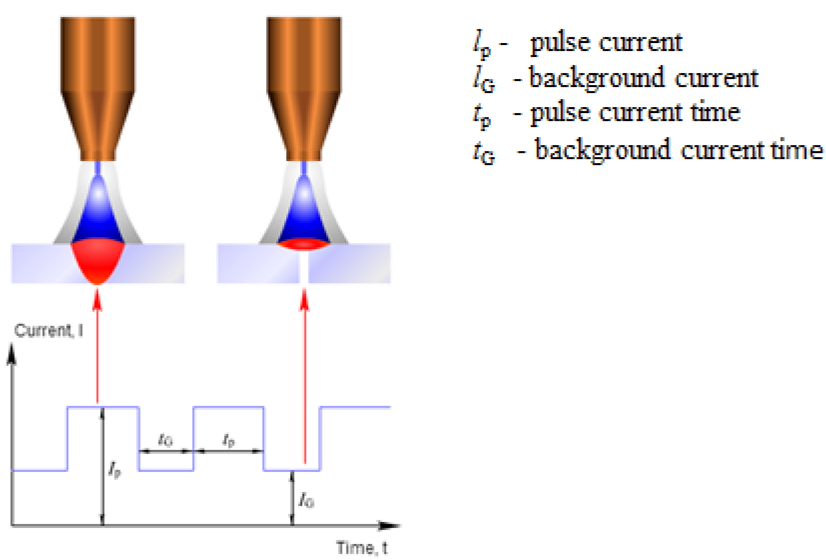


Figure 10. Pulsed TIG parameters [74].

During pulsed TIG arc welding the heat input to the base varies under pulsed current conditions, also the weld pool temperature and penetration shape vary. When current is varied at low frequencies, the base metal undergoes repetitive melting and solidification which enables heat input control, penetration control and a bead surface appearance improvements [75]. By using low current between the frequencies of 0.5Hz -10Hz in the background it is possible to avoid the interception and ignition problems [74]. The following advantages have been achieved with the use Pulsed TIG welding;

- minimizing distortions owing to control heat input
- easy positional welding
- elimination of weld porosity and thorough root fusion
- improvement in weld quality, low energy input (saving of cost)
- easy welding of sheets down to 1 mm which is normally difficult with standard TIG process.
- operator requires less skill
- mechanization is possible
- ideal for critical applications like root passes of pipes, joining dissimilar metals etc.

It disadvantages includes complicated setup and expensive welding equipment than conventional TIG.

3.2 Alternating and direct current (AC/DC)TIG

Direct current (DC) and alternating current (AC) are used for welding of different metals. The form of the weld pool, welding speed, weld quality and the weld seam form can be influenced by current type and electrode polarity. There several available choices of polarity and welding current these includes direct current electrode positive (DCEP), pulsed direct current (PDC), alternating current (AC) and direct current electrode negative (DCEN). Figure 11 shows the effect of electrode polarity on weld penetration.

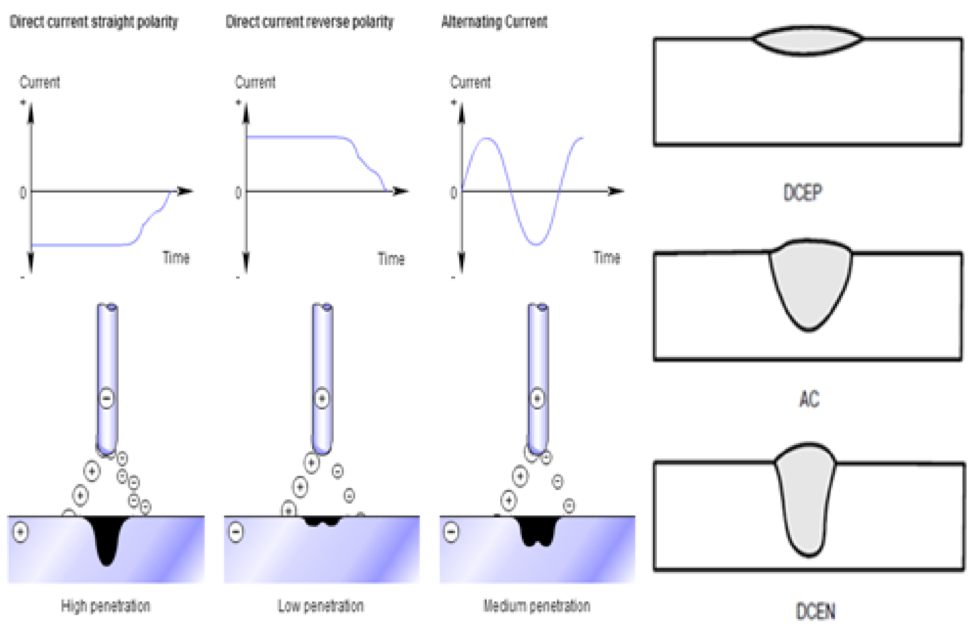


Figure 11. The effect of current and electrode polarity on weld penetration [74].

In welding of most metals DCEN (straight polarity) is used, this is because the greatest amount of heat is generated in the anode region on the surface of the base metal which helps in producing higher weld penetration depth and higher travel speed than DCEP (reverse polarity). However in welding of aluminium and magnesium which are exceptional metals DCEP or AC can be used in order to break down the insulates and the high melting point oxide layer on their surfaces [20, 60, 76]. DCEP has a disadvantage in terms of polarity which has a small current carrying capacity of the welding electrode even with large electrode diameters. Due to this disadvantage to gain both polarities AC is usually used in welding of aluminum and magnesium alloys due to the capability of balancing electrode heating and work-piece cleaning effects. Figure 12 shows the effect when frequency is increased in AC TIG welding. When AC frequency is increased the peak value of the arc pressure also increases whereas its width of distribution decreases, this makes it possible for it to come close to the arc pressure distribution of DC TIG welding which improves the directionality and concentration of AC arc [77].

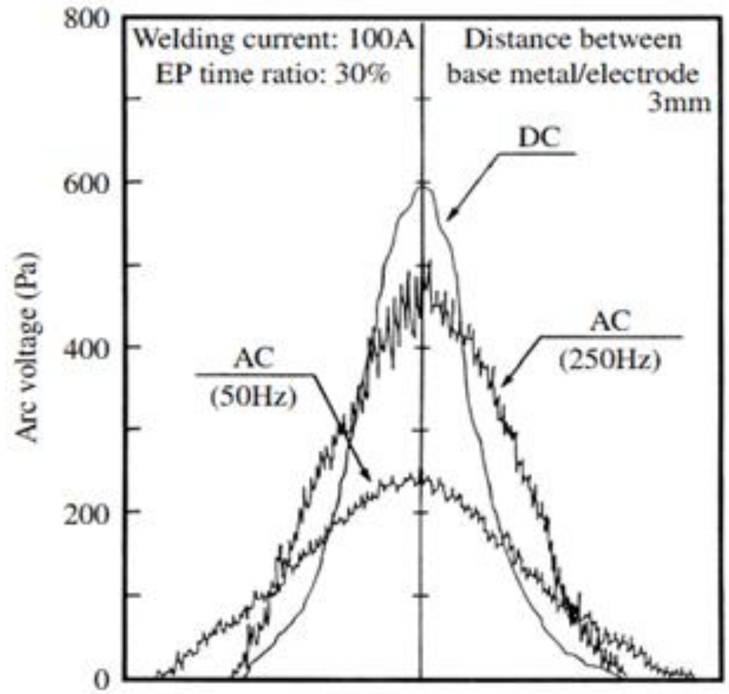


Figure 12. Comparisons between AC voltage distributions [78].

An example is shown in Figure 13 which shows the effects of AC frequency control on TIG welding of aluminum. During welding there is an increase in bead width which occurs due to the effect of heat conduction. Nevertheless, when welding is performed at 200 Hz AC wave frequency, there is no observable widening of the bead as the welding progresses [79]. A summary of current and polarity with its effect on penetration is illustrated in Table 2.

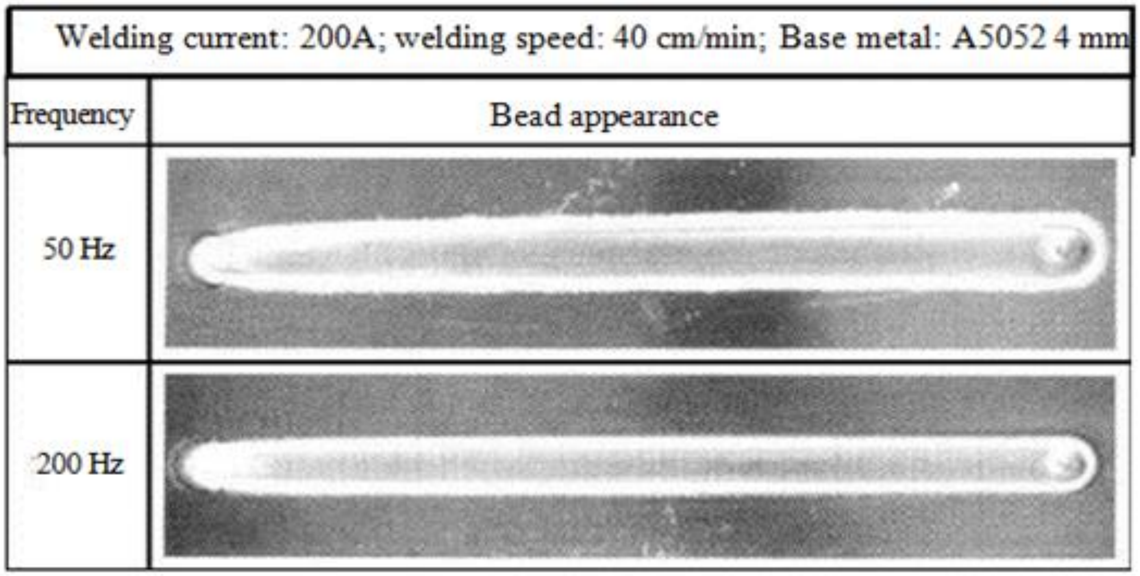


Figure 13. Effects of AC frequency control on AC TIG welding [78].

Table 2. Summary of current type and polarity

Current	**Polarity**	**Penetration**
Direct current (DC-EN)	Straight	Deep Penetration
Direct current (DC- EP)	Reverse	Low Penetration
Alternating current (AC)		Medium Penetration

Zhaodong Zhang et al. [80] carried out an experiment using AC TIG welding with single component oxide activating flux for AZ31B magnesium alloys. In their experiment the effects of welding speed, weld current and electrode gap on the weld shape and the weld arc voltage in AC TIG welding with oxide fluxes were investigated using three single-component fluxes namely; TiO_2, Cr_2O_3 and SiO_2. Figure 14 and Figure 15 show the weld pool shapes without flux during the experiment and Weld surface shapes with flux (a) and with fluxes of TiO_2 (b), Cr_2O_3 (c) and SiO_2 (d) respectively.

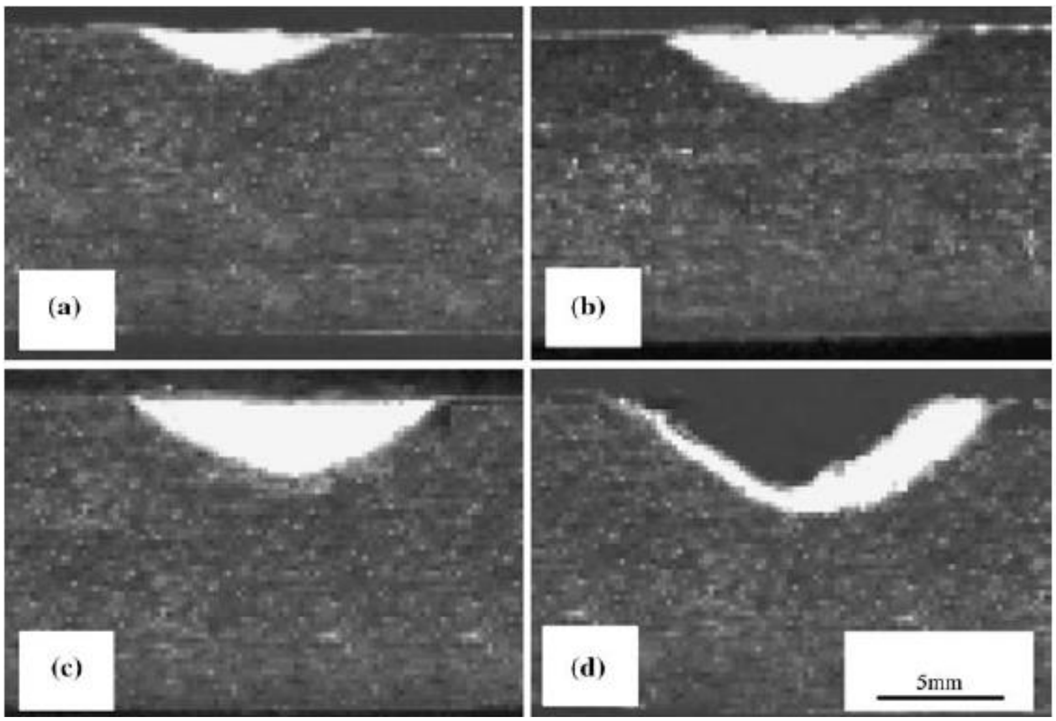


Figure 14. Weld pool shapes without flux (a) and with fluxes of TiO_2 (b), Cr_2O_3 (c) and SiO_2 (d) [80].

The result obtained, after carrying out the experiment implies that the TiO_2 and Cr_2O_3 which were used as oxide fluxes increased the weld penetration about two times greater than that of weld penetration of conventional AC mode TIG.

Secondly the SiO_2 increased the weld penetration, however with a very poor formation of weld surface due to an induced quantity of losing of Mg element as well as cavity existing in the surface of weld bead. The arc voltage was fluctuant also during the welding process with SiO_2 flux.

Lastly, from the results obtained with the use of SiO_2 it can be concluded, that SiO_2 cannot be a flux for welding magnesium, although it has been chosen as an experimental activating flux by many researchers and has been proved to improve weld penetration obviously in A-TIG welding for stainless steel, mild steel and aluminum alloy.

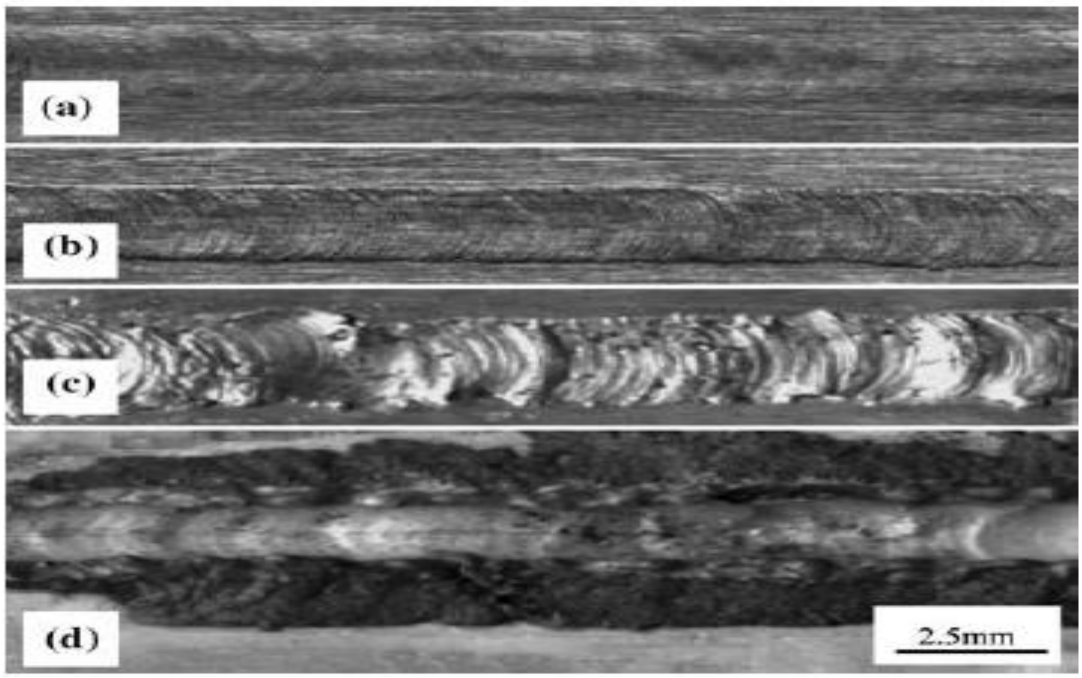


Figure 15. Weld surface shapes without flux (a) and with fluxes of TiO_2 (b), Cr_2O3 (c) and SiO_2 (d) [80].

3.3 Double shielded TIG process

The double shielded TIG welding process is a new development which has been introduced to help solve the disadvantage of low penetration which limits the use of conventional TIG welding on thick materials [81, 82]. In double shielded TIG welding process pure inert gas is passed through the inner pipeline which keeps the arc stable as well as protecting the tungsten electrode. A mixed gas which contains an active gas passes through the outer pipeline which serves as an active element to dissolve in the weld pool so as to change the Marangoni convection and the weld pool shape [83]. Figure 16 illustrates double shielded TIG process.

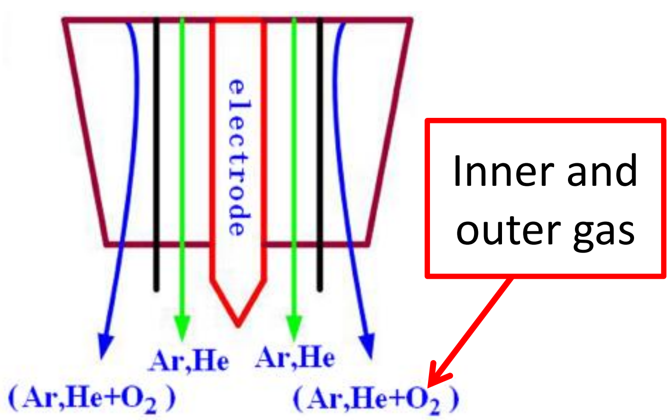


Figure 16. Double shielded TIG process [84]

It has been reported that the oxygen content in the molten pool in a particular range can change the Marangoni convection from outward direction to the inward so as to gain a deep and narrow weld pool shape [81, 85-91]. To ascertain this, Lu et al. carried out an experiment on the feasibility of double shielded TIG welding process on 0Cr13Ni5Mo martensite stainless plate [83]. Their experiment was carried out in three welding conditions:

- pure He with a flowrate of 10 L/min under traditional TIG
- He–5%O_2 with a flowrate of 10 L /min under traditional TIG

- pure He with a flowrate of 10 L/ min in the inner pipeline and He–10%O_2 with a flowrate of 10 L /min in the outer pipeline under double shielded TIG.

During the experiment the effect of arc length, welding and current on weld shape were all investigated. After carrying out the experiment it was concluded that at arc length between 1-5mm there was deep and narrow weld pool shape as illustrated in Figure 17a-c. Conversely, a predominantly wide and relatively shallow weld shape was realized at an arc length of 7 mm as shown in Figure 17. In summary the weld depth in double shielded TIG welding increases about two to three times as compared to conventional TIG. Also it was realize the oxygen content increases with increasing arc length.

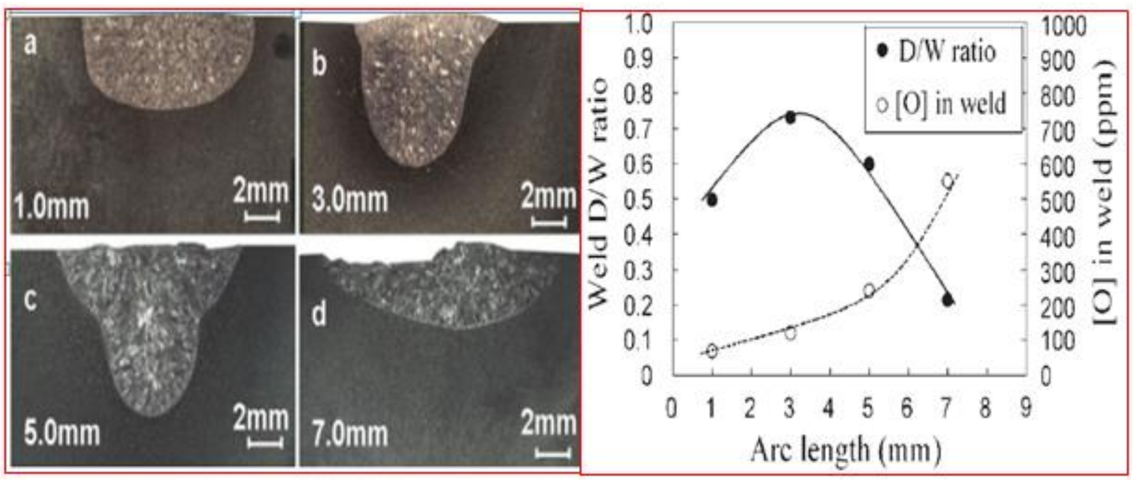


Figure 17. Weld shapes under different arc lengths and oxygen content in weld pool (D/W ratio under different arc lengths) [83].

The shallow welds shown in Figure 17 at arc length of 1mm is attributed to the difficulty for oxygen to dissolve into the weld pool, therefore reduces the oxygen content in the weld pool. Also the surface tension stress decreases with increasing arc length from 3 mm for the double shielded TIG process which intend increases the weld penetration. Nevertheless as the oxygen content in the weld pool intensely increases an oxide is formed on the surface at an arc length of 5 mm. At a longer

arc length (7 mm) the oxide gets very thicker which therefore decreases the D/W.
On the welding speed a ranged from 1.5 to 5 mm/s on the weld shape was investigated at a constant welding current of 160 A with an arc length of 3 mm. The results showed that the D/W ratio decreases with increasing welding speed. This has also been confirmed by previous researchers [92, 93]. This effect was attributed to the large melt velocities, low melt conductivities and large weld pool dimensions in the welding process of steel. Figure 18 illustrates the effect of welding speed on well pool shape, oxygen content in weld pool and D/W ration under different welding speed.

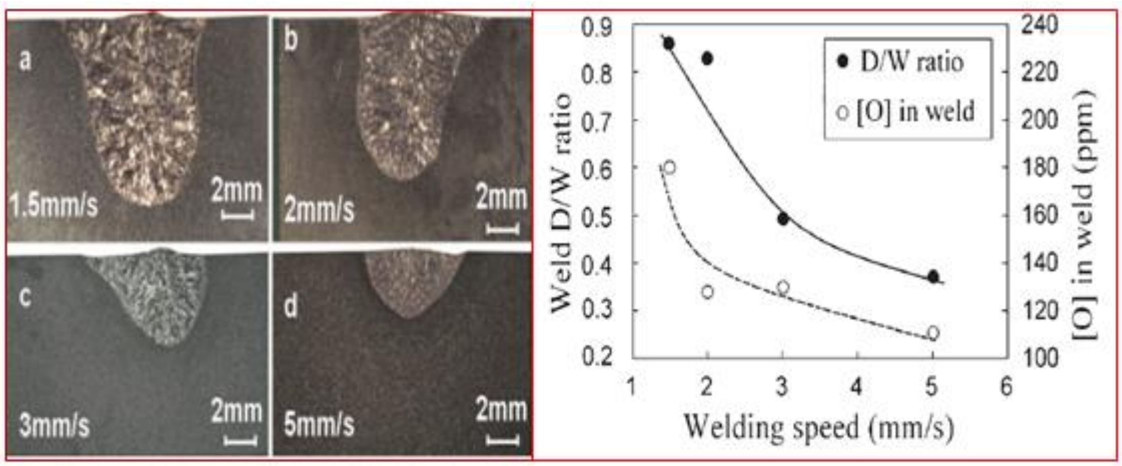


Figure 18. Effect of welding speed on weld pool shape, oxygen content in weld pool and D/W ration under different welding speed [83]

Additionally, at current between 120A to 240A at a constant welding speed of 2 mm/s, it was realize that the increase of welding current directly raises the arc power and the heat input on the anode. This is shown Figure 19 comparable to the effect of welding arc length, more oxygen both in the air and in the outer pipeline could decompose into the arc and enter the weld pool as the welding current increased.

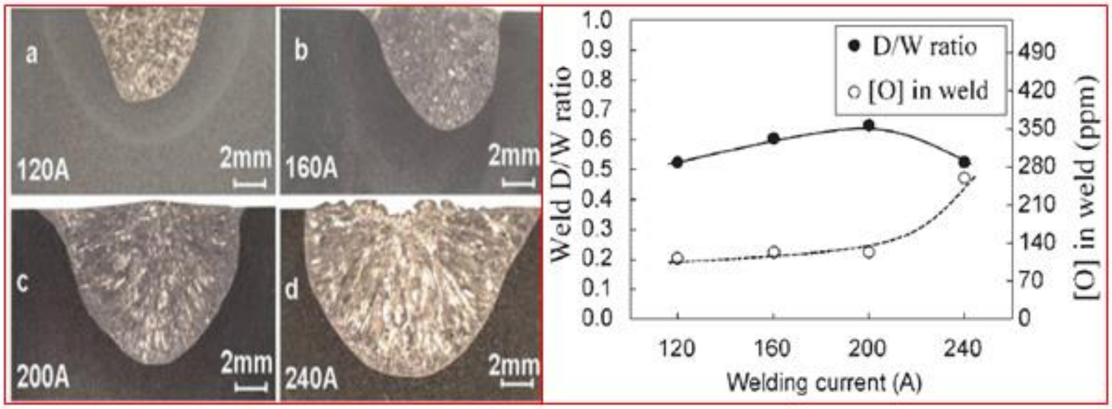


Figure 19. Weld shapes under different welding currents and oxygen content in weld pool (D/W ratio) [83]

Finally the experiment showed that by adjusting the process parameters, the oxidation of the electrode tip can be completely avoided in the double shielded TIG welding as illustrated in Figure 20.

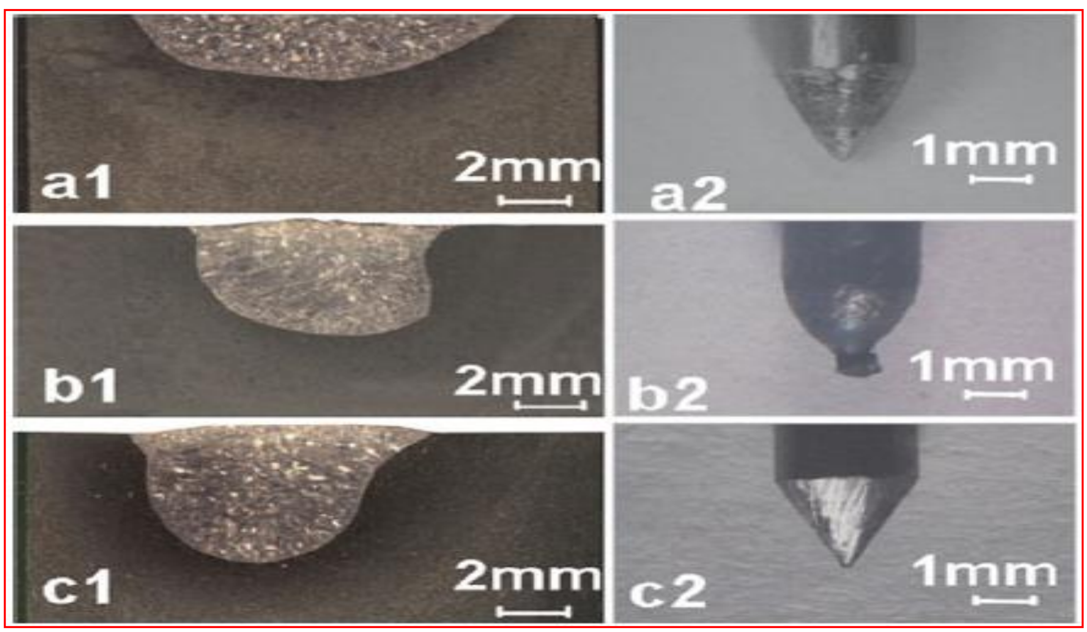


Figure 20. Weld pool shapes and electrode morphology under different welding conditions: a Traditional TIG (pure He, 10 L/ min); b traditional TIG (He–5%O_2, 10 L/min); c double shield TIG (inner: pure He, 10 L/min; outer: He–10%O_2, 10 L/ min) [83]

3.4 Other TIG combinations

In order to widen the scope of application of TIG welding process, different TIG welding combination has been developed. This chapter will discuss various combinations available for TIG welding process.

3.4.1 Hot wire TIG welding

The hot wire TIG welding which was developed as far back in 1960 but has been underutilized. Hot TIG can give a lot of pay back when used in the right application which requires high quality and high productivity. With the use of hot wire TIG welding especially in the downward direction it is possible to weld a larger diameter pipe with good quality. It has been reported that high deposition rate can be achieved with hot wire TIG welding which can be compared to that of MIG welding. Figure 21 shows the layout of hot wire TIG welding principle. Combining hot wire TIG welding process with a narrow gap preparation makes it possible to make huge gains without reducing the excellent quality gain from TIG processes. The main difference between hot wire TIG and cold wire TIG welding is the preheating of the filler wire. The preheating is usually carried out by a current which is produced by a supplementary power. The preheating of the wire increases the calorific value. It must be noted that at the entry into the weld pool the filler wire requires lower arc energy [94, 95].

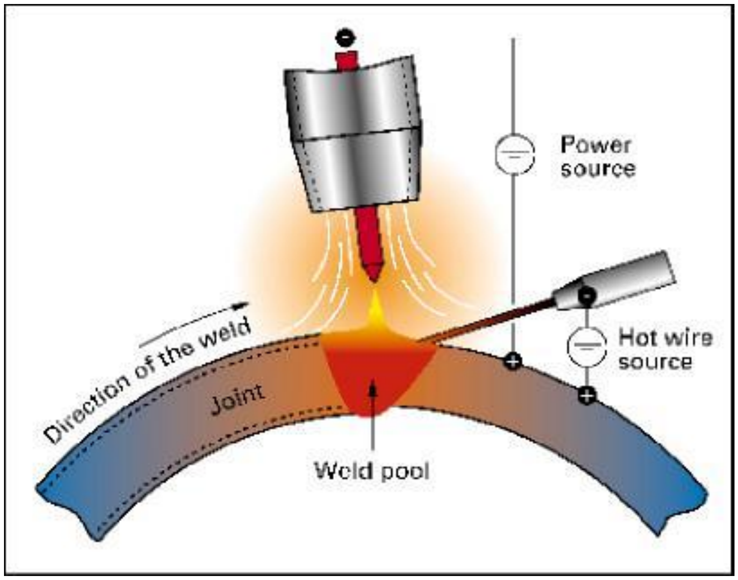


Figure 21. Hot wire TIG welding principle[95].

Hot wire TIG welding has several advantages which includes;

- allowing a managed separation of quantity of arc energy and
- quantity of filler material introduced into the welding pool

The main advantages of hot wire TIG are its ability to enable total control of starting and finishing (downslope) phases of the welding cycle as well as the possibility to carry out repair procedures. However, hot wire TIG welding has some limitations; it is not normally used for manual welding and an additional equipment costs for the hot wire power supply. In addition, cold wire TIG equipment is also needed. Also the power supplies are not especially compact and portable for moving around in the field. Figure 22 show a plot of deposition rate vs. arc energy for cold wire TIG and hot wire TIG welding. Hot wire TIG with oscillation on the hand produces higher deposition rate [94, 95].

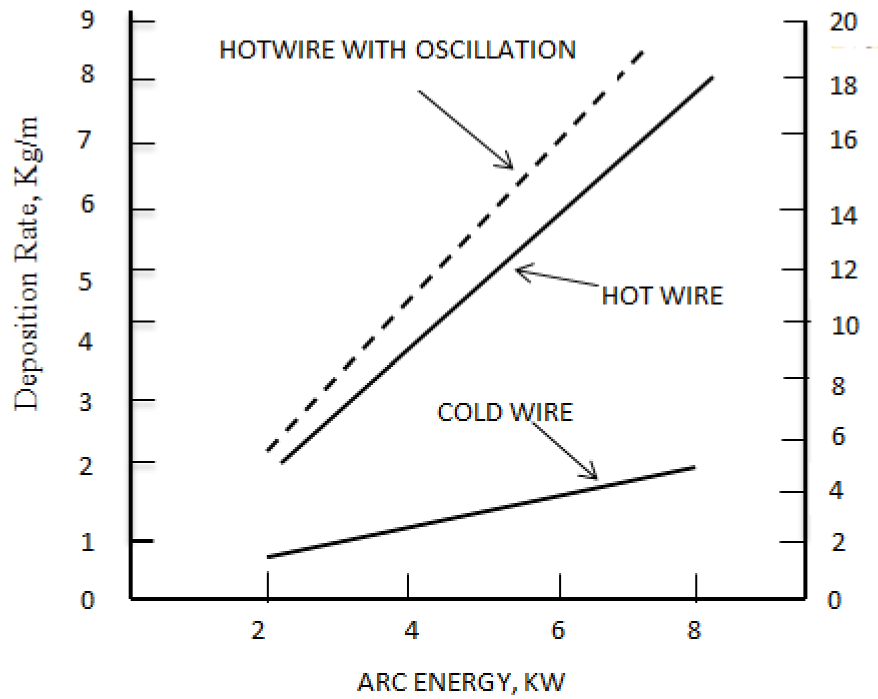


Figure 22. Plot of deposition rate vs arc energy for cold wire TIG and hot wire TIG [94]

3.4.2 TIP TIG

TIP TIG is a rather new process which was invented by Ing.Siegfried Plasch and patented in 1999 after about 1.5 years of development [96]. TIP TIG Hotwire power source adds current to the wire which influences the weld [97]. The main advantages of the TIP TIG Hotwire Process compared to those using a fusible electrode lies in the fact that TIP TIG welding allows a managed separation of the quantity of arc energy and of the quantity of filler material introduced into the welding pool. This advantage allows total control of the starting and finishing (down-slope) phases of the welding cycle as well as the possibility to carry out repair procedures [97]. TIP TIG efficiently provides TIG welding at MIG welding speeds. This implies that it combines the benefits of TIG welding particularly the cleanliness of the weld with the capability to weld at higher speeds. This therefore gives it an improved productivity over normal TIG welding. During TIP TIG welding, the wire supply which is feeding the wire into the weld pool is normally set constant speed to match the welding parameters. TIP TIG also applies secondary oscillation to the steady wire feed; this provides linear forward and backward motion. The linear and backward motion provides kinetic energy into the weld pool. The wire feed speed and the oscillation is continuously adjustable and can be independently controlled, this aids in producing a very stable and controllable weld process. This principle can also be applied to all TIG and laser processes. TIP TIG has lots of advantages, these are [96, 97];

- High welding speed, three times the welding speed of TIG and almost reaches the speed of pulsed MIG welding.
- Spatter free with no fumes
- Environmentally friendly
- Low heat input => low distortion => low rework => cost savings
- TIP TIG gives 100% x-ray quality welds
- TIP TIG can be easily automated and production increased by the use of hot-wire
- Excellent metallurgical and mechanical results for all materials

Welded products have better metallurgical and mechanical properties than conventional TIG process. The TIP TIG equipment for a wire feed unit costs approximately €7,035.07 [96]. A typical robot system would be in the order of €58,628.39 - €175,885.16; this means that a small additional cost which is given an improved performance is recovered very quickly. Table 3 showing cost per meter of cost per euros as at 2007 [96].

Table 3. Cost per meter of cost per euros [96]

Process	Steel	Aluminum
TIP TIG	3.3	3.6
TIG	10.9	11.2
Pulsed MIG	4.2	4.5

Various test carried out indicates that TIP TIG is possible of achieving over 20 per cent cost savings over pulsed MIG for every meter of weld and this makes it cost effective with quick payback and improved weld quality [98]. Table 4 shows comparison of welding process with TIP TIG.

Table 4.Comparison of welding process with TIP TIG [99]

Process	**MIG Plused**	**TIG**	**TIP TIG CW**	**TIP TIG HW**
Metals	Steel, stainless steel	All weldable metals	All weldable metals	All weldable metals (except Al)
Thickness	> 0,60 mm	> 0,25 mm	> 0,25 mm	> 10,00 mm
Relative Speeds	Fast	Slow	Fast	Fast
Deposition Rates kg/h	1,0-3,6	0,6-0,7	1,0-3,6	1,4-5,4
Required skilled level	Low	High	Low	Low
Relative Operating Cost (time& materials)	Low	High	Low	Low
Weld Dressing needed(Spatter or slag removal)	He	Low	Low	Low

A comparison of the cost for 1 meter of welding with an hourly rate of 30 euros is also considered. Figure 23 illustrates rough total cost for 1 meter of welding with hourly rate of 30 euros.

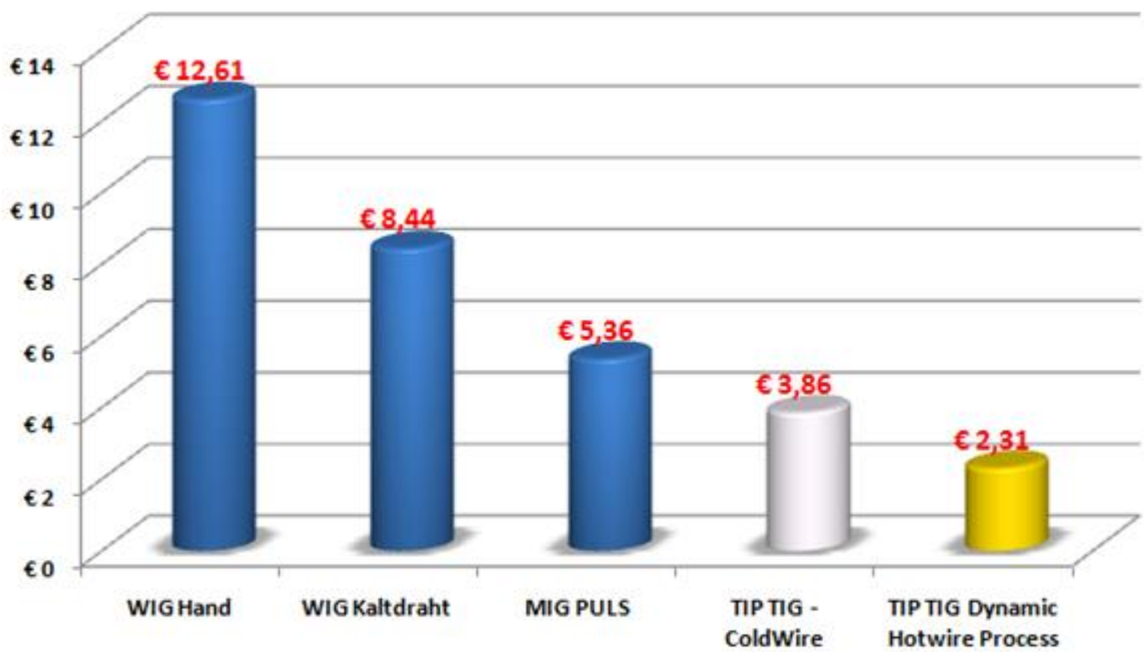


Figure 23. Rough total cost for 1 meter of welding with hourly rate of 30 euros [99]

3.4.3 TOP TIG

With much increase in the use of robotic welding in most industries, the need for excellent quality welds is of much priority. TOP TIG is a new tungsten inert gas (TIG) robotic welding process which combines both the quality of the TIG process and productivity of the MIG process. The main phenomena are the configuration of the torch: the weld wire which is fed directly into the arc zone at higher temperatures which ensures 'continuous liquid-flow' transfer as well as high deposition rate. This means that the filler wire is fed into the weld pool in front of the torch [100, 101]. Figure 24 illustrates the layout of TOPTIG welding torch.

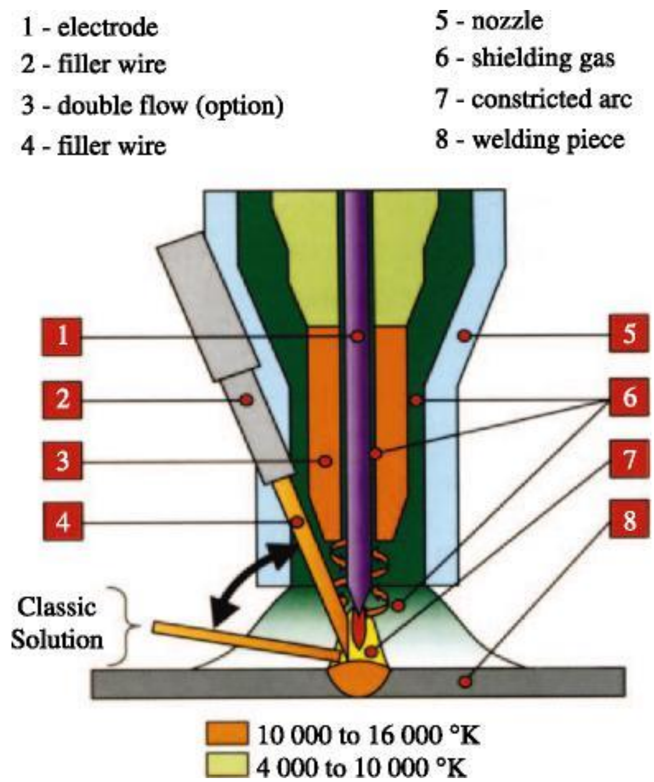


Figure 24. Layout of TOP TIG welding torch [100]

TOP TIG being a spatter free welding process gives it an edge over MAG welding which is limited because the weld current passes through the weld wire, causing unstable arc transfer. The quantity of wire is related to the weld current, and cannot be varied without altering the weld current itself. The TOPTIG process as achieved four main objectives:

- torch compactness, for robotic applications
- no limits to the characteristics of the robot
- high welding speed and
- automatic changing of the electrode

As illustrated in Figure 25, the wire is directed at an angle of approximately 90^{O} with respect to the electrode, and is parallel to the weld. In the standard TIG this is a major drawback as compared to integrated wire system in the TOP TIG. In TOPTIG welding process, the filler wire and the electrode spacing are very important parameters because they affect all other values during welding. The distance should be 1 to 1.5 times the diameter of the wire [100, 101].

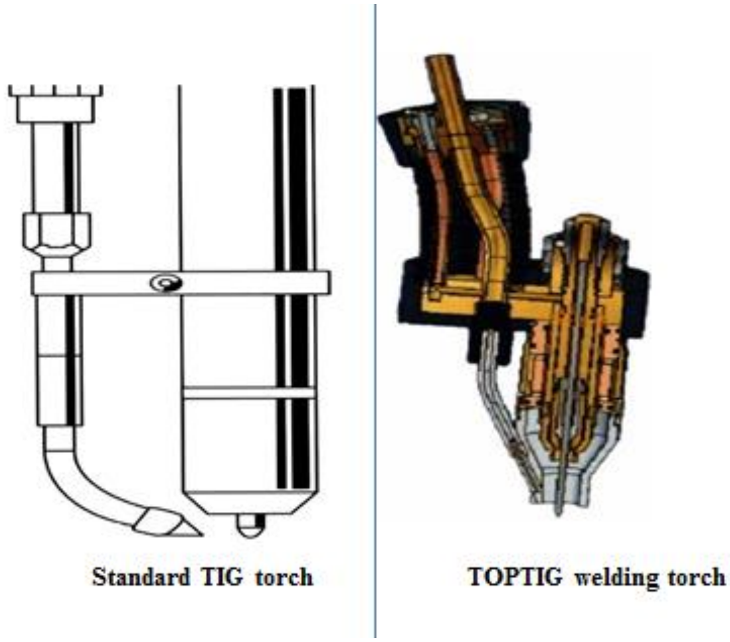


Figure 25. Standard TIG torch as compared to the cross section of TOP TIG welding torch [100]

With the possibility to adjust the parameters, it is possible to have two types of metal transfer namely continuous liquid flow transfer and drop mode transfer. With continuous liquid flow there is contact between the weld metal and the weld piece at the end of the arc cone. However, the liquid bridge transfer mode is usually preferred, since it gives a high rate of deposit at maximum speed. The drop transfer mode on the other hand is characterized by repeated contact of the drops with the melt bath, rupture of the metal neck, growth of the drop and detachment due to gravity or contact with the surface. Additionally, the speed of the filler wire can be pulsed or synchronized with current which generates a wavy bead appearance of the weld. Figure 26 illustrates the influence of speed on wire dripping.

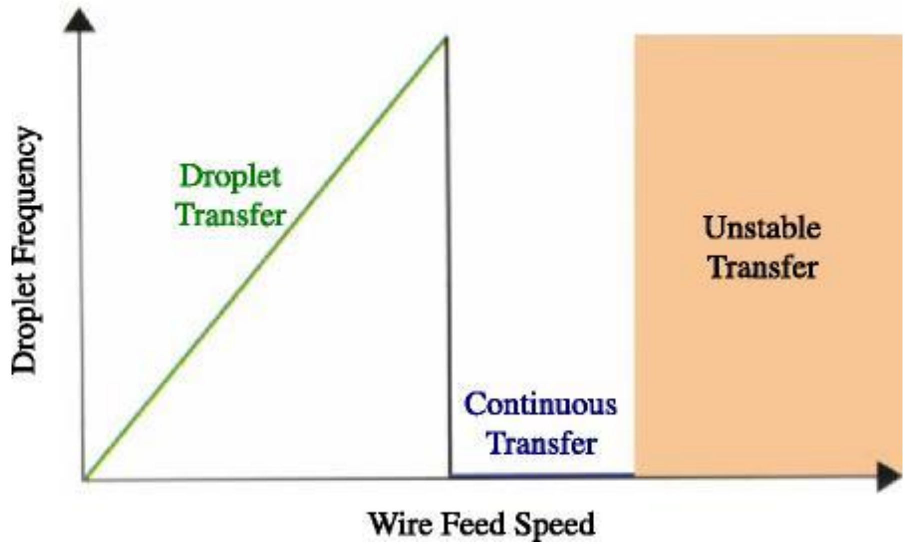


Figure 26. Influence on welding speed on wire dripping in TOP TIG welding [100]

The advantages of TOPTIG can be summarized as follows [100, 101];

- Absence of spatter (avoiding cleaning and polishing after welds)
- Low distortion
- High quality welds and productivity at reasonable cost
- Excellent appearance of weld bead
- A better accessibility for welding complex structures

4 LASER-TIG HYBRID WELDING PROCESS

There are various varieties of hybrid processes in existence which depends on the laser source used and the arc with which it is combined [102]. In laser–arc welding processes the laser beam which has high-energy density heat source usually serves as the primary heat source aiding in deep penetration mode welding while the arc which also acts as a secondary heat source carry out supplementary functions in order to improve the process stability, efficiency and reliability as well as the quality of the resultant weld seam [60]. There are two basic configurations used namely; laser leading hybrid process (the laser beam precedes the arc) [103, 104] and the arc leading hybrid process (the arc precedes the laser beam) [105, 106]. The arrangements of these two welding processes in hybrid welding process are illustrated in Figure 27.

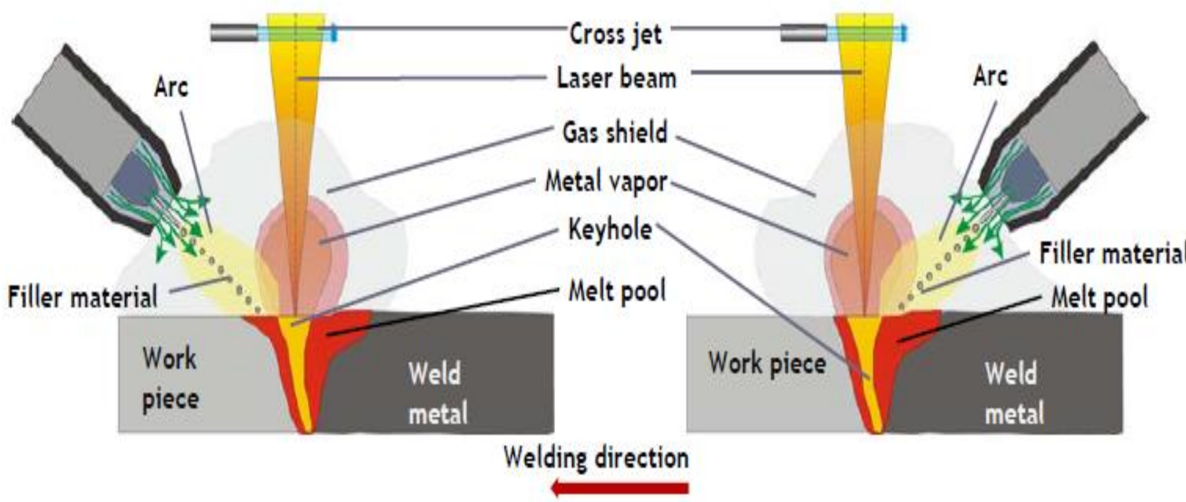


Figure 27. Schematic illustration of hybrid welding with leading arc (left) and leading laser (right) arrangement [107]

It has been reported that, the laser leading position is often used in the welding of aluminum since that arrangement removes the oxide layer prior to arc welding, resulting in a significantly more stable process [104]. Laser leading arc has an advantage in terms of improvement in the bead appearance, this because in the leading arc the assist gas flow does not affect the molten pool created by the arc. On the other hand the leading arc process gives deeper penetration; possibly due to the fact that the laser beam impinges the hot weld pool with better absorption than a solid surface and the energy losses from laser through heat conduction is reduced [4, 108, 109]. Hybrid process is not just a simple combination of laser beam and arc, but there are complicated physical interactions between the two heat sources [60, 76].

Laser-TIG hybrid has been investigated since the late seventies in the last century by Professor Steen and coworkers at the Liverpool University. Laser-TIG hybrid welding can be described as the combination laser beam welding and TIG arc welding processes. When a TIG arc is operated concurrently with a laser beam, heat condition is established in which theorized laser absorption is improved. In addition, absorption of the laser energy into the base material is enhanced in the heated region [110]. In laser-TIG hybrid technique, a TIG torch is placed on axis with a laser beam. Both are aligned with welding direction as illustrated in Figure 28.

Also it has been reported that, in hybrid laser-TIG welding, penetration can be increased and arc stability improved when welding of Al alloy is done, particularly through high rates of travel land low TIG current levels [111]. During laser-TIG hybrid welding, the electric arc dilutes the electron density of laser plasma which weakens the ability of laser plasma to absorb and reflect the laser energy and therefore improves the heat efficiency of laser beams [112]. The stabilizing effect of the laser beam arc which is an important factor in hybrid laser-TIG welding has been investigated. The results indicated that, when laser and TIG arc are on the opposite sides of workpiece, an increase of 300% in speed is obtained. However, on the same arc current, when the laser and TIG arc are on the same side of workpiece, there is 100% increase in speed in the welding of 0.8 mm thick titanium and 2 mm thick on the mild steel [10, 27] Additionally, undercutting which usually occurs at high welding speed is avoided when both the laser and arc are on the same side. Laser-TIG hybrid welding has proven to be a promising technique in welding very thin austenitic stainless steel sheets (0.4-0.8 mm) in a butt joint configuration [67]. Clarification on porosity reduction mechanism in hybrid laser-TIG welding has been studied by observing keyhole behavior and liquid flow in the molten pool during welding through the micro focused X-ray real-time observation system. It was established that the keyhole formed is long and narrow, and its behavior was rather stable inside the molten pool, which was useful to the suppression of bubble formation in hybrid welding [113]. Many advantages have been realized from the combining of laser to the conventional welding methods:

- improvement in arc stability because of the absorption of the laser energy by the arc plasma and the change of the arc plasma composition caused by strong evaporation of workpiece material and deep penetration
- current density of the hybrid is higher than that of electrical arc alone because of the constriction in the hybrid welding.
- the melting efficiency of laser arc hybrid welding is significantly higher than that of the system in which arc and laser operate separately.
- high efficiency and economy
- high gap bridging capacities, permissible tolerances and weld speed
- improvable weld appearances and the geometry when the ratios of the two heat sources are adjusted, etc. [4, 24, 114-121].

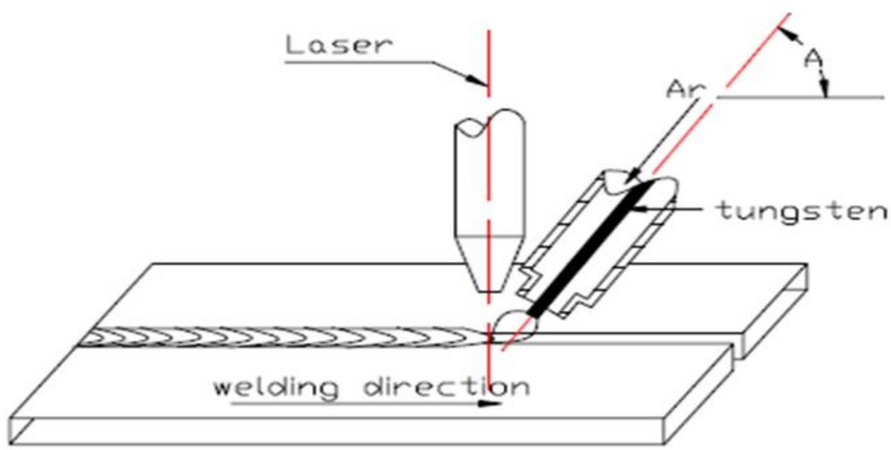


Figure 28. Principle of laser-TIG hybrid welding [122].

One advantages of laser TIG hybrid welding process compared to hybrid laser-MAG process is that the addition of filler material which is separated from the electric circuit. This enables an independent determination of welding current and filler material feeding rate. As there is no transfer of metal across the arc, there are no molten droplets to contend with [60]. Most researchers are of the opinion that an increase in welding speed of up to 100% over welding with laser alone and improvements in penetration of 20% may also be achieved by using laser and TIG welding device with a current of 100A [123]. It has been reported that, in arc welding at low currents less than 150 A, the arc becomes unstable as the welding speed increases. This makes the arc starts wandering on the workpiece surface as it roots to the spot of least resistance. When the laser beam is turned on and the power density on the material surface exceeds the threshold value of material vaporization, the high electron density in the metal vapour and plasma above the laser-workpiece interaction zone provides a high-conductivity path for the arc compared to the surrounding cold gas. The arc follows the path of least resistance from electrode to the workpiece and roots to the laser-material interaction zone. The rooting effect leads to a decrease in electrical resistance of arc column and stabilizes the arc which promotes the arc ignition. The stabilization of the arc and voltage drop immediately the laser beam is turned as illustrated in Figure 29 [10, 28, 124].

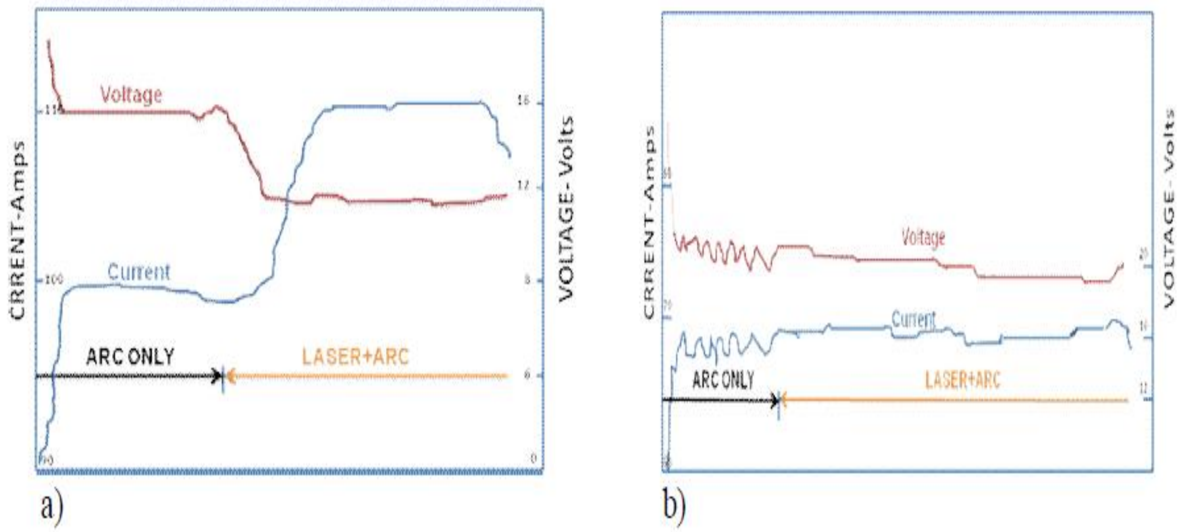


Figure 29. Characteristics of current and voltage during arc and hybrid welding; a) arc resistance decrease due to the presence of laser .b) laser stabilization of fluatations in arc voltage and current [125]

Different laser–TIG hybrid arrangements exist (Ar shielding gas supplied to the laser and TIG arc and coaxial hybrid process with hollow TIG and laser), as illustrated in Figure 30. The critical current of the transition of the welding mechanisms which is the droplet to spray mode is much higher in coaxial arc hybrid welding. This is because the laser trasverse's the whole arc in laser -arc welding particularly at a high current. The energy absorption of the laser by the TIG arc is more severe and therefore reduces the energy density of the heat source acting on the workpiece, especially in the case of a CO_2 laser and TIG arc combinations [126]. Nevertheless in coaxial hybrid welding the distribution of current density create an opening of the arc centre by the hollow tungsten electrode which makes the focus point of the laser rather small [126]. An example of combined welding method with a coaxial laser and arc is the configuration developed by Ishide et al. [5]. The aiming probems and size requirements of the TIG or MIG torch is avoided as the laser beam is focused immediately below the arc. Because the beam quality of the laser is impaired in this method, it is not appropriate for deep penetration welding of thick plates. As illustrated Figure 30, when a coaxial structure is utilized in which the laser beam is passed along the hollow cathode TIG central axis, a laser beam of high quality to form a deep keyhole can be used.

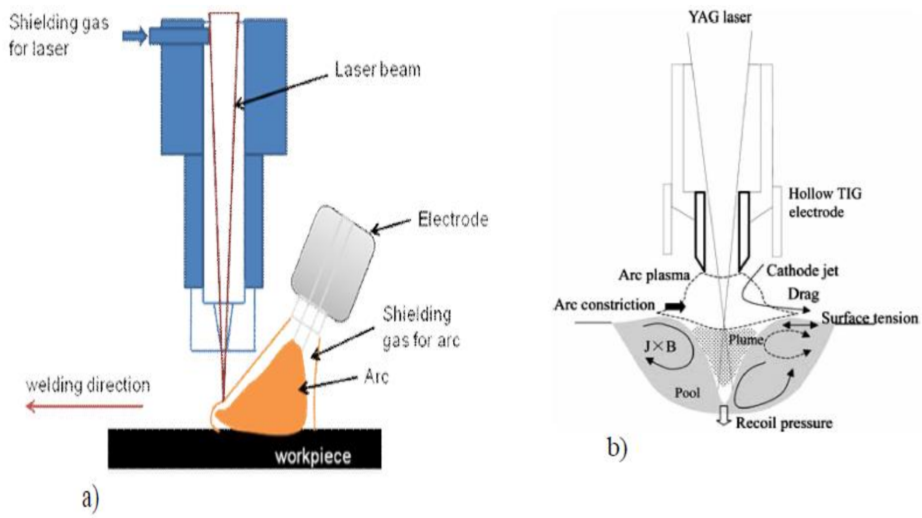


Figure 30. Schematic illustrations: a) Sketch of laser-arc hybrid welding, Ar shielding gas supplied to the laser and TIG arc b) coaxial hybrid process with hollow TIG and laser, redrawn from [126, 127]

Additionally, since the plasma flow is reduced and the outward convection currents are inhibited by the hollow cathode, it is projected that an inward convection current will be formed in the molten pool by a small inward drive and there is a possibility of intense increased penetration. The effects of these actions are listed below [127]:

- since the current concentration is moderated at the cathode tip and the plasma flow is reduced, the drive force of an outward-directed convection flow in the molten pool is reduced which makes the inward convection flow more readily induced.
- because the arc pressure is reduced due to the reduction in the plasma flow, the down humping bead formation can be slowed by increasing the current and speed of the welding process.

- by directing a high beam quality laser onto the centre of the molten pool directly from above, the arc anode region is constricted therefore making the inward-directed convection currents induced by electric current concentration.
- the arc pressure can be regulated by the inner gas type and flow, making it possible for penetration shape of the molten pool to be optimized.

The efficiency of laser –TIG hybrid and two other processes has been studied by Gureev et al. [128]. They reported that the melting rate for laser-TIG hybrid process is almost twice as high as the sum of the arc and laser welding process sepeartely. Authors like Matsudata et al. [129] also reported on an increase in penetration with 300A TIG arc augmentation compared to 5kW CO_2 laser alone. It was reported that the penetration was 1.3-2 times higher depending on the welding welding speed, as illustrated in Figure 31.

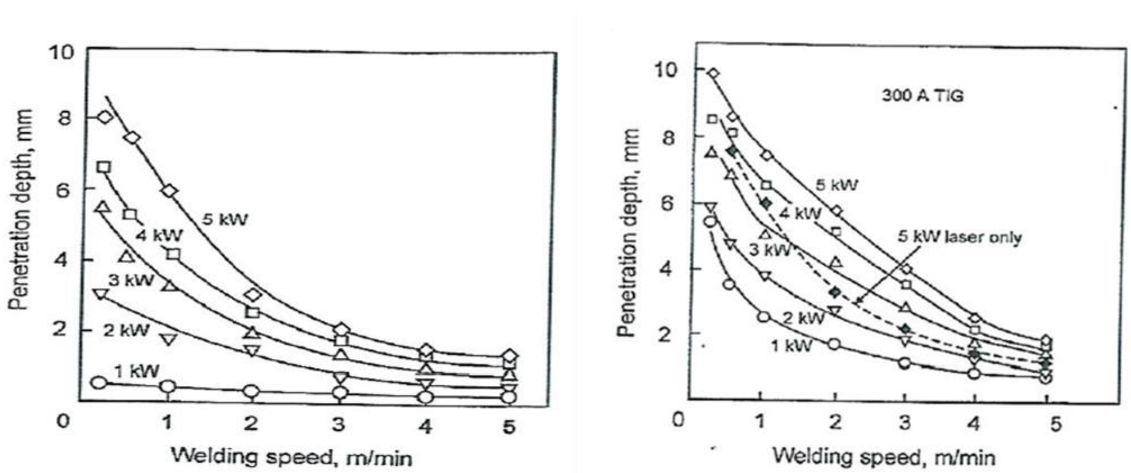


Figure 31. Comparison of penetration at different welding speeds in autogenous laser welding and hybrid laser-TIG welding at arc current of 300 A [129].

Several authors have reported that because laser-TIG hybrid welding doesn't have droplet transitions, it is easier to control the welding process than laser-MIG hybrid welding [5, 23]. Although several advantages have been realized in the combination of TIG arc to laser, a number of disadvantages are reported to be connected with TIG welding process. Possible contaminations on electrode surface caused by the hot metal vapor present in the process together with erosion of the electrode tip caused by the frequent use of high-frequency arc ignition region which causes destabilization of the arc has been reported. High affinity of tungsten for oxygen can also cause the electrode to oxidize quickly, causing arc instability [130]. TIG arc has been combined with different laser types in recent years and have been experimantally tested. This section will discuss the various combination of TIG arc with different laser types (YAG laser-TIG welding, CO_2 laser -TIG welding and fiber laser-TIG welding).

4.1 CO_2 Laser –TIG hybrid welding

Until the invention of hybrid laser arc welding, CO_2 laser has mentioned previously has been in existence for a very long time in welding of various metals. Since the invention of hybrid laser arc welding, various experiments have been carried out by different researchers in combining the CO_2 laser to different arc process. This chapter will elaborate on experiments carried out by the combination of CO_2 laser with TIG arc to ascetain its prospects in welding various metals. Figure 32 shows schematic setup of CO_2 laser-TIG hybrid welding.

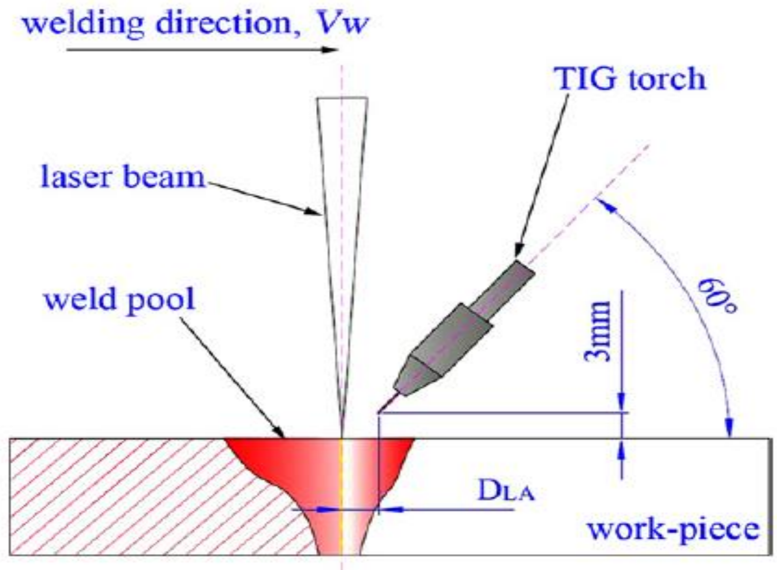


Figure 32. Schematic setup of CO_2 laser-TIG hybrid welding [131]

There are two types of CO_2 hybrid laser-TIG welding, namely CO_2 paraxial and CO_2 coaxial hybrid laser-TIG welding. Comparing CO_2 coaxial to paraxial hybrid laser-TIG welding, it can be said that the effect of current on hybrid arc and weld penetration is consistent in coaxial hybrid laser-TIG welding. However, there is maximum penetration during paraxial hybrid laser-TIG welding by approximately 20% as illustrated in Figure 33. In addition coaxial hybrid welding can effectively inhibit the energy absorption or defocusing of laser by hybrid arc plasma, enhance the critical current of the transition of deep penetration welding mechanism which can obtain deeper weld penetration [123].

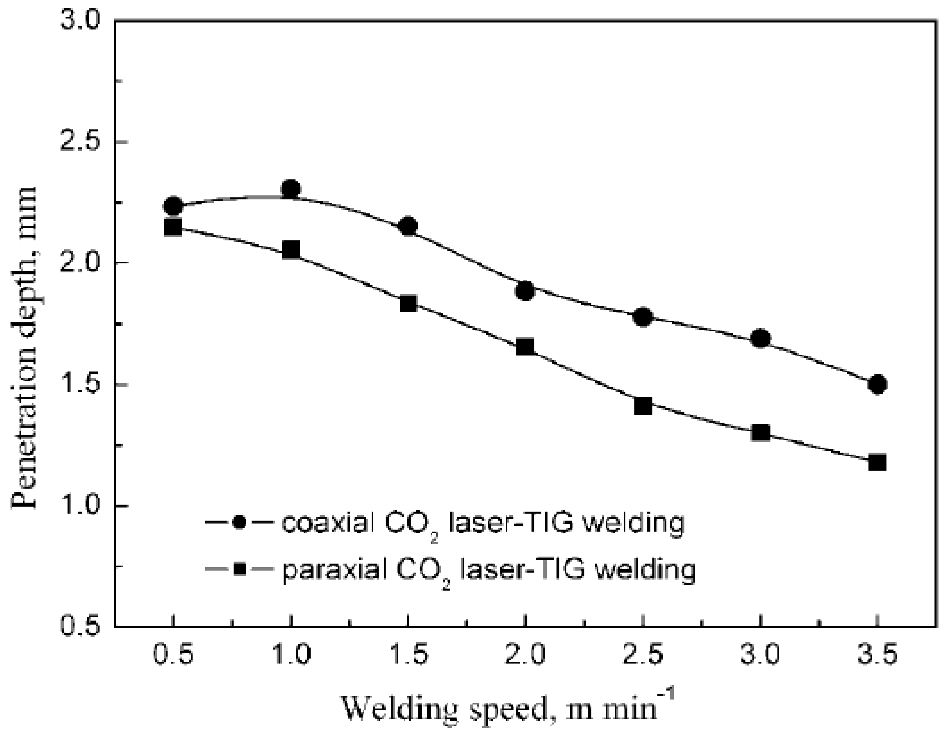


Figure 33. Illustrating the weld penetration of different coaxial and paraxial hybrid laser- TIG welding (P= 1000 W, I= 120A) [123]

The use of shielding gas is a major difference between the hybrid welding of the different laser sources. For CO_2 laser gas mixtures with high helium content are necessary. Shielding gases used in hybrid laser-TIG welding process will be discussed in details in subsequent chapters. As mentioned earlier hybrid welding is not only a combination of individual heat sources, therefore to be able to achieve synergetic effects of laser and the arc it is important that several parameters involved in hybrid laser welding must be resolved. It is be noted that, few experiment have been carried out to verify the effect of shielding gas on process stability and weld penetration in the CO_2 laser-TIG welding as compared to the CO_2 laser-MAG welding. Fellman et al. [132] had discussed how the shielding gas composition of helium–argon–CO_2 affected the weld quality, weld profile and process stability of the CO_2 laser-metal active gas (MAG) hybrid welding. Ming Gao, et al. [133] carried out an experiment on CO_2 laser-TIG hybrid welding with different shielding gas methods on the 316 L stainless plate, to investigate the effect of the shielding gas kinds and protecting methods on the process stability, the laser-arc interaction as well as the weld penetration.

After carrying out the experiment the following conclusion was drawn on process stability; The effect of shielding gas on the laser-TIG are strong and only the optimal combination of gas shielding parameters can result in the stable process and efficient synergetic effects between CO_2 laser and TIG arc. Also there was an increased penetration and stable welding process. On the other hand the inappropriate combination of gas shielding parameters produced an instable process and disturbing synergetic effects resulting in shallow weld penetration which was similar to and even shallower than that of single heat source welding process. Figure 34 (a-c) illustrates the surface and cross-section morphology of weld using different shielding gas parameters.

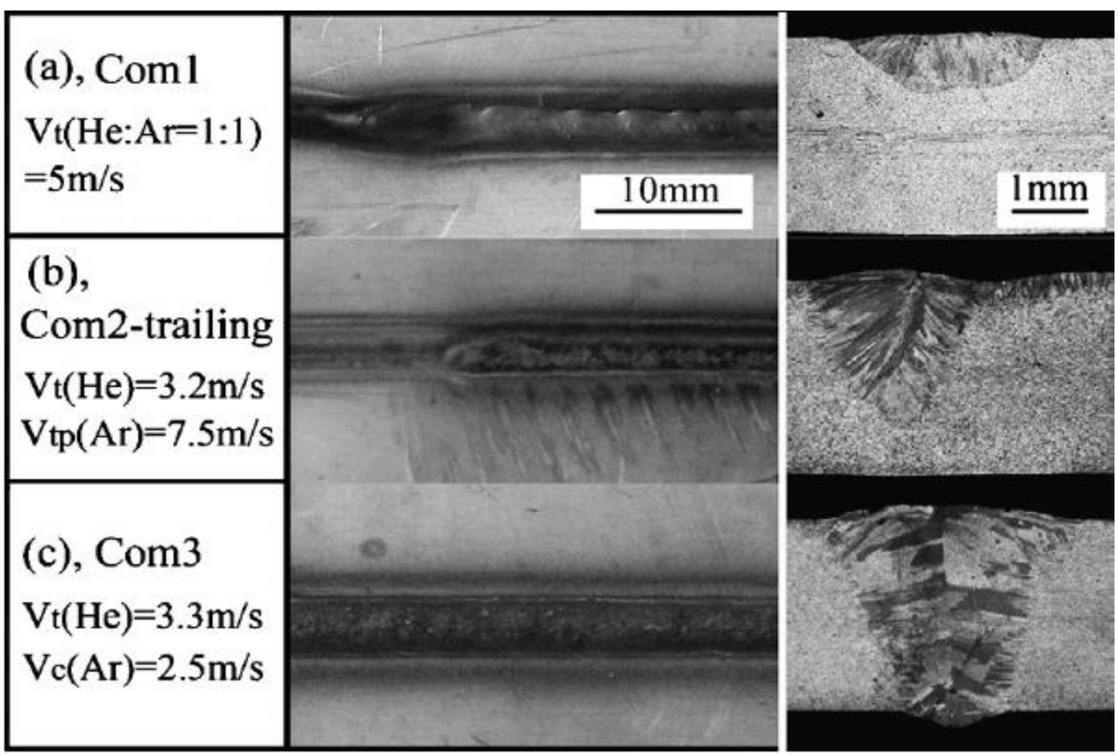


Figure 34. Surface and cross-section morphology of weld using different shielding gas parameters [133]

Secondly, on plasma shape the following conclusion was drawn, the weld penetration of hybrid welding varies with the plasma shape determined by the shielding gas parameters,particularly the plasma height interacting with incident laser. The higher the plasma height interacting with incident laser the shallower the weld penetration. Also the effect of shielding gas parameters on the plasma shape is achieved by two ways namely; laser-arc plasma interaction and gas flowing direction and velocity. Figure 35 shows plasma shapes of laser-TIG under different shielding gas parameters.

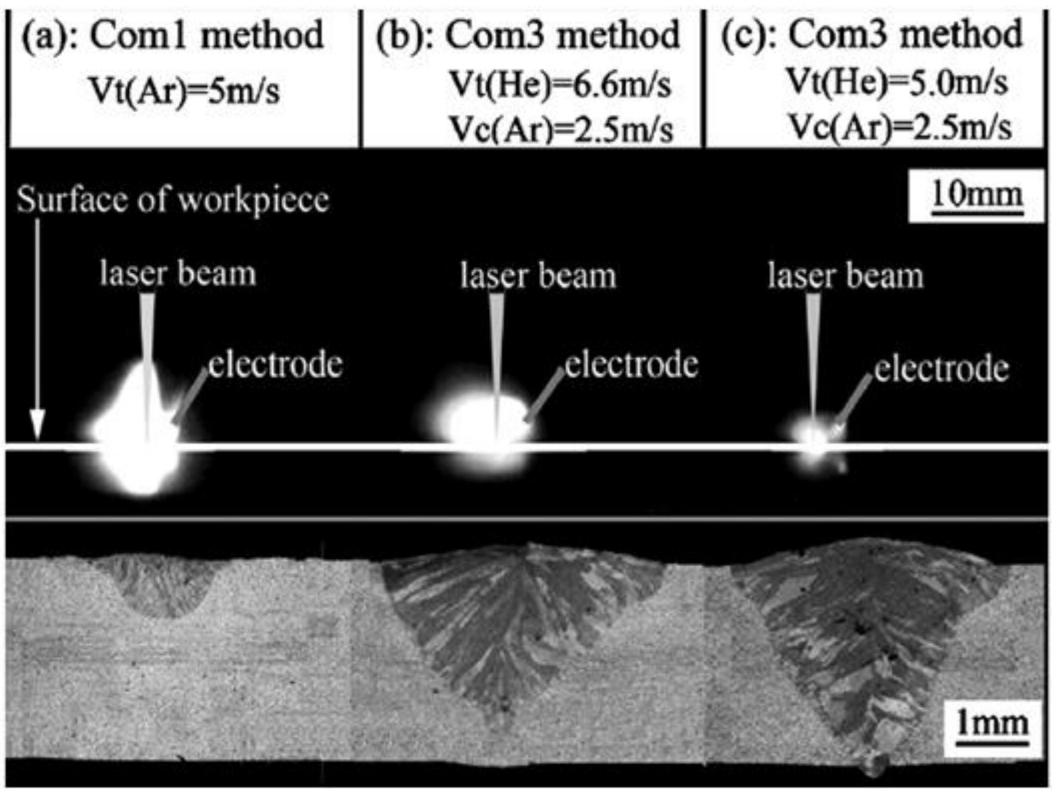


Figure 35. Plasma shapes of laser-TIG under different shielding gas parameters[133]

Lastly, Ming Gao, et al. [133] reported that full penetrated weld cannot be generated by pure TIG torch method, however it can be reached by the hybrid protecting method. The shielding gas parameter range with the full penetration weld of the hybrid protecting method combining the torch and paraxial nozzle is very narrow, but that of the hybrid protecting method coupling the torch and coaxial nozzle is considerably wide.

Till date Bagger is the only one reported to use pure nitrogen in the hybrid CO_2 laser–TIG welding of 4 mm X6Cr17 steel to 2 mm 316 L austenitic stainless steel and obtaining a good results as well as fulfling profuct demand [134]. Although nitrogen is seldomly used in hybrid welding, however given its application in single laser and arc welding they should play an important role in the hybrid welding of some special materials, for example copper alloys, nickel alloys and stainless steels. Although it has been reported that the combination of TIG welding process with different laser sources (CO_2, Nd: YAG) find its use mainly with thin materials [106]. The welding Institute (TWI) Granta Park in the United Kingdom in 2006 [135] carried out an experment by combining 5kW CO_2 laser with TIG arc to weld ≥10mm thick stanless steel. After carrying out the experiment the following conclusion were drawn, at a speed of 0.5 m/min there was significant loss of penetration due to attenuation by plasma generated by the wavelength of the CO_2 laser. Nevertheless, the attenuation formed by the CO_2 can be reduced using He jet, formed by a flow 8-10 *l*/min He down a 1.2 mm ID tube inclined at an angle 45^o, with a 10-12 mm stand off which is aiming either at the laser impingement or 1 mm ahead of it. With this setup a penetration of a 10 mm can be achieved as compared to 4 mm without.

Secondly, the combination of leading TIG arc in CO_2 laser-TIG could increase penetration compared with CO_2 laser welding without plasma control possibly due to the premelt or preheat effect of the TIG arc.

Thirdly, the CO_2 laser with TIG arc improves slightly the welding process tolerance to gaps when compared to welding with CO_2 laser with plasma control, this can be further improved through a cold wire addition.

Lastly, a copper plate can effectively sepearte the gas streams for shielding of the TIG arc and plasma control of CO_2 laser, this allows separate optimisation of the two gas compostion without producing an attenuating plasma. Initial results with such setups indicated that when Ar-25He-3H_2 is used as TIG shield gas may reduce porosity, however it still requires the sepearation of CO_2 laser beam to avoid the formation of Ar plasma [135].

4.2 TIG-YAG hybrid welding

As mentioned in previous chapter, the YAG laser offers easier beam transmission and more stable beam quality than the CO_2 laser. This therefore makes it more advantageous in coupling the YAG laser with TIG arc to gain the advantages of both. Cranfield University, Edison Welding Institute and TWI have been investigating the potential of laser welding pipelines with Nd:YAG lasers [136].

Investigation into how porosity occurs during YAG - TIG hybrid welding has also been studied, it has been reported that the amount of porosity increased in the weld metals at low currents of 100 A, however it decreased at 200 A. It was concluded that, in hybrid welding porosity tendency was reliant on welding conditions especially TIG arc current, at 200 A, the top inlet of the keyhole was wider in diameter and the surface of the molten pool was concave. However, only a few bubbles were generated in the molten pool which can result in reduced porosity or no porosity [137].

The effect of hybridization on TIG arc stability has also been investigated, the results obtained suggested that, during TIG arc welding at a welding speed of 1m/min, the arc oscillates without retention in the weldpool however, when a continuously oscillating YAG laser beam is superposed (coaxial TIG -YAG); the arc is retained in the weldpool.

The penetration characteristics of TIG-YAG welding have also been reported, all welds carried out showed that penetration of hybrid welds were deeper than that of YAG laser weld alone at constant TIG current value. However, in the case where different TIG current and constant laser power were used, the penetration did not increase with increase TIG power as illustrated in Figure 36 [138, 139]. Welding with TIG arc and YAG laser can help achieve the following:

- High quality welds
- Improvement on groove gap tolerance
- Reduction in photon loss
- Porosity formation control could be achieved for TIG-YAG welding under Argon atmosphere.
- Keyhole diameter of TIG-YAG weld is increased compared with weld made with YAG only
- Absorption of laser plume TIG arc can be ignored in coaxial TIG-YAG welding by keeping TIG arc fixed and stabilized at the point of laser irradiation

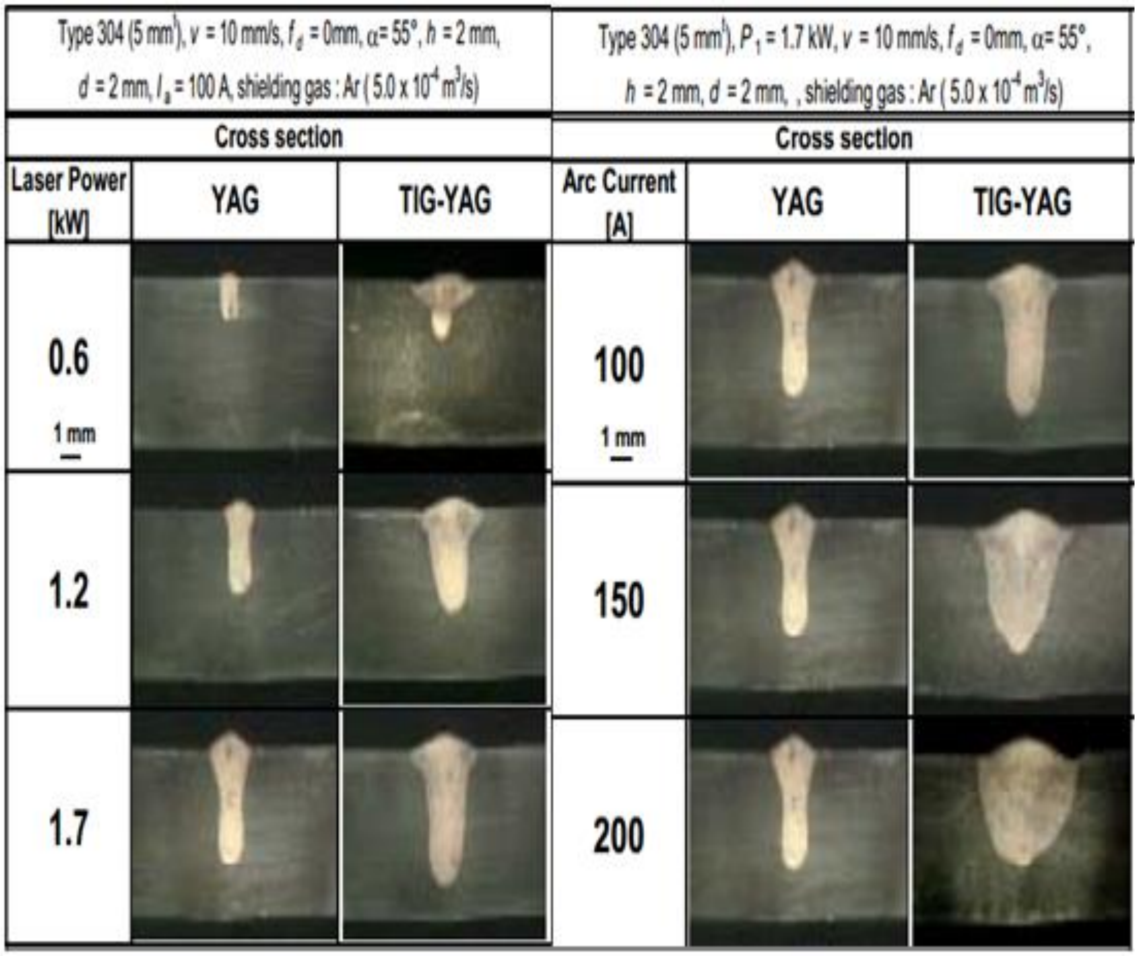


Figure 36. Cross sections of Type 304 stainless steel subjected to YAG laser only and TIG - YAG hybrid welding at various laser powers and various currents [138, 139]

An experiment was carried out by Wendelstorf et al. combined laser and TIG arc between 60 A to 80 A current to weld a 304L stainless steel of about 2 mm thickness by using a continuous wave Nd:YAG laser of output power between 100 to 1500W at speeds of 0.1m-2.8m/min. After carrying out the experiment they reported that they were able to use the TIG arc combined with Nd: YAG laser to higher welding speeds than using the TIG arc alone. This is because the laser was able to stabilize the arc even at higher welding speeds. However the results did not actually show any synergy between the two processes in terms of penetration.

Ishide et al [5, 140] in 1997 and 2001 used a coaxial arrangement of 1.3 kW Nd:YAG laser with a 100 A TIG arc at welding speed of up to 0.6 m/min to butt weld 3 mm thick sheet. After carrying out the experiment they reported on realizing full penetration, improved stability as well as reduction in porosity. Also the arc was seen to preferentially root on the laser keyhole, this accounted for the improved stability. The reduction in weld porosity was attributed to an observed increase in keyhole diameter size, which was assumed to help the escape of entrapped porosity. A doubling in gap bridging ability compared with laser welding was also observed. It is also reported of having less undercut in the hybrid welds. Finally Ishide et al. noted that, no attenuation was observed of an Nd: YAG probe laser passing through the area above the weld pool, by either the metal vapor plume above the keyhole or the TIG arc [5, 140].

4.3 Fiber Laser- TIG hybrid welding

Lately there has been a major advancement in the laser technology, the introduction of high power fiber laser which has seen some great development. In recent years the available laser power has changed from 1 W to 20 kW in a period of 16 years. Although Nd:YAG lasers demonstrated potentiality with increase in welding productivity, however due to wall plug efficiency, physical size and cooling requirements, these lasers are not suitable for onshore pipeline applications [141]. Hence the new high power fiber lasers present good potential for these applications [142]. The fiber laser can boost of the following advantages;

- high efficiency,
- low running cost and long lifetime of diodes
- good beam quality
- no limitation in power
- requires small space and high mobility due to its compact design

In addition, high power fiber lasers can be used for deep penetration welding in a diversity of materials since the low wavelength that characterizes these lasers allows its absorption by almost all metals and alloys, and the fiber delivery system provides the necessary flexibility on the positioning of the beam. In terms of the cost, fiber laser technology up to 1 kW output is said to be below or comparable with lamp-pumped YAG lasers. However, the cost is greater for fiber laser greater than 1 kW. On the other, when all factors namely, floor space, chillers and maintenance, are accounted for, the fiber lasers should be more cost effective than equivalent power rod-type Nd:YAG lasers [143]. Powers of up to 7 kW via a 0.3 mm diameter, 20 m length optical fiber cable which has the capability of producing a power density of 2×10^6 W/cm^2 powers which is equivalent to high power Nd:YAG lasers. Applications of fiber laser on welding in recent years have been expanded [17-19].

The characteristics and advantages mentioned previously has made the fiber laser welding process developed very rapidly [20].

The fiber laser beam can also be operated in two modes that is continuous wave (CW) mode and pulse mode. The mode selection is usually based on the processes and objectives. It has been reported that the fiber laser achieved high quality micro welds with single mode for stainless steels foils of 10-100 μm with high speed, using an ultra-fine keyhole welding mode [144]

As mentioned previously, the possibility of delivering power to the workpiece via a flexible optical is an important advantage in the use of fiber laser in the processing of thin sheet for high volume manufacturing.

The Welding Institute (TWI) Granta Park in the United Kingdom in 2006 [135] carried out an experment by combining 5kW CO_2 laser with TIG arc to weld ≥10 mm thick stainless steel also carried out this same experiment with same parameters but this time by combining the Yb fiber laser with TIG arc welding process. On the basis of the experiment they concluded that since the Yb fiber laser has no significant loss of penetration due to plasma attenuation, therefore makes the Yb fiber laser a favourite choice for thick section welding. This has also been demonstrated in the welding of thick section C-Mn steels and aluminum alloys by

Verhaeghe G. [145].

R. Miranda et al. carried out an experiment on X100 pipeline steel which is a new high strength steel for pipeline applications which enables the use of thinner walled pipe, making them lighter to transport and easier to handle on site, allowing greater operating pressures and reducing overall costs [146] with fiber laser and TIG. After carrying out the experiment the microstructures developed were analyzed in order to have a better understanding of the transformations induced in this material by the thermal cycle associated with fusion welding. The results showed that, the base metal microstructure had a fine grained ferrite and pearlite structure. However after laser welding a fine structure of martensite is exhibited (with hardness values around 375 HV in the fusion zone). For higher heat inputs, the structure became coarser in Widmanstätten morphology and the hardness in the melted area, dropped. However TIG welds presented coarser microstructures than the ones observed in laser welds, mostly constituted of bainite with hardness values lower than those observed in laser welding [144].

4.4 Pulsed Laser-TIG hybrid welding

Due to the latest trends in the welding industries and with focus on the welding of thin sheets a new laser –arc hybrid welding process was projected (Pulsed Laser-TIG) [147]. The pulsed laser TIG process combines pulsed laser source and a pulsed TIG process. Comparing with continuous wave laser, pulsed laser can reduce the interaction time, which means that it can effectively restrain the growth of plasma, decrease the absorption or defocusing of laser energy and obtain deeper penetration. Though the pulsed laser-TIG hybrid welding can increase weld penetration, it brings more parameters to adjust as compared with continuous wave laser-TIG hybrid welding. The pulse duration of laser plays a dominating role in affecting arc shapes. If the pulse duration is short, it is not enough to complete the compression and stabilization of arc, also the longer the pulse duration, the absorption or defocusing of laser may be increased and the arc itself will expand [123].

A.-V. Birdeanu et al. [148] also reported on the effect of various parameters on pulsed laser TIG hybrid welding. After carrying out the experiment the following they came out with the following conclusion: at low average welding current pulsed TIG hybrid process becomes unstable. Additionally, they observed that changing the TIG torch angle influences the weld pool with an increase in dimension at an angle 45^0 as compared to an angle of 39^0. Figure 37 illustrates the influence of TIG torch on pulsed laser TIG hybrid welding at an angle of 39^0 and 45^0 respectively.

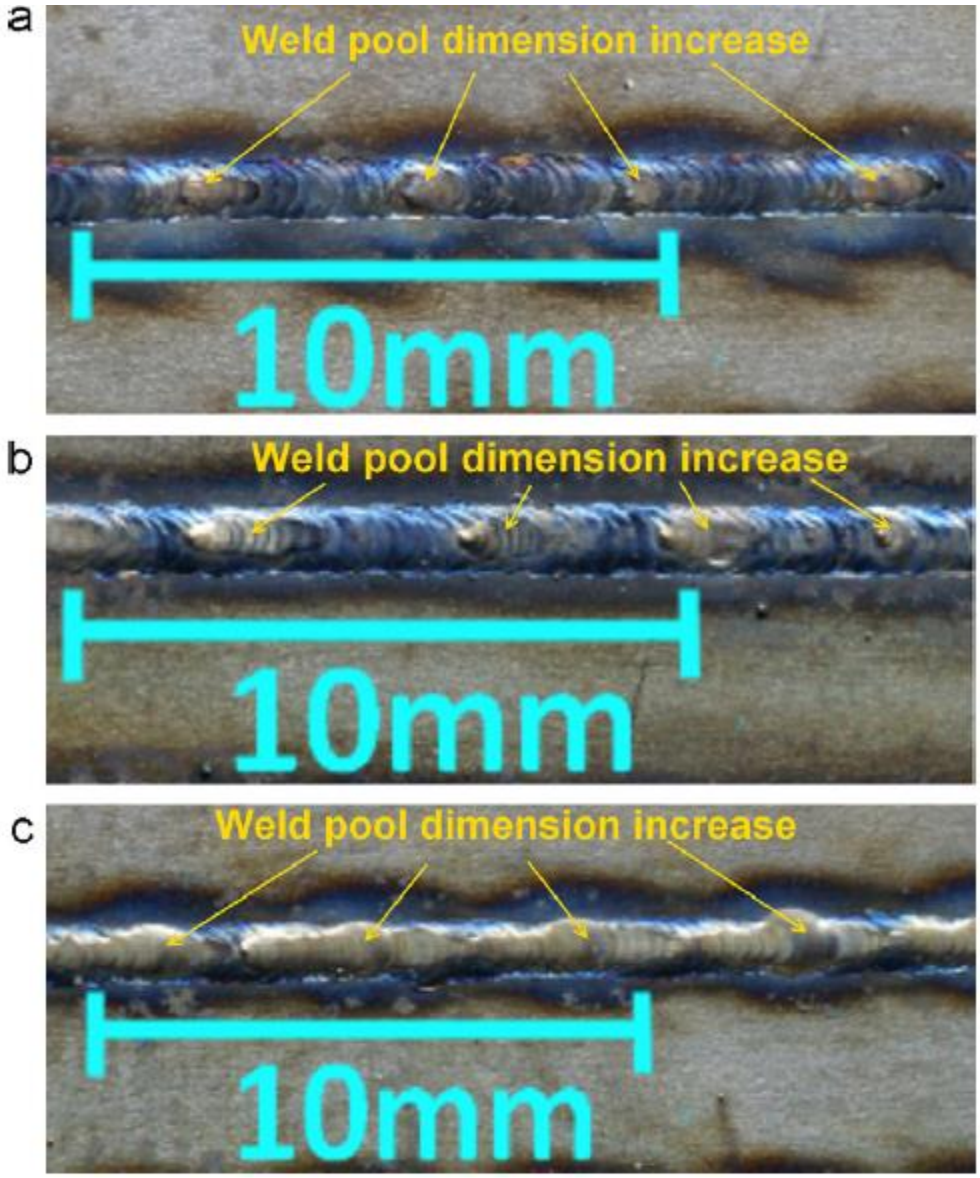


Figure 37. Influence of TIG torch angle on pulsed laser-TIG hybrid welding - laser beam angle variation (a - 39^0; b - 45^0; c – 60^0) [148]

In respect with the angle 39^0 the region of accumulation was changed which lead to a bigger width. Depending on the leading process or travel direction, it is possible to have either pulsed laser (micro) TIG welding [148]. Figure 38 shows pulse laser-(micro) TIG hybrid welding process.

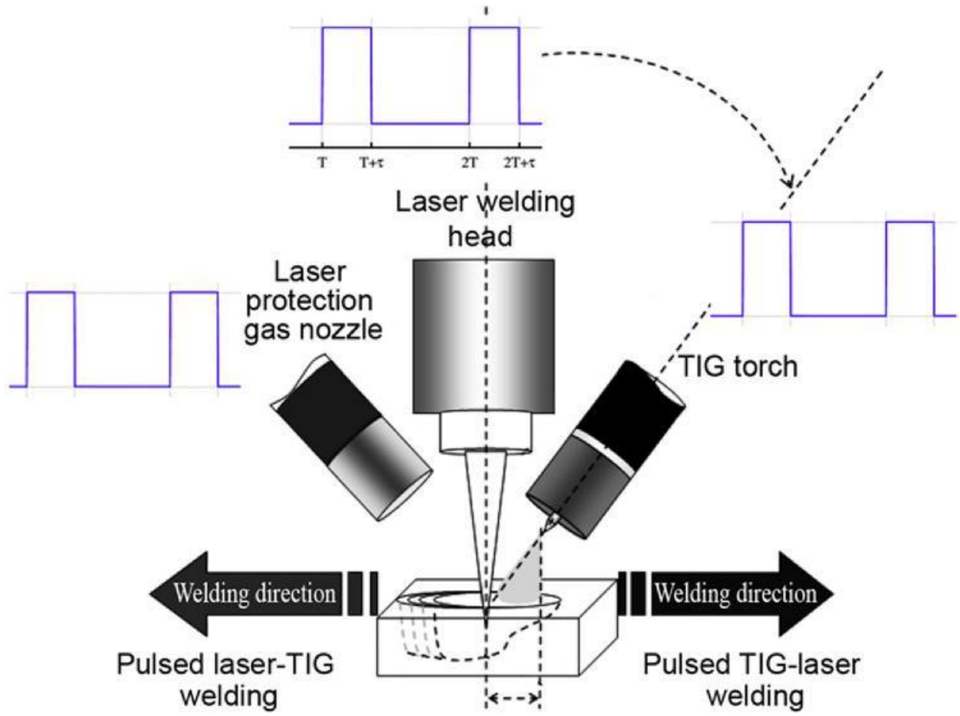


Figure 38. Pulsed laser-(micro) hybrid welding principle [148].

Kim et al. also carried out an experiment by combining 100 W pulsed Nd:YAG laser with 30 A TIG arc to weld 1.2 mm thick 304 stainless steel plate. The arrangement had the laser leading the TIG arc that is positioned on front edge of TIG melt pool. The results showed that when an external magnetic field was applied to it the TIG arc there was no deflection, therefore improving stability of the arc.Secondly, there was a reducton in spatter as well as increase in penetration since non of the single process was able to fully penetrate the 1.2 mm thick plate.

V.Birdeanu et al. [147] carried out an experiment using Pulsed Laser-TIG hybrid welding on butt welding of 1.5 mm thick coated unalloyed steel thin sheets. In their experiment the TIG lead the process and also there was no special preparation on the welded joint. After carrying out the experiment, base on the obtained results, they came out with the following conclusions: In the terms of efficiency Pulsed laser-TIG welding showed an increased in penetration as compared to using each of the processes individually. Figure 39 illustrates the obtained penetration depths using each of the welding process seperately.

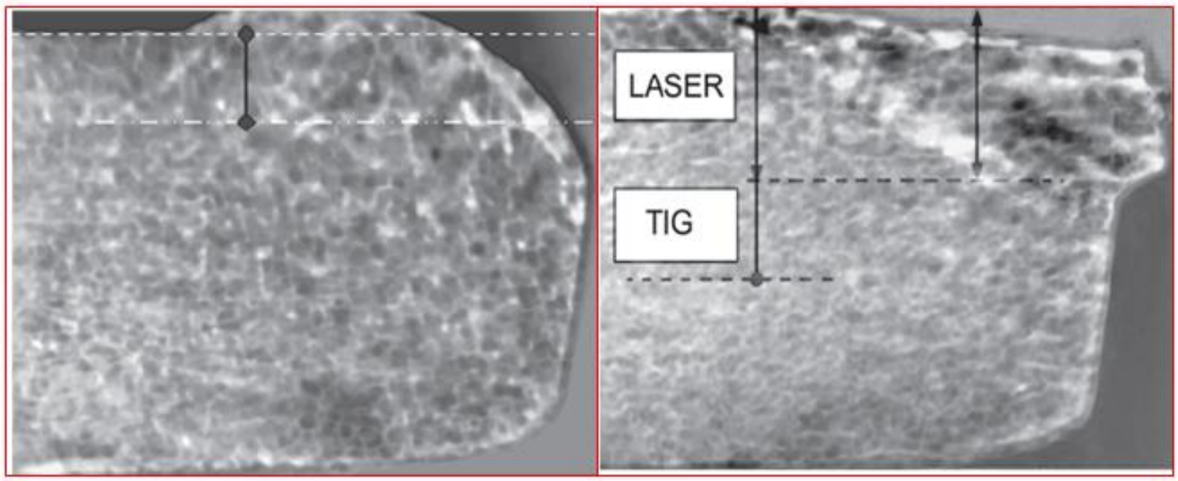


Figure 39. Maximum penetration depth using pulsed TIG process and pulsed laser process. Same joint configuration, same laser process parameters and lower travel speed [147]

Secondly, sound welds were also obtained with less thermal induced stresses while no joint preparation was used for butt welding of the covered coated thin sheets. Also based on the analysis carried out on various samples no imperfections was realised.

Finally, a lack of symmetry was observed for the micro- hardness values variation measure in the joint area which properly could be related to a slight miss-alignment of the TIG arc plane to the laser-beam travel direction plane or asymmetrical current flow and the inherent magnetic blow of the arc [147].

5 LASER-TIG HYBRID PARAMETERS

Process variables in Laser–TIG hybrid welding have similar effect on the welding performance as in autogenous laser welding. These include the laser beam properties such as focusing parameters, beam quality and wavelength and laser power. In laser hybrid –TIG welding process, since two processes are combined in a single process zone the variables arising from process combination must be adjusted to obtain quality welds. The increases in the number of variables as compared to the single process are considered to be a disadvantage because it complicates the process. Nevertheless, laser hybrid –TIG welding has a lot of flexibility in its parameter selection and therefore widens the area of suitable applications. It is important that, during the arrangement of laser and arc technicalities involve are followed to ensure full benefits of hybrid welding

5.1 Defocusing value

This characterizes the position of laser focus in relation to the surface of the workpiece. The defocusing value influences the power density of the laser beam in contact with the surface of the base metal and flow of molten pool. The focal plane position has an influence in weld penetration as in autogenous welding process; however in hybrid welding since the weld pool surface is concave as a result of arc dynamic pressure; optimal focal plane position is shifted deeper into the material. As illustrated in Figure 40, when the defocusing value is within -0.8 mm ~ 0.8 mm the penetration of hybrid joint is the deepest and the formation of the weld seam is the best [149]. Arc current and welding speed affect focal plane position since this defines weld pool size and concavity. With higher welding speeds the focal plane position on penetration decreases. The penetration depths as a function of focal plane at different arc levels is illustrated in Figure 41.

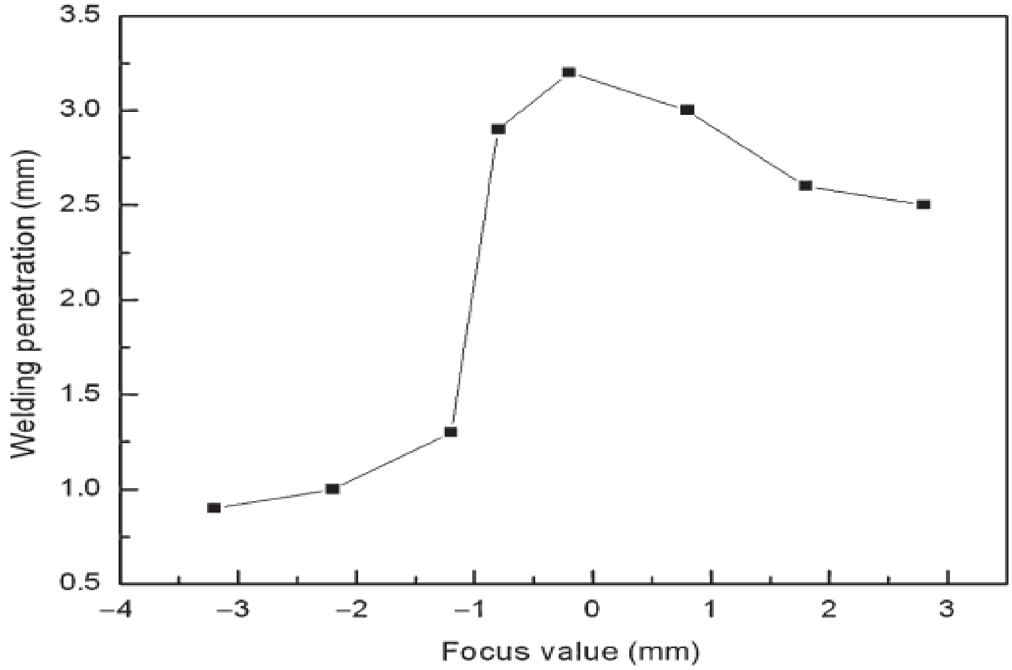


Figure 40. Influence of focus value on the welding penetration (P = 400 W, fd = −0.8 mm, I = 100 A, h = 2 mm, D_{LA} = 2.0 mm, V = 1200 mm/ min, argon 10 L / min) [149].

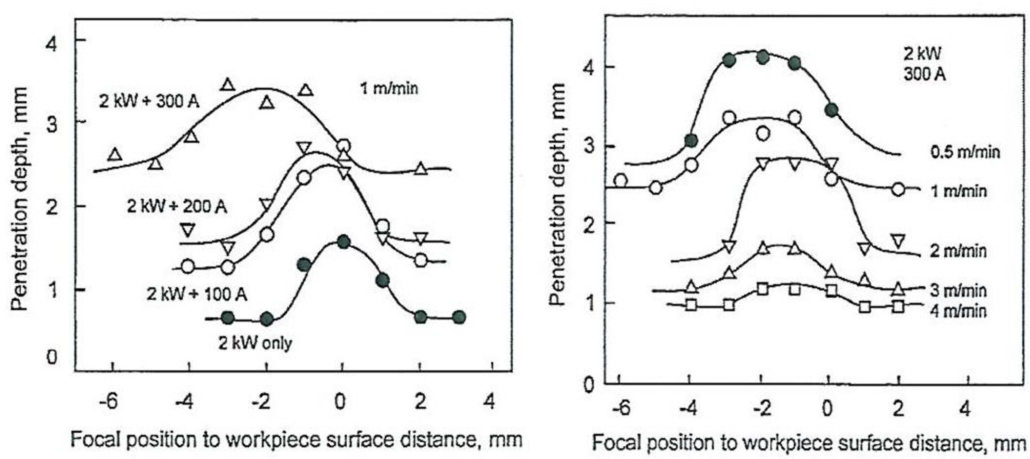


Figure 41. Penetration depth as a function of focal plane position at different arc current levels (left) and welding speeds (right) [129]

5.2 Electrode

Tungsten alloys are preferred as electrode during TIG welding because tungsten has the highest melting point of all non-alloyed metals (3410^{o}C). The electrodes are usually produced with sintering process, and different kinds of additives are added to enhance the electrode performance. Some of the additives are thorium oxide or zirconium. It is important that right electrodes are choosing in respect to current in order to avoid instability. Electrodes are available in standard diameters from 0.5 through 6.3 mm, however, the common ones are 1.6, 2.4 and 3.2 mm [150, 151]. Table 5 illustrates recommended electrodes diameters for different current power source [61, 124]. Also, the shape of the tip of the electrode has an influence on the arc properties. Similarly, the optimal tip angle is determined mainly by the current and the penetration needed. It must be noted that, at high current, the tip angle widens the arc root as well as the fusion zone which leads to a lower penetration. As the tip angle rises, arc root tapers and penetration increases as well. Figure 42 illustrates the effect of tip angle on size of bead and penetration.

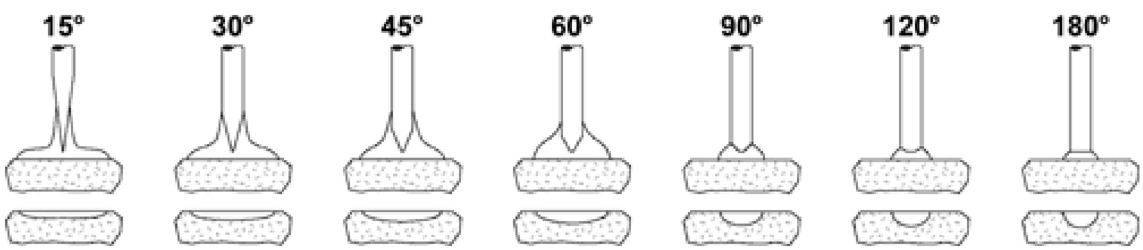


Figure 42. Arc shape and fusion zone profile as a function of electrode included angle [152]

Grinding an electrode to a needle –pointed shape is sometimes desirable for certain applications, specifically where arc starting is difficult or short duration welds on small parts are performed. In order to reduce erosion and melting off the tip of the electrode which may cause tungsten inclusion, a flat spot or tip diameter at the end of electrode is beneficial. Table 6 illustrates benefits derived from using larger and smaller tip diameters.

Table 5. Recommended electrode diameters for different current ranges [150]

Electrode diameter (mm)	DCEN [A]		DCEP [A]		AC [A]	
	Unalloyed tungsten	Alloyed tungsten	Unalloyed tungsten	Alloyed tungsten	Unalloyed tungsten	Alloyed tungsten
0.5	2-20	2-20	-	-	2-15	2-15
1.0	10-75	10-75	-	-	15-55	15-70
1.6	40-130	60-150	10-20	10-20	45-90	60-125
2.0	75-180	100-200	15-25	15-25	65-125	85-160
2.5	130-230	170-250	17-30	17-30	80-140	120-210
3.2	160-310	225-330	20-35	20-35	150-190	150-250
4.0	275-450	350-480	35-50	35-50	180-260	240-350
5.0	400-625	500-675	50-70	50-70	240-350	330-460
6.3	550-875	650-950	65-100	65-100	300-450	430-575

Table 6. Benefit derived from using larger and smaller tip diameters [152]

Smaller Tip	Larger Tip
Easier arc starting	Usually harder to start the arc
Potential for more arc wander	Good arc stability
Less weld penetration	More weld penetration
Shorter electrode life	More electrode life

The position of the electrode is also base on the configuration type been it a leading or trailing arc. It has an effect on the weld properties because the weld pool dynamics is different in leading and trailing arc setups. Table 7 shows the effect of electrode positioning fusion zone area in laser-TIG hybrid welding of stainless steel.

Table 7. Effect of electrode positioning fusion zone area in laser-TIG hybrid welding stainless steel [39]

Electrode position	Laser power [W]	Arc current [A]	Welding speed [m/min]	Fusion zone area [mm^2]
Leading arc	950	100	2.4	2.370
Trailing arc	950	100	2.4	1.856

To achieve maximum penetration during welding; the distance between the electrode tip to the laser beam axis should be in the range of 2-3 mm. For distance lower than 2-3 mm there is a possibility for electrode to be consumed by laser beam, whereas distances larger than 3 mm decreases the penetration due to the disappearance arc rooting and contraction [129]. Figure 43 illustrates the effect of distance between electrode tip and laser beam axis on penetration in hybrid CO_2 laser-TIG welding with arc current of 300 A (CO_2 laser power of 2 kW and welding speed of 1 m/min)

Cheolhee Kim et al. [153] carried out and experiment on the relationship between the weldability and process parameters for laser-TIG hybrid welding of galvanized steel sheets they also confirmed that the electrode height should be maintained over 2.0 mm to prevent damage of the electrode tip. Figure 44 illustrates the damage of electrode during the experiment at different heights; they reported also that there was a rapid increase in the welding voltage at an electrode height of 0.4 mm. However, it must be noted that when the height of the electrode was 2 mm, it was not blunted even after ten experiments and there was no rapid rise in the voltage waveforms.

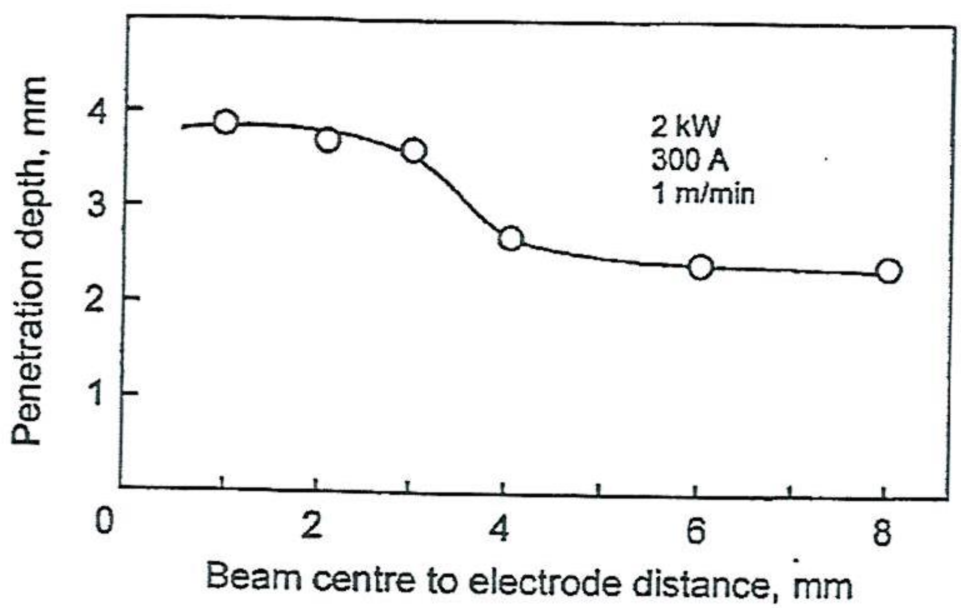


Figure 43. Effect of distance between electrode tip and laser beam axis on penetration in hybrid CO_2 laser TIG welding with arc current 300 A, CO_2 laser power of 2 kW, and welding speed of 1.0 m/min [125, 129]

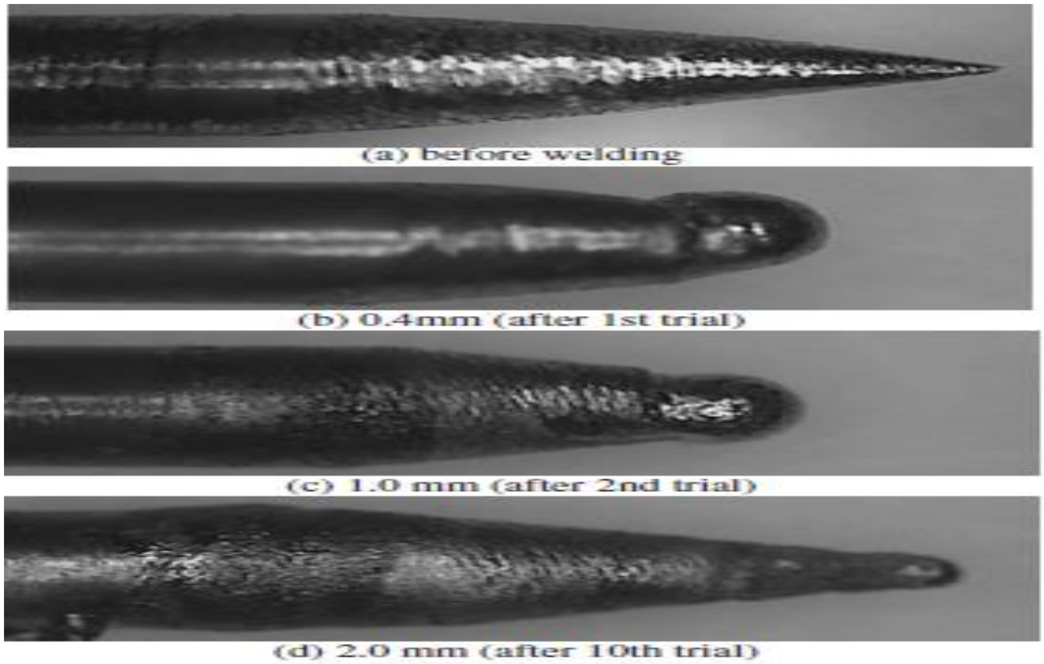


Figure 44. Illustrating deterioration of electrode tip for various electrode heights after experiments [153]

5.3 Process variables

As mentioned previously, in Laser-TIG hybrid welding so many variables has an effect on the performance and quality of the weld. Factors such as defocusing value, welding speed, arc power, angle of torch, distance between laser and arc (D_{LA}) will be discussed in this section.

5.3.1 Angle of Torch and rod positioning

During welding, the electrode and welding rod must be held at special angles for welding a bead on plate. However, for butt welding the angle of the torch is kept fixed. The torch is held 60º - 75º from the metal surface. This is the same as holding the torch 15º - 30º from the vertical. Figure 45 shows the angle of the rod and the torch during TIG welding.

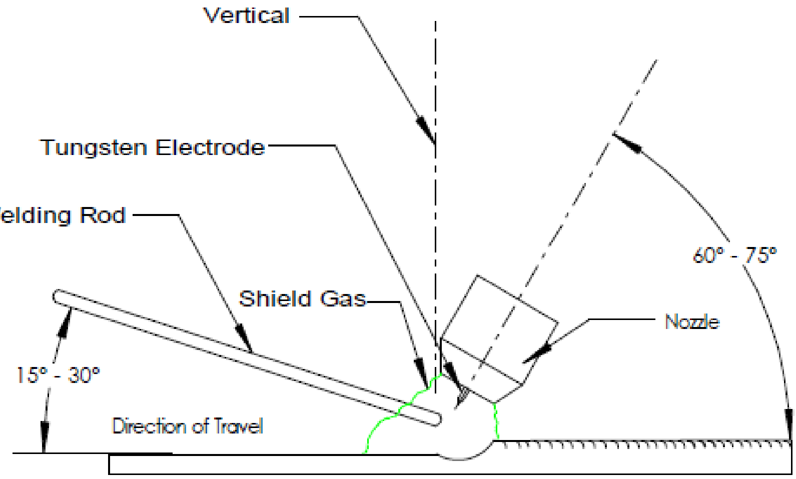


Figure 45. Schematic illustration of angle of torch during TIG welding [154]

The laser beam axis is kept normal to the workpiece surface, whereas the arc torch is inclined with an angle between 35-45^0 relative to the laser beam [3]

5.3.2 Travel speed

Travel speed has influence on the weld width and penetration, but it is more enunciated in the weld width. As illustrated in Figure 46 the effect of welding speed on bead is very simple. With an increase in the welding speed there is a decrease in both width and penetration. This happens because the thermal input to the base metal decreases when the welding speed is increased. It must be noted however that in the welding of magnesium alloys using low-power laser-TIG hybrid welding the welding arc is stable even at high welding speeds in the range of 1500-200 mm/min [149]. The travel speed has an effect also on cost and therefore it is usually kept fixed in mechanized welding whereas others like voltage, current are varied. Jasnau et al. [155, 156], reported on the influences of welding speed on the melt pool dynamics, the formation of process pores.

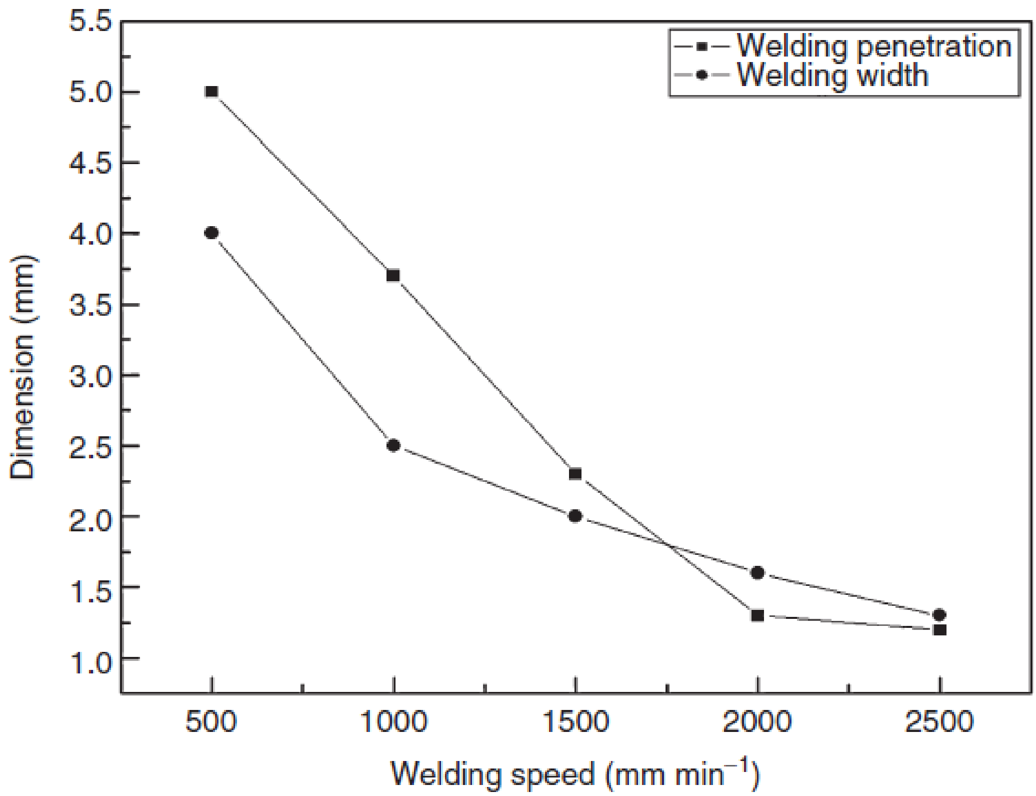


Figure 46. The effect of welding speed on penetration [157]

5.3.3 Filler wire

Filler wire is sometimes required when TIG welding either heavy gage metal or a joint that needs to be reinforced. The selection of filler material depends on the base metal to be welded, kind of weld joint as well as the coating on the filler wires [158]. It has been reported that, filler metal with lower melting point and wider freezing range than the base metal will provide good weldability and minimize weld cracking for arc welding [159]. Four types of filler metals exist; covered electrodes, bare electrode wire or rod, tubular electrode wire and welding fluxes. The use of filler metal requires a higher power and lower weld speed [156] . During

TIG welding in electrode negative mode, the electrode tips need to be grounded at a fixed angle in order to increase the stability of the process. Since changes in the electrode geometry can considerably influence the weld bead shape and size, consistent electrode geometry should be maintained [153]. Filler wire alloys and configurations are optimized to [20, 36, 160-162];

- Improve feed ability and process stability
- De oxidation and scavenging of weld pool contaminants
- Increase conductivity for higher and weld pool fluidity
- Replacing key base material alloying elements that are vaporized and lost during welding process
- Reduce porosity

5.3.4 Distance between laser beam and arc

The distance between the laser beam and tungsten electrode (D_{LA}) can be classified as the most important parameter which has an effect between the laser beam and the arc plasma. The D_{LA} also has an effect on the weld seam as well as the penetration. It has been reported that, the weld penetration increases very much with the decrease in of D_{LA}. Nevertheless the penetration decreases when the D_{LA} is set at 0.5 mm. On the other hand, when the D_{LA} is too short, the tungsten electrode will be burnt by the laser beam which intends increases the instability of the arc plasma and induce defects.

L. M. Liu et al. [163] carried out an experiment to investigate the effective of relative location of laser beam and TIG arc (D_{LA}) in different hybrid modes on melting efficiency and penetration depth in the welding of magnesium alloy. Figure 47 illustrates the D_{LA} for different modes. On the basis of the experiment carried out they came out with the following conclusion; firstly the penetration depth decreases with an increase in D_{LA} in the laser-TIG mode, however in TIG-laser mode penetration depth first increases and then decreases. However, they noted that the penetration depth can attain a maximum value of 4.1 mm at D_{LA} of 4 mm in TIG-laser mode and penetration depth of 2.5 mm is obtained at DLA of 1 mm. On the other hand, the penetration drops to <1 mm when DLA reaches 5 mm which is similar to that of a single TIG welding process.

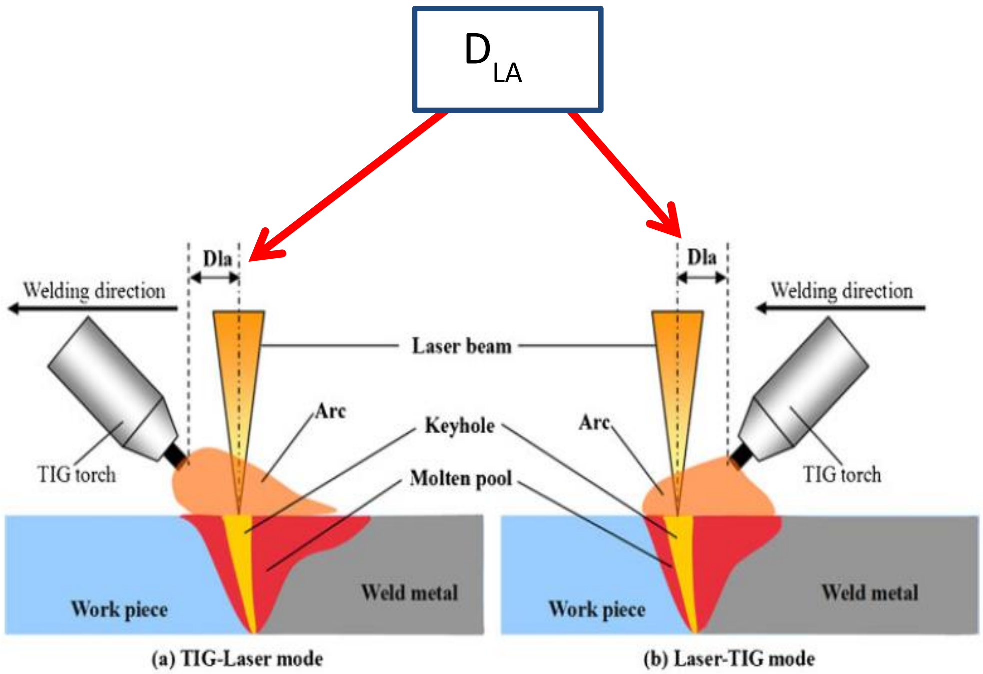


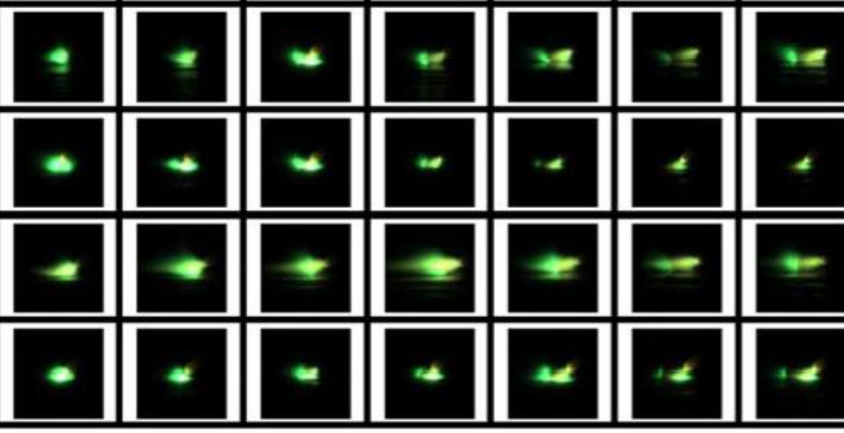
Figure 47. Illustrating of D_{LA} in different hybrid modes [163].

Secondly in terms of its effect on the melting efficiency, there is a percentage increase which remains at approximately 20 % at the laser-TIG mode. However, in the TIG-Laser mode, there is a change in the percentage (53.14%) which occurs at an arc current of 120 A.

Finally, they started also that the different plasma behaviors and the characteristics of molten pool are the fundamental reasons for the differences in penetration depth. Table 8 shows the plasma arc behaviors in different hybrid welding mode.

Table 8. Plasma arc behaviors in different hybrid welding modes [163]

TIG	Hybrid	Dla, mm						
		1	2	3	4	5	6	7
90A	TIG-Laser							
	Laser-TIG							
140A	TIG-Laser							
	Laser-TIG							



G. Song et al. also carried out an experiment using low power laser-TIG hybrid welding of magnesium alloys and concluded that D_{LA} must be between 1.0-1.5mm.This is shown in Figure 48 [149, 164].

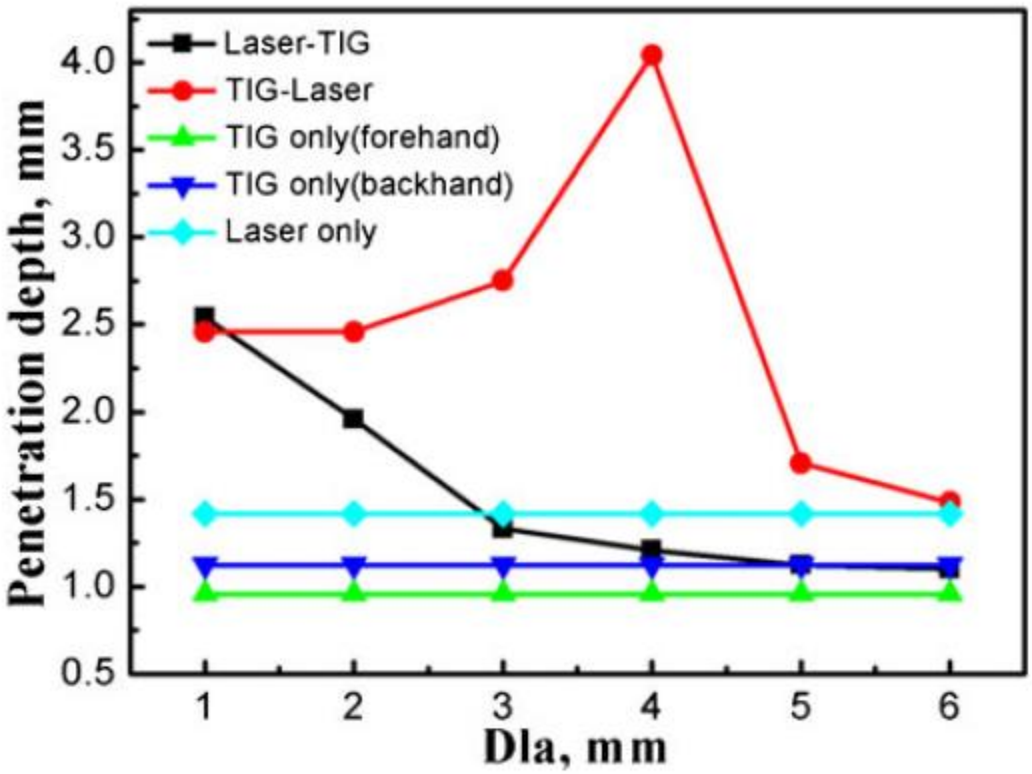


Figure 48. Effect of D_{LA} on weld penetration in magnesium welding [163]

5.3.5 Arc power

The arc power also has an effect on the weld penetration. It has been reported that the penetration of hybrid welded joints is much deeper than the sum of that TIG and laser welding. The arc power important to achieve the deepest penetration in hybrid welding is 1500 W at a speed of 500 mm/min and 2500W at the speed of 1000 mm/min. Figure 49 illusrates the stability of hybrid laser-TIG welding and TIG only at various travel sppeds as function of TIG current. The arc is also reported to be more stable at the presence of the laser beam in laser-TIG hybrid, especially at low TIG current. The reason been that laser generated plasma arc has a greater electron density which reduces arc resstance and allows themionic emission to take place readily when laser is present.

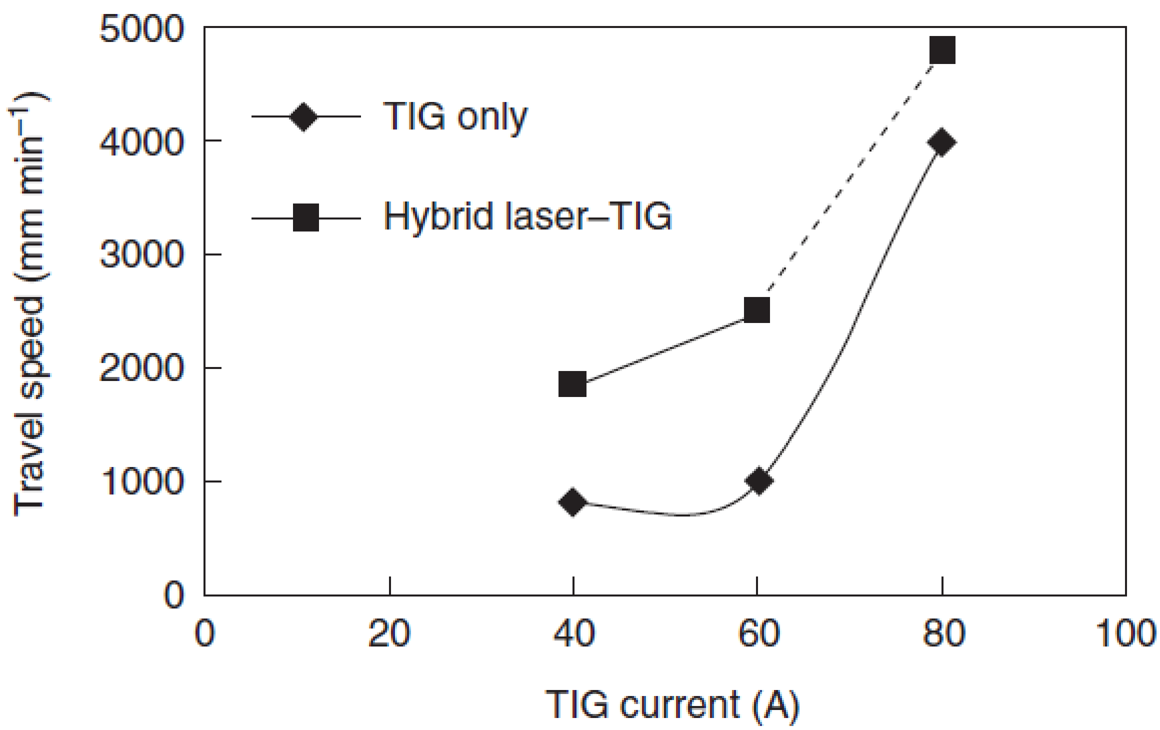


Figure 49. Stability of hybrid laser–TIG welding and TIG arc at various travel speed as a function of TIG current [157]

5.3.6 Shielding gas

Shielding gas is commonly used to stabilize the welding process, to improve the welded joint features and to protect the welded seam from oxidation [165]. The chemical composition of the shielding gas is a key factor in achieving the final quality of the welded joints. There are two categories of shielding gases, namely inert and semi inert gases. The most cost effective ones among the noble gases used for welding are helium and argon. Wide range of shielding gases varying from the pure gases to complex mixtures based on helium, argon (Ar), nitrogen and CO_2 which are commercially available. During welding with a CO_2- laser, the input of the laser beam energy is supported by employing shield gas; usually Ar. shield gas increases and stabilizes the absorption level of the laser-induced plasma. Thus, the energy of the laser beam can almost completely penetrate the material and increase the deep penetration welding effect.

5.3.7 Properties of Shielding Gases

In welding there is what is called "controlled electrical discharge" which is formed and sustained by the establishment of a conductive medium called the arc plasma. This plasma consists of ionized gas, molten metals, slag, vapors, gaseous atoms and molecules. The formation and structure of the arc plasma is dependent on the properties of the shielding gases [166]. Ionization potential is the energy, expressed in electron volts, necessary to remove an electron from a gas- atom making it an ion. Ionization establishes the ease of which an arc is formed, as well as its stability. Arc starting and arc stability are greatly influenced by the ionization potentials of the component shielding gases used in welding process. A gas with a low ionization potential, can dissociate in ions easily, whereas a gas with high ionization potential cannot dissociate easily and hence makes formation of the arc very difficult. The most important property of shielding gas is its purity, which most of the time exceeds 99.8%.

5.3.8 Characteristics of shielded gas blends used in TIG welding

Shielding gas gases used includes Argon, Helium, Oxygen, Hydrogen, Nitrogen and Carbon dioxide. Argon is most economical gas used in TIG welding; it has no color, odor or taste. As an inert gas, argon does not react to other elements and compounds. It has lower flow rate which aids in the improvements in the weld blanket. Argon is about 1.4 times heavier than air and 10 times heavier than helium, which gives better shielding properties. It ionizes easily and this inert properties of argon enables it to form a stabilize arc with an excellent current path. It also produces a narrow arc cone and narrow penetration. It also has an easy arc start and stable arc operation.

Helium is the second lightest element, after hydrogen, and lighter than air and has a low density and is nontoxic. Due to its high thermal conductivity and high ionization potential, more heat is transferred to the base material, thus enhancing the penetration characteristics of the arc. These properties make it most common shielding gas used in most welding processes as it allows higher penetration. Helium also allows higher weld travel speeds to be obtained. In order to reduce its high cost, helium is frequently combined with argon or argon mixtures to enhance the overall performance of the blend while minimizing its cost as well as achieving maximum efficiency. Also it is important that when using helium the gas flow has to be three times greater compared to argon in other achieve an efficient shielding [61].

5.3.9 Mixed Gases

Mixed gases has two main benefits, these include balancing the qualities of inert gases and also reducing production costs. This is because inert gases are expensive; hence combining a low –priced reactive gases and inert gases reduces expenses which occur by using them and influences bead shape. The picture in Figure 50 illustrates the effect of using argon and oxygen, CO_2 and helium.

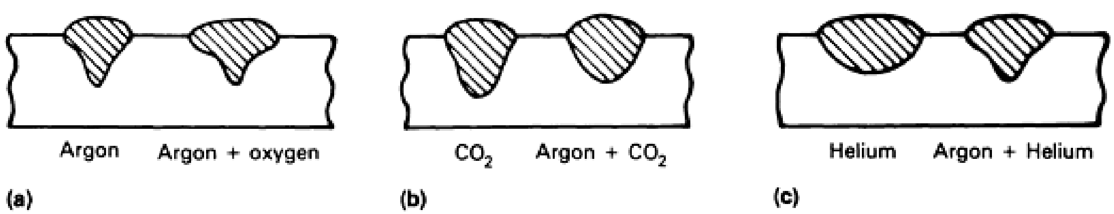


Figure 50. (a) Effect of argon and oxygen (b) effect of argon and CO_2 (c) effect of argon and Helium on weld bead shape [166]

When solid lasers are used in hybrid welding, because the lasers are not sensitive to the laser –induced plasma, pure argon produces a stable synergistic effect between the laser and the arc [167]. During laser hybrid-TIG welding a mixture of helium and Argon are usually used, helium is usually mixed with Argon to give advantages of both gases. These blends are usually used for nonferrous base materials, such as aluminum, copper, and nickel alloys. Helium increases the heat input to the base material and thus is used for joining thick metal. Raising the percentages of helium usually from 50 % to 75 % raises the arc voltage [61]. Shielding gas plays a similar role in hybrid laser-TIG as it is in autogenous laser welding. Fujinaga et al. carried out an experiment combining YAG laser and TIG arc in welding of aluminum using pure argon shielding gas, after the experiment it was found out that, the penetration depth of the hybrid weld (10 mm) was nearly twice that of the single laser weld, indicating an obvious enhanced laser–arc synergy effect [168]. Nevertheless, in the pure argon shielded YAG laser–TIG hybrid welding of 304 stainless steel carried out by Natio [169], the penetration depth of the hybrid weld was only 0.5 mm deeper than that of the single laser weld 5 mm as stated in previous chapter. His study also demonstrates that the increase in the gas ratio of O_2 to argon shielding gas had an influence on the weld bead shape especially at an arc current of 100 A, in YAG laser and hybrid welding: the surface widths decrease and the penetration becomes deep with the increase in oxygen ratio as illustrated in Figure 51.

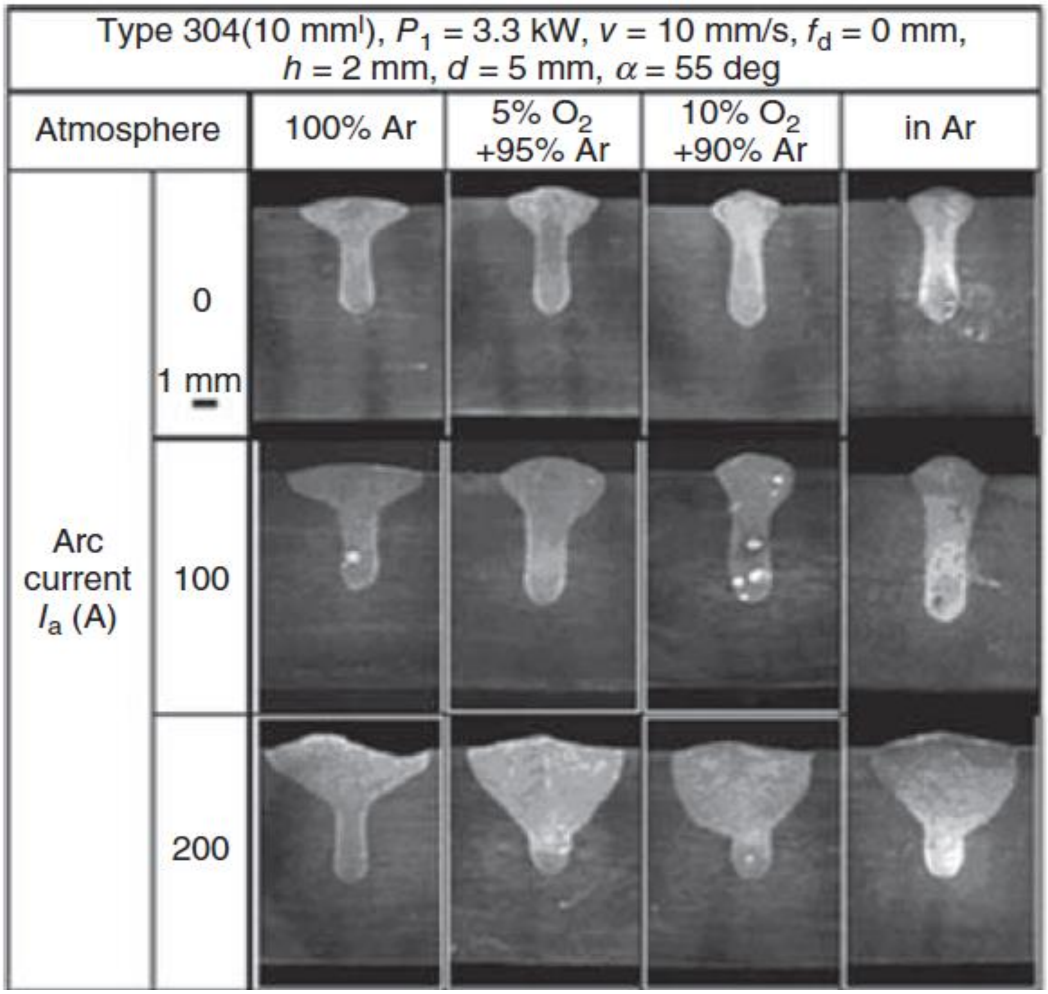


Figure 51. Effects of oxygen content on hybrid YAG laser-TIG weld shape of 304 stainless steel [169]

In recent years, in order to produce deeper penetration, hybrid YAG laser and double flux TIG welding with $Ar+H_2$ center gas and Ar environmental shielding gas has been developed. YAG–TIG hybrid welding using double flux TIG arc has been applied to the cover plate welding for a superconductive coil of stainless steel [170, 171].

Owing to their chemical composition and their favorable microstructure of about 50% ferrite and about 50% austenite, the duplex stainless steels offer highly economical combinations of strength and corrosion resistance. These advantages make it suitable to build chemical and oil tanker vessels in shipbuilding industry and bridges [172-175].

As mentioned previously, in CO_2 laser–hybrid welding, the composition of the shielding gas should be considered because of the strong plasma-defocusing effect. Generally, helium must be used in CO_2 laser–hybrid welding in order to obtain the deep penetration weld mode due to its high ionization energy. As illustrated in Figure 52, under similar conditions , the penetration depth of the hybrid CO_2 laser–TIG weld with low helium content in the shielding gas was shallow, due to heat conduction welding. Nevertheless the weld penetration depths increase with the increasing helium content in the He–Ar mixed shielding gas. It is important to realize that, when the helium content is greater than 50%, the 3 mm stainless steel plate is fully penetrated and the hybrid welding mode clearly presents deep penetration welding [176-178].

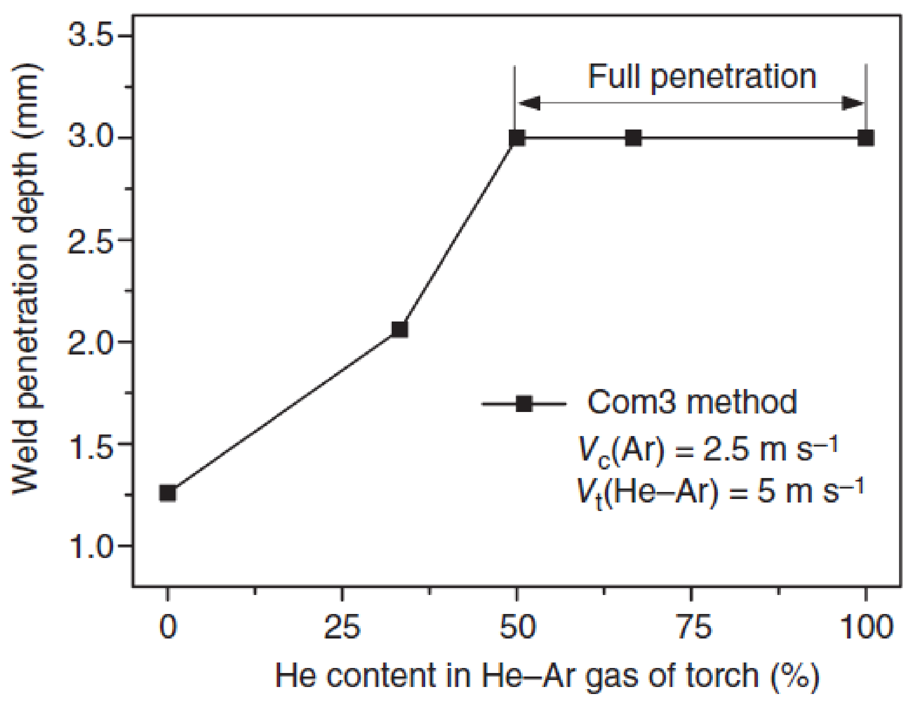


Figure 52. Effects of helium content in He–Ar shielding gas on penetration depth of CO_2 laser–TIG hybrid weld, the substrate is 316L stainless steel plate with 3 mm thickness [167]

6 WORKPIECE PARAMETERS

As discussed in the previous chapter about process variables, the workpiece parameters also play an important role in achieving quality welds in hybrid laser-TIG welding process. This chapter will discuss the effect of material parameters and design parameters. The following will be introduced; properties of material surface quality, gap geometry, and preparation of joint. Figure 53 illustrates workpiece parameters in laser –TIG hybrid welding.

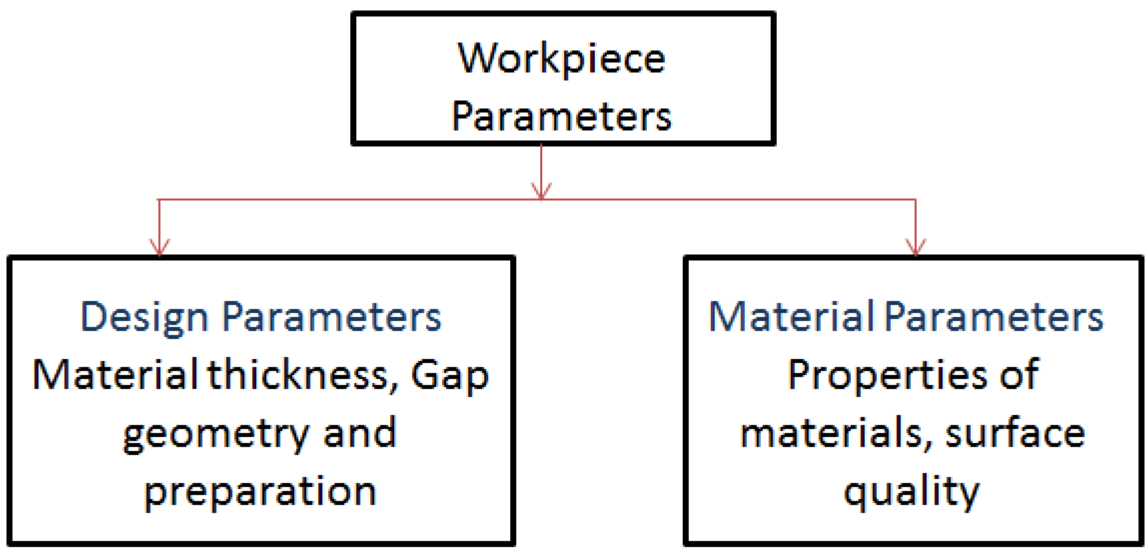


Figure 53. Illustrating workpiece parameters in laser-TIG welding

6.1 Material thickness and gap preparaton

It is important to consider the thickness of the workpiece. The thicker the material to be welded, the higher the beam intensity needed. In order to achieve deep penetration, the welding speed should be slowed as the thickness increases so has to increase the heat input. From the view of productivity, this is not good because the production rate becomes low. In laser-TIG hybrid welding, the use of filler material is optional as stated in previous chapter; hence during laser-TIG hybrid welding of butt joint configuration a square groove edge and zero air gap between the joint faces is preferred. However it must be noted that, if the air gap exceeds 3 % of the material thickness of the thinner joint member, there is a possibility of underfill resulting from welds. In addition, parts must be arranged properly in order to have a good fit so as to get the right air gap. The formation of keyhole is not possible without a special technique when the air gap is kept wider than the focused laser beam. This is because the laser beam passes the joint without touching the groove faces. Nevertheless, in order to prevent this from happening it is important to widen the weld by defocusing the beam or splitting the beam transverse to the welding direction in order to melt the groove and to aid in keyhole formation. Since the TIG arc melts the groove faces during laser-TIG hybrid welding there is an increase in the air gap [165, 166]. Although it has been reported that the addition of filler metal improves gap bridge ability it does not guarantee a successful process. However, the necessary procedures must be followed to control the allowable air gap such as increasing surface tension by root protection with inert gas, proper parameter configuration, avoiding gravitational effects and reducing melt velocity by ensuring a stable process with low dynamics [179].

6.1.1 Workpiece properties

This is an important factor to be checked before welding, some metals decrease in strength when heated above certain temperatures. Example Tempered aluminum alloys are dramatically softened due to the dissolution of strengthen precipitates magnesium silicate (Mg_2Si). To maintain the mechanical properties while welding, the heat input and the time of exposure to very high temperatures must be minimized. When compared to arc welding processes, laser welding offers the benefits of low-heat input and extremely rapid cooling rate. This minimizes the metallurgical problems in the fusion zone. For steel it is important that the oxygen content is of low content in order to achieve good welds as well as minimal nonmetallic inclusions. It has been reported that best welding occurs in low carbon steels of less than 0.2% of carbon. Welds in these materials are usually uniform and contain less porosity. Generally, the ratio of Manganese to Sulfur should be maintained below 40 to 1 for acceptable weldability [165]. Carbon euivalent (CE) can be a used in determing the weldability of steel. This is defined as:

$$CE = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15 \qquad \text{(Equation 1)}$$

Each element symbol refer to nominal steel composition in Wt %. Steel with a CE value less than 0.4 are considered to be weldable, nevertheless above this value pre/postweld treatment should be applied as well as slower welding speed [164].

6.1.2 Surface preparation

The surface condition of the materials to be welded may influence the energy absorption of incident laser beams as well as the threshold power density for keyhole welding. Also the surface quality of the workpiece as an influence on the welding process and weld quality. During welding without filler material, it is recommended that, the maximum surface roughness of the joint faces should be around 5% of the thickness of the thinner joint member. It is important that this is considered during the selection of the groove preparation method. Also, thermal cutting methods such as laser or plasma when used for cutting during surface preparation, heat- affected zone must be so narrow so as to enable to proper fusion during welding [165]. Additionally, it is recommended that before welding all surfaces and edges of the workpieces as well as welding wires are cleaned to remove oxide and hydride layers, grease or realeasing agents, surface coating as well as any dirt picked during assembly and fixturing. In the welding of magnesuim and aluminium, methods such mechanical cleaning with aluminium oxide abrasive cloth, stainless steel brushes, aluminium or stell wool, chemical degreasing alloy using alkaline cleaners, picling using chromic acid [159, 160]. Generally, materials that have vaporization temperatures below the melting point of the material being welded will vaporized by high-intensity laser beam. This can lead to the formation of high density plasma above the workpiece surface, which can lead to poor welds [165]. Proper surface preparation aids in preventing lack of penetration, subtantial spatters, under filled surface, porosity, solidificaton cracking etc.

7 INDUSTRIAL APPLICATIONS

The industrial application of laser hybrid welding usually depends on the arc process used. In hybrid laser-TIG, as stated previously, the TIG arc can be operated with or without filler metal. Hence the combination of TIG arc with lasers such as CO_2, Nd:YAG and Fiber laser usually find its use in thin sheet applications. However, in recent years there has been various research carried out in applying hybrid laser-TIG in welding of thick materials. Zhank Shenghai et al. carried out an experiment using laser-TIG hybrid in the welding of high strength low alloy structural steel of 16 mm thick 10CrNiMnMoV. This type of steel is widely used in the nuclear power, electric power equipment and the ship industry. 10CrNiMnMoV has high hardness and high tendency of hardenability in heat affected zone of weld joint, where some big coarsing martensite will generate easily after welding because of too many alloy elements and high carbon equivalent. Also, the ductility and the toughness of the joint will decrease significantly [180]. Y- groove was used in the experiment. After carrying out the experiment the following conclusions were drawn;

The joint had good transitional properties in microstructure and crystal grain size, also more excellent mechanical performance was achieved which is higher than the Marine standards CCS requirements to meet industry needs fully.

Also, the results showed how laser-TIG hybrid welding uses laser energy more efficiently. Additionally, there was an improvement in the energy coupling between laser, plasma as well as the molten pool. The requests for laser power can be reduced during welding of thick metal plates, therefore significantly optimize the energy input and aspect ratio of the weld seam and enhancing the welding speed. This benefit is very beneficial in the reduction of pores emitting in the molten pool due to its possibility of reducing their formation.

Lastly, the assembling clearance and misalignment adaptability of weldment had a big improvement when laser-TIG hybrid was used to weld thick plates.

From the results obtained, it can be said that, laser-TIG hybrid is gradually finding itself into welding of thicker materials and hence its application in the nuclear power, electric power equipment, ships is increasing. As stated previously the automobile industry is one industrial which in recent years necessitating the importance in weight reduction. Hence the use of lighter materials plays an important role in the automobile industry. Laser-TIG hybrid welding has good possibility of welding these lighter materials such as aluminium and magnesium. For example parts like engine hood, trunk rid cover, body panels and suspension components are all manufactured with aluminum as means of reducing weight [181]. The possibility to also couple the TIG arc to new lasers makes it more versatile in its application in areas such as vessel fabrication, pipe welding and the aerospace industries. In summary it can be said that laser-TIG hybrid has prospects in the following applications; road transport, shipbuilding, rail transport and oil and gas. In recent years a lot of research institutes are helping in the development and implementation of this process, e.g. Lappeenranta University of Technology in Finland, The Welding Institute (TWI) in England, The Welding and Joining Institute (ISF) of RWTH Aachen University in Germany, Osaka University in Japan, etc.

8 SUGGESTION FOR FURTHER STUDIES

Recent studies on laser-TIG hybrid welding technologies have mainly concentrated on two aspects. One is the interactions between electric arc and laser, and the other is the influence on the laser welding parameters caused by the property of electric arc. Both studies explore how the bonding technology affects the welding process as well as the forming of the welding seam [182-185]. Presently the most proven laser systems for hybrid laser-TIG technology are CO_2 and Nd:YAG lasers. On the other hand, with recent development and commercially available Fibre and disc laser systems, they should be considered as an attractive alternative to the conventional laser beam sources due to their unique properties (high output, excellent beam quality and short wavelength). It is anticipated that by the use of these new laser sources, further improvement and development of laser-TIG hybrid can be supported. Initial investigation that made use of fiber laser as the primary heat source in hybrid laser-arc welding confirmed the assumptions [46, 186].

Another interesting trend is the possibility to investigate laser-TIG hybrid with different shielding gas mixtures (i.e. mixtures with active gas content). Additionally, studies of gas nozzle arrangements, which are important for the design of the hybrid welding head, are also scarce and therefore further investigation is needed. Also, the laser-TIG hybrid welding experiment with pulsed TIG arc would be of great interest. Examination of the laser-TIG hybrid welds defects using different technologies such as ultrasonic test is also of major importance. Experiment on the use of TIPTIG and TOPTIG on the welding of different metals to give more clarity on their cost effectiveness. Further experiment on the use of the double shielded TIG welding process is needed. Investigation into robotized laser-TIG hybrid is would be of great interest as well.

Lastly, investigation into the use of low-power laser beams for guidance and stabilization of electric arc welding processes would be of great importance in hybrid laser-TIG technology.

9 CONCLUSION AND SUMMARY

This paper presented the reasons why laser-TIG hybrid welding has good prospects in becoming the most versatile welding process in the welding industry. The aim was to assess various studies and experiments carried out using laser-TIG hybrid welding as well as ascertain its pros and cons, elaborate on various possible combinations on laser-TIG hybrid welding and benefits in welding various metals. Lastly, investigate the possibilities of using hybrid laser-TIG in welding of thick metals in the near future. The research has shown that, hybrid laser-TIG welding has great potential in the welding of various metals (stainless steel, ultra fine-grained steel, aluminum, magnesium, galvanized steel sheets etc.). Undercut was the most common weld defect identified during welding with hybrid laser-TIG. This occurs due to the direction of the arc which is usually deflected aside. However, this can easily be eliminated by choosing correct welding parameters. The major defect reported by most authors in laser hybrid-TIG welding process is the incomplete filled groove which occurs with the leading arc configuration at arc current exceeding 300 A.

One important finding was the possibility of welding with filler wire or without filler wire. This gives an advantage in terms of cost reduction especially when the metal to be welded thus not need the addition of filler metal. The second major finding is the capability of laser-TIG hybrid welding to join reactive materials such as aluminum and magnesium. Gang Song et al. who carried out an investigation on the weldability of wrought (AZ31, AZ61) and cast magnesium-based alloys (AZ91) attest to the fact that based on the results obtained laser-TIG hybrid welding is an excellent welding process in welding of magnesium. Thirdly, the findings indicated that in order to obtain good efficiency and capabilities of laser-TIG hybrid welding, it is important that geometrical arrangements of the laser and arc are critically look into. In relation to the geometrical arrangement most discussions from different literature described the use of leading arc configuration as the best in laser –TIG hybrid welding especially when increasing penetration is needed. Lastly, when increased fusion zone in relation to width is needed a trailing arc configuration should be chosen. Various experiments analyzed also showed that smaller process separations would make it possible to increase the penetration. In addition, using smaller electrode tip angle there is a possibility of achieving accurate positioning of the arc. Laser –TIG hybrid welding is also noted to have increase melting efficiency as compared to single welding process. It is not possible to give a general recommendation for optimal basic setup since there are so many specific factors that must be taken into account. Nevertheless, the most proven arrangements combine the laser beam and electric arc within a common process zone which leads to a single process plasma and common pool.

In relation to possible combination with laser-TIG hybrid welding, the study found out that, with newly developed TIG process such as TIPTIG and TOPTIG there is a possibility of achieving quality welds, welding speed equivalent to MIG/MAG and pulsed MIG. Also since materials welded with these newly developed processes are capable of obtaining low distortion and low rework, it is economically advantageous in terms of cost. In addition, the TOPTIG gives very good possibility in terms of robotic application. One significant finding of the TOPTIG is that the filler wire is fed into the weld pool in front of the torch that ensures continuous liquid flow. Secondly, combining the TIG arc with other available high- power laser types, which offer an advantage of shorter wavelength, gives more flexibility in the use of shielding gas, hence this combination provides good possibility in the prevention of plasma shielding effect that occurs in the use of CO_2 laser. However there is still limited research on the use of these new lasers.

Finally, the finding on the possibilities of using laser-TIG hybrid welding on the welding of thick plate suggest that, laser-TIG hybrid makes use of laser energy more efficiently, improves the energy coupling between plasma and molten pool. In addition it can reduce the request for laser power, enhance welding speed and optimize the energy input as well as the aspect ratio of the weld seam when use in the welding of 16 mm high strength lower alloy structural steel like 10CrNiMnMoV. The findings mentioned imply that there is decrease tendency in the formation of pores. Also laser –TIG hybrid has proved to be able to weld ≥10 mm stainless steel with good quality.

From the findings and critical analyses of the various research papers the following conclusion were derived about laser –TIG hybrid:

1. The combination of laser and TIG will be very effective in the welding of high heat conductive materials.
2. In laser-TIG hybrid welding, the direction of the arc configuration (leading or trailing) is an important factor to consider in order achieving highly improve performance.
3. There is also an increase in the melting efficiency of up to 10% compared to the two processes alone.
4. In laser-TIG hybrid welding problems such as cracking, brittle phase formation and porosity can easily be overcome by choosing right parameters. Also due to increase in heat input and modified dendrite orientation in the solidifying weld.
5. Laser-TIG hybrid welding is a promising technology, especially in applications where filler material addition is not allowed.
6. Laser-TIG hybrid welding adds additional energy to the welding process.
7. In laser-TIG hybrid welding using of helium and argon has shielding gas will help improve penetration especially in the welding of nonferrous metals.
8. In laser–TIG hybrid welding, because of pre- heating the magnesium alloy by TIG arc not only is the interaction between laser and the plate changed but also the laser attracts arc.
9. In Laser hybrid –TIG welding penetration is double that of TIG, four times that of laser beam welding.
10. The size of grains produce in welding of Magnesium alloys is intermediate as compared to TIG.
11. Laser-TIG hybrid welding saves energy and the generation of spatters accompanied by laser-induced plume is suppressed owing to the formation of wider molten pool enough to accommodate keyhole expansion.

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