Review Article

Developments and Improvements Using Hot Wire Gas Tungsten Arc Welding – A Review

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Abstract
Gas tungsten arc welding (GTAW) is a high quality welding process widely used in most industries. However, the process is limited to higher welding speed and higher deposition rate. To overcome this limitation, the GTAW process is modified in such a way that filler metal is heated prior to entering into the weld pool. This heating is carried out by resistance heating. Hot wire GTAW (HW-GTAW) ensures the availability of arc energy to melt the base metal. This results in an increase in deposition rate and additionally, increases the welding speeds to a large extent. Welding is an important form of joining materials and is most significant for the application of structural components. This paper reviews the application of the hot wire technique during conventional GTA welding, thereby providing the benefits in terms of metallurgical control, energy efficiency and rate of deposition. This process has the potential to achieve high efficiency and welding faster with lower heat input. The HW-GTAW process is widely used in welding various novel materials and it is a promising alternative to the conventional GTAW process with lower heat input and narrower heat affected zones. This process not only eliminates the various defects in the weld joints but also increases productivity in industries.

Keywords: Deposition rate, Heat input, HW-GTAW, Magnetic arc-blow, Resistance heating

1 Introduction

Gas tungsten arc welding (GTAW) is known as the tungsten inert gas (TIG) welding process, in which heat is produced by an arc between a non-consumable tungsten electrode and the base metal. Generally, the direct current electrode negative (DCEN) mode is used for the welding process [1]. GTAW process is a relatively cleaner process, which produces smooth and uniform weld beads and needs the least finishing process. The filler wire is melted in arc instead of direct transferring [2]. This process is environmentally friendly by consuming less energy compared to other arc welding processes. The quality of weld and precision achieved by this technique is very high [3]. Even though the later developed processes like plasma arc, electron beam and other gas metal arc applications are evolved, this process is widely in use due to its excellent weld quality. A major drawback of this process is limited filler metal deposition due to low welding speeds. If the deposition rates are increased by using mechanized GTAW, it will be more beneficial to the industries [4]. The performance of the GTAW process can be increased by using the developments such as activated TIG (A-TIG), twin tungsten inert gas welding (T-TIG), super TIG, hot wire TIG etc. [5], [6]. One of the problem with conventional GTAW is lower welding speed and higher heat input into the work piece, which may alter the precipitation of alloying elements and change the physical properties of the base metal obtained prior to heat treatment. This change may affect the mechanical properties of weld and heat affected zone. Therefore, the welds made with relatively higher welding speeds are less affected by welding and are desirable for welding heat treatable materials. The hot wire (HW) GTAW is one of the processes, which provides TIG quality with high deposition rates [7].

The HW-GTAW process is a variant of the cold wire (CW) process. In this process, the filler metal is preheated nearly to its melting temperature at the point of contact with the weld pool. As the filler wire is in a heated condition, the arc energy available to melt the base metal is more compared to the conventional GTAW or cold wire GTAW (CW-GTAW). This increases the deposition rate leading to higher welding speeds. HW-GTAW was invented by Manz and then further developed by the Linde Division of Union Carbide [8]. Later plasma arc welding, submerged arc welding and other several versions were developed using hot wire technique and most recently combination with lasers is also attempted [9], [10].

To improve the performance of GTAW, many authors implemented the A-TIG process. Vora *et al.* used the A-TIG process to enhance the penetration of 6 mm thick carbon steel plates in a single pass by using the TiO_2 flux [11]. The study reveals that the depth to width ratios of weldments was enhanced from 0.4 mm to 1.65 mm against the 0.4 to 0.5 mm in conventional GTAW welding. Whereas penetration depth has increased from 1.5 to 4 factors by using A-TIG as revealed by Berthier *et al.* [6]. Vidyarthy *et al.* compared the P91(9Cr-1Mo) steel weldments by welding A-TIG and conventional GTAW process [12]. Joint penetration was significantly increased, upto 200% and 300% by using CeO_2 and MoO_3 based fluxes, respectively. Tensile properties of the weldments obtained by using A-TIG were better than the base metal. Lower tensile properties than base metal were seen by Vidyarthy *et al.*, during their study in 8 mm thick single pass P91+316L dissimilar welding [13]. This could be due to higher heat input in the weldment in presence of activated fluxes. Lower welding speed is one of the primary reasons for high heat input. HW-GTAW, which operates at a relatively higher speed, is the best suitable technique to reduce the heat input by increasing the productivity.

In HW-GTAW, the necessary deposition rate can be met by selecting the proper welding current, wire current and wire feed speed. Deposition rates up to 300% can be achieved compared to CW-GTAW and are equal to Metal Inert Gas (MIG) process [14], [15]. Figure 1 shows the variation of deposition rates with respect to arc energy for the GTAW process with normal wire, only HW and HW with oscillation. It is observed that the deposition rate is linearly varying with arc energy. Arc energy is the product of voltage and current. In HW-GTAW, the arc energy contributes to increasing the rate of deposition compared to the cold wire process. For example, at 6000 W of arc energy, the maximum deposition rate for the cold wire technique is about 2 kg/h, and for hot wire, it is around 6 kg/h. If the mechanical oscillation technique is adopted, then the deposition rate can reach up to 8 kg/h. The improvement in the welding speed has a large influence on the production rate [4]. CW-GTAW is inefficient considering total energy input to metal deposition ratio, compared to processes e.g. GMAW or SAW. It is possible to deposit filler metal at 3 to 5 times more in the HW-GTAW process than CW-GTAW [2]. A deposition rate of 8 kg/h is achievable under the right circumstances. When the wire is introduced in a heated condition, maximum arc energy is utilized in generating the weld pool and penetration, and hence 2–3 times faster travel speed can be achieved. Preheating of filler increases the welding speed, but increased welding speed reduces the weld bead width, which can be compensated by adding more hot wire deposit to get enlarged bead width. There should be an optimum

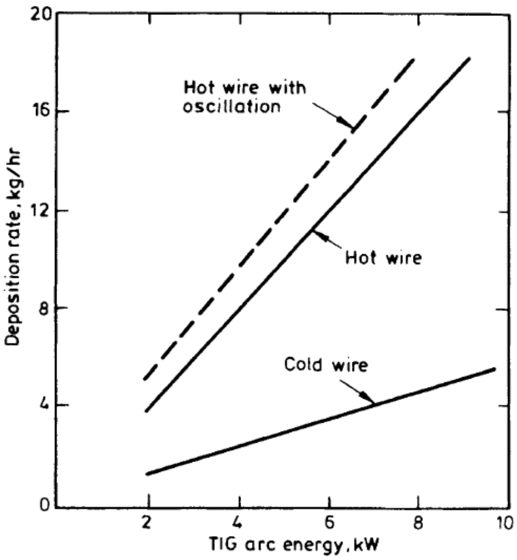

Figure 1: Comparison of deposition rates in steel for GTAW welding with cold and Hot wire [4].

relationship between welding current and wire melting rate for high speed welding. This is always independent of the plate thickness [16].

One of the major significance of the HW-GTAW process is the complete removal of porosities from the weld deposit. Due to resistance (I^2R) heating of the filler wire as it reaches the weld pool, it removes most of the volatile impurities from filler metal. The efficiency of HW-GTAW is higher than the CW-GTAW with improved weld bead appearance [4], [17], [18].

Das *et al.*, studied the welding of 2.25Cr-1Mo steel by a combined process of regulated metal deposition (RMD) and GMAW by using metal cored wires [19], [20]. This technique is used for welding medium to large thickness Cr-Mo steels to get specified mechanical and metallurgical properties. To increase the deposition rate they used metal cored wires instead of flux cored wires. They adopted step cooling heat treatment to ascertain the weld temper- embrittlement susceptibility. However, the productivity of Cr-Mo steel welding can be increased by using the HW-GTAW process as investigated [21], [22]. The HW-GTAW experiments were carried out on 30 mm thick 9Cr-1Mo steel indicating that even though the impact strength of weldments is inferior to those of welded with CW-GTAW, high deposition, very good weld profile, reduced dilution and porosities are the key benefits [21], [22]. The melting rate of filler wire is increased by resistance heating to more than 200 °C and deposition rates are enhanced.

Santangelo *et al.* conducted the experiments to deposit metallic alloy by robotic automated welding using hot wire technique. To increase the rate of droplet detachment and deposition rate, low frequency vibrating filler wire was adopted. Different experiments were carried out at constant heat input, welding speed and wire feed to get the required weld pool shape. No major changes in weld bead geometry and arc shape were observed by adopting vibration to hot wire except for a slight narrowing of the arc [21], [23], [24].

Magnetic arc blow is one of the known phenomenon in HW-GTAW. To overcome this event, Hori *et al.* devised a system with high frequency pulsed current for heating the filler wire [10]. Ugeri *et al.* studied the relation between melting rate and arc current during welding with magnetic arc blow [16]. The increase in weld pool width was observed with an increase in arc current along with hot wire current. Another method to overcome the magnetic arc blow is heating the wire by conduction instead of resistance heating as investigated by Cao *et al.*, [25]. Ungethum *et al.*, proposed an alternate heating method of wire by using an additional preheating unit between two points on the filler wire [26]. Continuous heating of filler wire to higher current is possible without deflection of arc.

1.1 *Modes of heating*

The heating of the filler metal is done mainly by 3 methods viz. 1) Resistance heating, 2) Arc heating, 3) Induction heating [25], [27]. Out of these, resistance heating is more widely used. The heating equipment is very simple, economic and easily attachable. The heating of wire takes place as per the Joule effect. When current is passed through a wire connected to an auxiliary power source, electrical energy is converted into heat energy and the heating effect is produced. This heat energy is given by $H = I^2R$, where I, the current passing through the wire and R, the resistance of the material, $R = \rho L/A$; where ρ, the resistivity of the material, L, length of wire and A, cross section area of the wire. However, one of the major demerits of this type of heating is a deflection of arc caused by a distortion of a magnetic field produced by electric current. This leads to loss of arc stability [14], [15], [27]. To overcome this problem, the AC technique can be used to heat the filler wire. The polarity alteration between positive and negative terminal at a certain frequency by using AC current minimizes the magnetic blow significantly. The pulsing of the main current and heating current in out-of-synchronization is another method that reduces the magnetic arc blow. Many studies also adopted electromagnetic induction technique to avoid magnetic arc blow problems [15], [28]. It is also seen that other applications, such as GTAW with tangential wire feeding, GTAW with dynamic feeding, hot wire techniques using laser and GMAW process are also envisaged [29]. Limited literatures are available in which the wire heating is done by conduction or induction method. In conduction heating, the wire is heated indirectly, hence the maximum temperature is attained around 225 °C [25]. It was also noticed that as the wire feed rate increases, the wire temperature decreases, which makes welding operations at higher currents. Electromagnetic induction technique is a transformer that the primary coil is an induction coil and the secondary coil is a work piece, electric current induced in work is eddy current [28]. However, this eddy current will be maximized on the surface and decreased towards the interior of the work. As the coils are positioned close to the arc, the construction becomes very complex and expensive. That is why resistance heating has become more popular in practical due to its simplicity and easy setting.

1.2 *Applications*

Hot wire GTAW can be used almost for all the welding applications where ever conventional cold GTAW process is used with additional benefits like higher speed, high deposition and enhanced productivity. This process has been used successfully for welding a variety of steels, stainless steel, copper alloys and titanium [2]. HW-GTAW process is having a potential application in the welding of a newer variety of materials, such as enhanced creep strength ferritic steels, high strength Ni-based alloys, high temperature property material, 9Cr-1Mo alloy including a range of dissimilar weld joints. 9Cr-1Mo material, used in the construction of steam generators for fast breeder nuclear reactors [21], [30]. Another area in which this process is widely used is cladding operation. This process is mainly used for additive manufacturing of materials, such as alloyed steels and titanium and nickel-based alloys which are highly reactive. Welding of pipe for high temperature and high pressure service is one of the major applications of HW-GTAW. This technique will produce excellent and controlled penetration for root passes in the pipe using Single-V groove joint preparation. The process makes it attractive for welding relatively thin materials where weld joints must be free from all defects due to its porosity free characteristic [4]. Therefore, the HW-GTAW process is suitable for welds that have specific quality requirements, such as fabrication of pressure vessels, heat exchangers, marine vehicles, nuclear, aerospace and ship building applications [25]. Another important application is in the fabrication of rocket motor casings from high strength maraging steels. The materials with a low resistance to electrical heating current like aluminium, and copper alloys are not acceptable for the HW-GTAW process. HW process is the best choice for cladding and additive manufacturing in addition to metal joining.

In the present competitive scenario, industries are forced to acquire newer techniques that provide higher productivity without losing quality. Conventional GTAW provides sound welds but lack of productivity makes its usage highly uneconomical, especially, while welding components of large thickness. Lower welding speed and lower deposition rates are the major problems of the GTAW process. To increase the performance of GTAW, hot wire technique can be adopted to tap its multiple advantages. The HW-GTAW system makes very efficient use of welding heat input and welds can be produced at speeds and deposition rates equal or more than GMAW at a lower level of heat input. The purpose of this review study is to understand the various HW techniques, which are under utilized in industry. This is because HW technique can be used only in automated or mechanized conditions in which control of parameters, such as HW current, wire feed rate, welding current can be done. HW-GTAW is progressively eliminating the conventional GTAW in one or the other applications in the industry. From the literature survey, it is observed that various researchers are worked on the hot wire technique on different materials. Also, the knowledge of HW-GTAW is limited with respect to its application in the industries.

1.3 *Novelty*

It is revealed from the literature survey that heating of the filler wire during welding has been carried out very rarely. The HW-GTAW process is not fully exploited in the industries to get its benefits where high quality and productivity is required. The objective of this review study is to reveal the application of hot wire technique during conventional GTAW to improve the productivity. To utilize the potential benefits of hot wire process to achieve high efficiency and welding faster with lower heat input while joining various novel materials.

2 Welding Technique and Equipment

The HW-GTAW uses two power supplies. The Tungsten electrode is energized by the first power supply to produce a welding arc and other power supplies to heat the filler wire. The second power source does not produce an arc, it is used for electrical resistance heating of the wire, which is fed into the weld pool through a contact tube. This power source may be AC or DC [31]. Single power sources for both arcing and

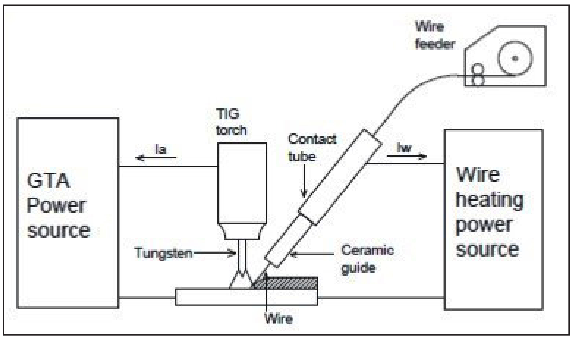

Figure 2: Schematic diagram of HW-GTA.

wire heating are also commercially available. Typical HW- GTAW system is illustrated in Figure 2. Hot wire unit mainly consists of a power supply for wire heating, a wire feeder, a contact tube and a ceramic guide. The heating tube is mounted near the welding torch, and filler metal is passed through its internal diameter. The heating of wire takes place between the contact tube and the weld pool and is put into the arc by a wire feeder. The hot filler metal is melted in the welding arc. The melting of wire is directly proportional to arc heating & wire preheating. Once the gas tungsten arc is formed, the wire is fed into the weld pool. This closes the hot wire loop and the current starts flowing through the wire. This produces the resistance heat in the wire. A separate gas shield is not required for the filler wire as the wire extension is inside the shield gas cup of the torch. Generally, the wire is fed into the pool at the rear of the arc at an angle with respect to the tungsten electrode [2]. The heat produced by resistance heating depends on the resistance of the wire extension and its electrical resistivity. The diameter of the wire and length of extension determines the resistance and in turn the resistance heat. This heat is used to raise the temperature of filler metal near its melting point, which results in an increased deposition rate. If the hot wire contact tube is energized, then it creates a separate arc. This arc will create a spatter near the tungsten electrode and contaminate the electrode. Hence, the hot-wire power source is kept separately to prevent the formation of this additional arc. If the system is working much below the minimum voltage required for the formation of the process arc, then no longer arcing between the filler metal and tungsten occurs. Due to this reason hot-wire power source in HW-GTAW operates below the open circuit voltage [32].

3 HW-GTAW Process Parameters

The quality of weld obtained by HW-GTAW is governed by welding parameters, mainly welding current, hot wire current and wire feed rate. Each welding parameter should be properly selected for a given base material and filler metal to obtain a good quality of weld [33]. The deposition rate in the HW system mainly depends on the wire feed rate and the total heat input, which is the sum of main arc energy and auxiliary energy. In combination with GTAW arc, deposition rate and energy input can be varied over a wide range. This added auxiliary heat due to wire heating is one of the main characteristics of HW-GTAW.

The wire dimensions and wire material plays an important role in producing auxiliary heat in HW-GTAW. If the resistivity of the wire is higher, then the current required will be less to get the same heat. The wire diameter directly influences the I^2R heating. A larger wire diameter reduces the resistance of the wire subjected to heating since resistance is inversely proportional to the square of the diameter. Hence, it is essential to increase the stick-out distance of the wire to maintain the heating current. This would also necessitate a reduction in the wire feed rate to maintain the deposition rate. As a thumb rule, the diameter of the filler wire should not be more than one half of the desirable deposited thickness. Stick-out length of filler wire can be considered as one of the controlling parameters. For a given constant wire diameter and material, the change in stick-out length causes a change in resistance of the wire. It is more convenient to change the HW current instead of stick-out length as heat produced varies with the square of the current. Generally, stick-out length varies between 12 mm to 50 mm. The higher stick out will provide higher resistance and minimizes current, thus arc interference is minimized. Whereas, lower stick-out needs higher current for melting thus higher voltage. The typical parameters used in HW-GTAW are shown in Figure 3 [34]. Generally, hot wire torch angle is kept between 0° to 60° from the axis of the tungsten electrode whereas few authors carried out the experiments keeping this angle between 40° to 60° [7], [34]. The wire should enter the weld pool approximately 3–9 mm behind the tungsten depending on the size of the weld pool, which ultimately depends on the current and voltage being used.

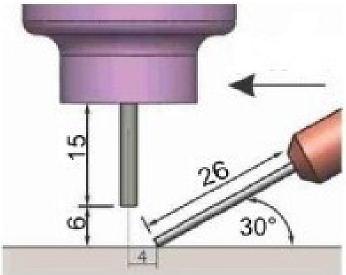

Figure 3: Typical Parameters used in the HWT process [34].

In GTAW, welding current is the most dominant variable in the arc welding process, which controls the extent of fusion, electrode burn off rate and geometry of weldment. The degree of weld penetration is greatly affected by the welding current. As the welding current increases, penetration increases. Welding voltage controls the shape of the fusion zone and reinforcement. Higher the welding voltage, the wider and flatter the weld beads compared to the lower welding voltage. Higher welding voltages produce less deep penetration. There should be an optimum arc voltage to obtain the maximum depth of penetration [35]. Generally, an increase in welding speed reduces the penetration. At constant current and voltage, increasing the welding speed will reduce the bead width and increases the penetration until an optimum speed is reached at which penetration will be maximum [36]. Further increasing speed beyond this optimum will result in decreasing penetration. Welding speed directly affects the heat input in the weld metal. In the arc welding process, an increase in welding speed causes a decrease in heat input/unit length, a decrease in electrode/filler burn off rate and a decrease in the weld reinforcement [37].

In HW-GTAW, as the wire feed rate increases, it is necessary to increase the welding current to melt the increased filler wire, otherwise the welding arc will not be stable. Padmanabhan *et al.*, studied the welding of high temperature super 304H austenitic stainless steel material by HW-GTAW. Their study indicates that for a stable arc at a higher wire feed rate of around 2000 mm/min, a minimum 150 A welding current is irrespective of hot wire current [38]. The weight of weld deposition also enhances with the increase in welding current. On contrary at a constant welding current, an increase in hot wire current and wire feed rate increases the weight of weld deposition and area of fusion. An increase in hot wire current and wire feed rates beyond 800 mm/min may create arc deflection due to the appearance of the magnetic field surrounding the welding arc. At constant hot wire current and wire feed rate, with an increase in welding current, weld pool shape and size changes remarkably along with wider HAZ. The increase in weld bead width is seen no matter whether the wire feed rate is slow or high. A similar effect is observed when the wire feed rate is increased at a constant welding current. This implies that bead width is a function of welding current, hot wire current and wire feed rate. This is mainly due to heat input changes in the weld pool through arc and resistance heating. Elevation in hot wire current enhances the resistance to heating of filler metal, which makes the lateral displacement of liquid in weld pool resulting in higher weld bead and weld deposition [2]. At a given hot wire current and wire feed rate, an increase in welding current exhibits an irregular pattern in the depth of penetration. Similar results are noted by Agarwal *et al.*, [39]. Depth of penetration is mainly influenced by arc current and very little to heat of filler wire as informed by Radaij [40]. Pai *et al.*, successfully welded the 9Cr-1Mo steel for the application of a steam generator for a fast breeder reactor. HW current of 35A and typical wire feed speed of 900 mm/min have been used to qualify the weld joints in bend and toughness tests [41]. Dinesh *et al.*, evaluated the effect of HW-GTAW parameters, such as welding current and hot wire current during the welding of bead on trials of alloy 617 [2]. The effects of these parameters on cooling rate, heat input and weld bead characteristics were studied. They carried out the experiments with varying HW currents at 30, 40, and 50 A and at a constant welding current of 200 A. Their study reveals that as the HW current increases, it increases the deposition rate significantly. This will result in a flow of liquid sideways into the groove and increases the bead width. Another study carried out by Selvan *et al.*, shows that increasing the HW current beyond a certain limit, could not get the penetration, even though the heat input is maximum [42]. This may be due to heat transfer in a transverse direction of the weld joint across the thickness, thereby increasing the bead width. The effect of welding parameters on the grain size shows that as welding current along with HW current increases, there will be growth in the grain size, that is fine grains of the weld beads becoming coarser. This is because of experiencing the recrystallization temperature by the welds due to increased heat input. Cooling rates are controlled by the heat input. Faster cooling rates will lead to a finer microstructure with increased hardness and strength. A decreasing trend in cooling rate is observed with an increase in welding current. The more the current, the higher the heat input resulting in slower cooling rates. Higher heat input resulted in grain coarsening of the weld zone and reduced ductility and toughness. By controlling the heat input by HW-GTAW, desired ductility and toughness can be achieved [20], [43]. Similar observations are seen during the welding of SA516-G70 plates using HW-GTAW and GMAW by Midawi *et al.* [44].

In the GTAW process, there is a major constraint to enhance the welding current beyond a certain limit. This is due to the limited current carrying ability of a single electrode and arc pressure in the weld pool. This limits the productivity of the process. Along with HW addition, the productivity can be further increased by using the twin tungsten (T-TIG) welding process [5]. One torch consists of two tungsten electrodes connected by different and synchronized power sources. A pulsed power source is used to reduce the heat input. In pulsed welding, total heat energy is smaller than the constant current process. Authors concluded that by combining these three techniques (T-TIG, HW & pulsed power), metal deposition rate can be increased with increased arc current and decreased arc pressure resulting in high speed of welding and better weld bead property.

Shah *et al.* described the influence of welding parameters of HW-GTAW on weld bead properties [5]. They mentioned that HW current, arc current and wire feed rate are having a strong influence on each other. Resistance heat depends directly on the dimension ‘L’ (stick-out length) and inversely on ‘d’ (diameter of wire). More the stick-out length, higher the heat input, but it shows more corrosion behavior due to increased temperature. Smaller diameter wire decreases the deposition rate. Hence, it is necessary to optimize the value of L and d accordingly to get lower heat input and higher deposition. Poolpern *et al.*, carried out the hot wire laser welding experiments. With a welding current of 120 A and HW current of 35 A, a satisfactory weld bead was obtained and achieved a bead width of 7 to 13 mm in a single run. Higher welding speeds of 110 mm/min were used [45].

4 HW-GTAW Applications

4.1 *Narrow gap welding*

The productivity of the HW-GTAW process is further enhanced by developing Narrow Gap HW-GTAW technology. The narrow gap welding process is specifically designed to reduce weld metal volume in butt joints. In conventional V groove joints, joint volume is more compared to square butt joints and takes more time to fill the joint. In square butt joints angle of preparation is reduced, weld metal volume and weld completion rate are decreased. If a narrow parallel-sided gap is used, the difference becomes significant, especially in thicker sections. In a narrow gap GTAW, better side wall fusion can be achieved by using a special torch, power source and controller [46]. Because of substantial joint depth, specially designed torches with precision control along with seam tracking and depth sensing systems are employed. The main attributes of a narrow gap torch are longer electrode stick-out, dual gas shielding at the front and rear of the electrode, additional gas shielding from the top of the joint and water cooling up to the tip of the electrode to minimize electrode erosion. A number of techniques, such as tilting, and twisting the tungsten electrode have been developed to ensure side wall fusion in the narrow gap. As the wire is heated close to its melting point, when it enters the arc, the fluidity of the molten pool increases, which makes molten metal flow and fills the groove very close to the side walls. The volume of the deposited weld metal and total heat input are lower than the CW-GTAW. This process gives high productivity and does not cause any fusion defects [47]. The process is mainly used for thick wall sections of pipes, turbine rotors, ship building parts, etc. This process is cost effective and enhances the corrosion resisting property of the weld joint [48]. Several investigators have confirmed that the mechanical properties of narrow gap joints are better than those achieved with traditional ‘V’-butt configurations [49]. This may be due to lower heat input and continuous refinement of the weld bead by succeeding weld passes. Included angles for the joints are smaller, varying from 2–20°, hence requiring minimal weld deposition resulting in reduced weld fill time. This reduces drastically welding man-hours and significant reduction in consumable costs. An added advantage is a reduction in residual stress & distortion, resulting in better and improved weld quality [27]. The joint preparation in a narrow gap is almost parallel, which leads to low angular distortion. However, the Chandan *et al.*, studied the mechanical properties of P91 steel with V groove and narrow groove pipe joints and noticed that welds with V groove are superior strength whereas ductility is higher for the narrow groove welds [50]. Taraphdar *et al.*, studied the effect of equal double V and unequal double V groove configuration on the residual stress distribution in thick high strength low alloy steels [51]. By implementing an unequal double V configuration, peak residual stresses can be reduced. These stresses can be further reduced by using hot wire narrow gap welding as the net heat input is very minimal. The narrow gap welding technique is also best suitable for cladding and buttering applications, in which faster welds can be produced on thicker sections. Along with other materials, reactive materials like titanium can also be welded by the narrow gap HW-GTAW process.

4.2 *TIP-TIG welding*

Recently, TIP-TIG technology has been used for welding equipment with hot wire [52]. A TIP-TIG is an innovative welding system in which wire is fed similar to the GTAW process, but it is different for the vibratory effect on the wire at the weld pool. Vibration is created by a customized wire feeder system to achieve linear to and fro motion of the wire. This to and fro motion of the filler wire creates an oscillation which is transferred to the weld. The stirring effect of the molten weld pool occurs resulting in the disruption of the surface tension of the liquid pool. This benefits the weld with increased fluidity, increasing travel speeds 4–6 folds. Consequently, reduced cycle time and reduced heat input lead to high deposition rates without compromising weld quality. Weld deposition rates up to 5 times can be achieved by using TIP-TIG system compared to CW-GTAW. When the cumulative heat input is lower, distortions are significantly reduced than manual GTAW [53]. Other investigators have carried out a similar study but with a reciprocating HW feeding system. Reciprocating HW agitates the molten metal of the weld pool effectively prior to solidifying. It was seen that hot wire reciprocating TIG welding has given the best results in terms of strength and hardness. Welds are showing finer microstructure compared to CW-GTAW joints, resulting in phenomenal improvement in the mechanical properties [54]. Silva *et al.*, used the wire forward and backward oscillation in the automatic feeding TIG process for achieving high productivity. The wire oscillation enables decoupling between power and feed rate, which improves TIG flexibility further [55]. Double sided synchronous TIP-TIG arc welding is carried out to weld 5 mm thick duplex stainless steel plates without grooving with a gap of 2 mm. A wire is preheated and oscillated [56]. Experiments show that it is possible to obtain sound welds with excellent appearance and properties using this process. Austenite fraction in the weld metal is 52%, slightly higher than the base metal (46%). Joints have higher tensile strength and micro hardness and lower elongation than the base metal.

4.3 *Welding of dissimilar metals*

HW technology can be successfully used for the welding of dissimilar metal joints. Pratap *et al.*, studied the dissimilar joints of SS304H and T91 alloy using the HW-GTAW process to assess the weldability and mechanical properties [31]. Weld edge preparation (V-configuration) of 9 mm thick base metals was done and welding was completed in 6 passes. Authors have carried out the microhardness, bend test and tensile test on these welds and they demonstrated the dissimilar defect free welds by using Inconel filler wire. The transverse tensile strength of the weld was closer to base metal T91 and qualified the welds for high efficiency boiler components. It is observed that the heat affected zones of the welds are thinner as compared to ordinary GTAW welding. This is due to lower net heat input by the HW technique. Similar findings are made by Amit Sharma *et al.*, and in their study, the effects of PWHT on microstructure and mechanical properties of HW GTA welded joints of SA213 T91 steel were studied [30]. Chandan *et al.*, studied the dissimilar weld joint of P92 and SS304 by CW-GTAW process and characterised the microstructure and mechanical properties [57]. Charpy toughness of welds show lower toughness than the required, this may be due to higher net heat input during the cold wire GTAW process compared to HW-GTAW. Kannan *et al.*, produced the dissimilar weld joints of T92 and S304 by using HW-GTAW process [58]. The effect of welding current and wire feed rate on the weld bead geometry was studied by using different filler wires. It was found that energy consumed to melt filler metal is the same for each filler wire because of constant feed rate. However, energy consumed to melt base metal is not same irrespective of filler wire addition, bead width and bead area are directly proportional to the welding current.

Aluminium and stainless steel joining is done by using the welding-brazing technique [59]. This type of joint will have dual characteristics of both welding and brazing. Filler metal is heated to a high temperature of about 400 °C. The heating of filler wire is done by high frequency induction heating device. As the filler wire temperature is higher, the welding currents up to 85 A are sufficient to get a good joint. Aluminium alloy is melted by an arc and it mixes with the liquid filler metal producing a joint. Stainless steel remains in solid state and joins with liquid filler metal forming an intermetallic compound (IMC). The thickness of the intermetallic compound should be thin and uniform to get the sound joint. A significant improvement in stability and an average value of mechanical properties of the TIG welding brazing joint was obtained with HW. In addition, they concluded that by employing HW with a small welding current had a strong influence on the microstructure of the interface. Along with reduced IMC thickness, it is observed that in-homogeneity of thickness along the interface is drastically reduced by using the HW technique.

Karthik *et al.*, compared the mechanical properties of super 304H tubes welded by manual and semiautomatic HW-GTAW processes [60]. Semi-automatic hot wire welded joint has higher yield strength, ultimate tensile strength, and % elongation than manual weld joint. This may be due to low heat input because of higher welding speed in the case of the semi-automatic welding process as compared to speeds of manual welding. They have carried out the microhardness survey of weld, fusion zone, HAZ, and parent metal. It was seen that the microhardness of semi-automatic hot wire welds is more than manual welds. Finer grains in the weld are the reason for higher hardness [25], [61].

4.4 *Cladding & additive manufacturing*

Additive manufacturing (also called 3D printing) technology is CAD/CAM based component modeling and depositing material layer by layer to produce 3-dimensional objects. This technology uses powder or wire as a filler material and is melted by laser, electron beam or arc processes [62]–[64]. Arc-based processes are mainly fit for manufacturing of relatively less complex and bigger parts. Beam-based processes are specifically suitable for complex and small size parts. Arc-based processes are preferred over beam-based processes because of their high melting rates, resulting in higher productivity. Moreover, the initial costs and operating costs of arc-based processes are much less. One of the major disadvantages of this process is excessive local heat input, causing dimensional inaccuracy, distortion, and even undesirable changes in microstructure along with increased thermal stresses.

To overcome the above mentioned disadvantages, the HW-GTAW process is used for additive manufacturing of metallic parts. Zhillian *et al.*, studied the advanced welding and cladding methods by using auxiliary cold and hot wires [65]. The comparison of automatic HW-GTAW, automatic conventional GTAW and manual GTAW processes for cladding operations were carried out by using auxiliary filler wire. The deposition performance of HW-GTAW for cladding operations can be significantly improved compared to the CW process. Welding speeds of 1000 mm/min were achieved in the HW process compared to 200 mm/min in the case of CW-GTAW, which resulted in a reduction of welding time, narrower HAZ and reduced risk of hot cracking. This work evaluated the result of the HW process on the transverse shrinkage of welds. Materials of various thicknesses (1.2, 1.5, and 3.5 mm) were welded by using automatic HW, automatic CW-GTAW and manual GTAW. Linear dimensions of the plate before and after welding and angular deformations were measured. It is observed that shrinkage is the smallest for the welds welded with HW-GTAW for all the thicknesses. This indicates that the HW process works on bare minimum welding current, that is minimal heat input with low distortion and reduced residual stresses in the part. Silwal *et al.*, achieved the continuous cladding on SS347 substrate by using Inconel filler wire with a minimum current of 70A. Welding results are found with lower dilution and higher contact angles [66].

GMAW processes are also widely used in the arc additive manufacturing processes, but the introduction of much heat in the part is a cause of concern. By using the GTAW process with HW, it is feasible to control the heat much better [67]. The application of additional HW to the GMAW process improved the characteristics of the GMAW process and achieved the overlay welds with a dilution of 5% and deposition rates of 12 kg/h [68].

Brownli *et al.* compared the HW-GTAW stellite weld cladding with lost wax cast stellite under corrosive wear conditions [69]. The study reveals that actual corrosion rates are much lower where as higher electrochemical corrosion rates are obtained for the stellite casts produced by the HW-GTAW process.

Spaniol *et al.* implemented the hot wire GTAW process for additive manufacturing of metallic components [70]. This work carried out the bead on plate experiments by HW-GTAW to find out the effect of weld parameters on bead geometry. It is seen that increase in wire feed rate enhances the bead width and height. The reason for this may be enhanced cooling of a molten pool by more filler addition. Hot filler wire is at a much higher temperature compared to the cold filler wire, but it is still lower than the weld pool temperature. Increased wire feed rate means more addition of material in the weld pool, resulting in the reduced average temperature of molten metal. This raises the viscosity and surface tension of the molten metal causing reduced flow in width leading to added reinforcement. This results in increased contact angle, which is not recommended for additive manufacturing. For additive manufacturing main aim is to obtain low penetration and low levels of melting to get lower contact angles to eliminate undercuts. This work demonstrated that by using selective parameter sets of wire feed rates, it is achievable to make smooth weld surfaces. It is seen that with lower heat input and low penetration the productivity in the order of 15000 mm/min is achieved, which is essential for arc-based additive production. This minimizes the residual stresses and distortion in the component due to reduced heat input.

5 Magnetic Arc Blow in HW-GTAW

The disadvantage of resistance heating is the strong magnetic blow that affects the electric arc due to the magnetic field produced by the current flowing in the filler wire. Hori *et al.*, studied the fundamental problems hindering the workability of HW-TIG welding [10]. Magnetic arc blow and arcing from wire are major problems associated with HW-GTAW. Countermeasures for the magnetic arc blow are: 1) wire heating with lower current and it should be less than half of the arc current, 2) increasing length of wire to be heated, 3) use of AC power source than DC for resistance heating and 4) pulsing of the HW current. During pulsing, the phase where current is not flowing there will not be any arc blow. It is understood that by using pulsed hot wire current, high wire feeding rates up to 9 m/min could be attained. Arcing takes place only when the tip of wire is separated from molten metal. This arcing forms a large droplet disturbing the TIG arc and further welding become problem. They developed techniques (touch detection) to identify whether the wire tip is in touch with a molten spool, from the wire voltage during no current phase of pulsing. During DCEN TIG welding, separation of wire from base metal will be detected and phenomenon of arcing can be avoided. Another method used to preheat the wire, which is independent of the resistance of the wire was proposed by Lv *et al.*, [71]. This method is suitable for low resistance materials such as copper and aluminium. A separate assistant torch is used to preheat the wire just prior to its entry into the weld pool and irrespective of the wire touching the main arc, heating will take place and avoids the problem of magnetic arc blow. The maximum temperature of the wire can be attained at around 60% of its melting point by using the HW current of less than 50 A. With arc-assisted hot wire, 96% of deposition can be increased. During the repair work of the pipeline, Baklanov *et al.*, identified that magnetic blow does not allow using direct current for shielded metal arc welding (SMAW). By using AC with rectangular waveform, it is useful to control magnetic arc blow, which gives promising results in terms of arc stability and metal transfer during SMAW [72].

In HW-GTAW, even though the temperature of hot wire is increased, the filler metal is completely melting by a molten arc. Part of the arc energy is utilized for melting the filler wire. This indicates that arc heat and deposition rate are dependable. This dependency decreases the operation controllability to meet the requirements of desired deposition rate for various applications. Thus, the productivity is reduced along with undesirable process controllability. Additionally, when the resistivity of the filler material is small, a larger arc is essential to melt the wire faster.

Hence, the deposition rate is at the cost of an increased molten pool.

6 Alternate Wire Heating Methods to Avoid Magnetic Arc Blow

Cao *et al.*, investigated HW-TIG welding based on the heat conduction method [25]. This method of heating avoids the magnetic arc blow problem due to resistance heating. They conducted the comparison experiments between HW-TIG, in which filler metal is heated to a temperature of 220 °C and ordinary TIG welding. There was a sensor that measures the heater temperature. Based on the heater temperature and welding speed, the wire temperature was measured. They developed a mathematical model for the same. The wire temperature was measured as a function of welding speed; a linear relationship [Equation (1)] was established between heater temperature and welding speed. By pre-setting feeding speed, heater temperature was maintained to get the required wire temperature of 220 °C.

$$T = 0.1522\ u + 252.1 \tag{1}$$

Where T = temperature of heater (°C), u = feeding speed (mm/min). Results showed that HW-TIG based on the heat conduction method could improve the appearance of the welding and increases the wire feeding speed.

Further, they investigated the effect of wire temperature on the weld beads. Increased wire temperature from 25 °C to 250 °C, weld width becomes greater from 12.4 mm to 13.3 mm and weld height reduces from 2.2 mm to 1.7 mm. This implies that weld reinforcement increases and penetration decreases. This means weld spread increases, which are beneficial for cladding operations where deposition on the surface is required. To find out the consequence of hot wire on the welding process various trials were conducted. From the trials, it is observed that welding speed for root pass can reach up to 160 mm/min in the case of HW-GTAW against the 90 mm/min of CW- GTAW when other parameters are kept constant. Also, the maximum wire feeding speed can be attained at 2000 mm/min. With increased welding speed and wire feeding speed, it is possible to increase the melting efficiency significantly. Melting efficiencies up to 100% for root welding and 200% for cap welding has been achieved by using the HW-GTAW.

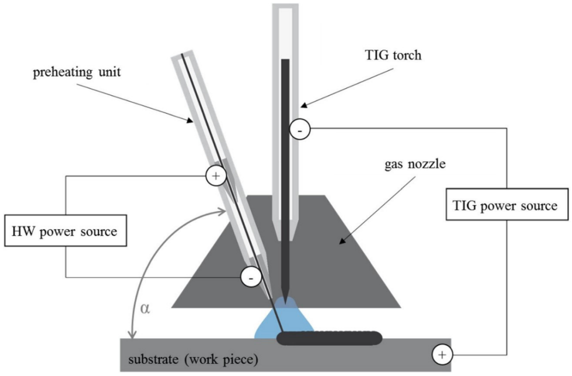

Figure 4: Schematic of HW-TIG used by indirect resistive preheating [26]

Ungethum *et al.*, carried out the study of metal transfer and weld geometry in HW-GTAW using indirect heating [26]. In this process, an additional preheating unit was used between two points on the filler wire instead of between the wire and melt pool. This method of heating the filler wire completely avoids the magnetic arc blow problem. It means that it is not necessary to contact between filler and molten pool. Irrespective of whether the wire is in proximity to the weld pool or not resistance heating takes place. As shown in Figure 4 indirect resistive heating is used for a bead on welding trials. They studied the influence of TIG current, HW current and wire feed rate on the metal transfer and bead geometry. They found that increase in TIG current adds up heat input through the arc resulting in higher melting of filler wire resulting in increased depth of penetration. A similar effect is seen by increasing the hot wire current, which leads to increased bead width due to the higher temperature of the weld pool. The effect of wire feeding rate on metal transfer is reverse to the effect of HW current, where weld penetration and bead width decrease with increased wire feed rate whereas bead height increases slightly. This is due to reduced temperature in the molten pool resulting in increased viscosity of the weld pool.

Erick *et al.* worked on the HW-TIG process, in which wire heating is done by using constant DC, working on Joule effect [34]. They specifically analyzed the magnetic blow and its effect on productivity and dilution of the AISI-316L weld beads. They demonstrated

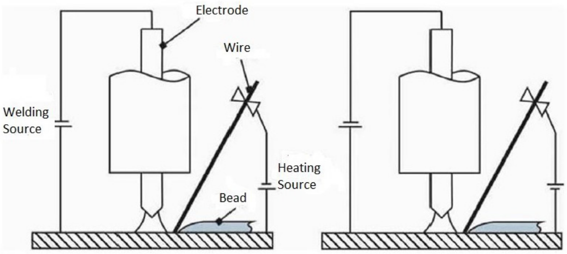

Figure 5: Electric circuits used for HW-TIG process: wire connected to (a) negative (b) positive terminal [34].

the magnetic arc blow forming. When current is passed through the wire, the arc changes in the direction of current carrying wire due to interaction between the magnetic fields of the wire and the arc.

Magnetic arc blow affects the direction of arc pressure and distribution of current density at anode. Due to this arc is not focusing at the centre of the molten pool. CW-GTAW has not given desired productivity and it is not possible to get the acceptable welds for the speeds (4.5 m/min) used in HW process. Authors conducted a study to find the change in magnetic arc blow due to polarity of the filler metal during HW welding. Figure 5 shows the scheme of electric circuit used for the GTAW and for the wire heating. Tungsten electrode is connected to the negative terminal while the wire heating system is either negative or positive. Figure 5(a), in which the filler wire is connected to the negative terminal, the energy of the electric arc is completely towards the filler wire. On the other hand, when the filler wire is connected to the positive terminal as shown in Figure 5(b), the arc is directed towards the direction of the TIG torch. As per the Ugeri *et al.*, this state is more favorable for working with high welding speeds and it guaranties the formation of a molten pool [16]. However, as per the results of Erick *et al.*, this configuration leads to less energy movement between the arc and filler wire resulting in incomplete melting of wire. Similar observations are made by Rebiero *et al.*, that HW negative polarity provides a more stable arc than HW positive polarity [73]. This may be due to repelling of arc by negative HW polarity avoiding a short circuit. However, it is recommended to use the AC power supply instead of DC to overcome the problem of magnetic arc blow.

7 Heat Input Calculation

In arc welding processes, heat input (HI) is the amount of heat or energy supplied to the workpiece to form a weld. The unit of heat input is energy per unit length. An important characteristic of heat input is that it controls the heating & cooling rates and weld pool size. Generally, a high heat input rate results in a lower cooling rate and in turn larger fusion zone. Grain size in the fusion zone and HAZ depends on heat input. If the weld metal alloy is spent a longer time above the grain coarsening temperature, then the coarser structure will be formed in weld and adjacent HAZ. A high heat input rate process is accompanied by a longer thermal cycle and tends to produce a coarser structure. Hence, it is needed to control the heat input in the arc welding process to get the required weld quality. Heat input rate in a welding have a serious concern on the toughness of weld and heat-affected zone. Therefore, maintaining an optimum heat input rate is very important to get the required grain size and cooling rate [74]. In HW-GTAW process, two heat sources simultaneously act on the weld pool. One is the heat source from the main arc which melts the base metal and forms the initial weld pool. Other is resistance heating of filler wire, governing the deposition rate and weld pool size.

Padmanaban *et al.*, studied the resistance heating produced under different HW current [38]. This heating can be changed by altering the hot wire current (I_h) and filler wire extension (L). They established the correlation between heat input (Q), L and I_h, and is given by Equation (2). This equation gives the precise heat input calculations for welding super 304H material by the HW-GTAW process.

$$Q = 0.00038 + 0.00000273 I_h - 8.168L + 0.177\, L\, I_h \quad (2)$$

Heat input calculations for HW-GTAW have been calculated by various authors by different heating methods. Net heat input in the HW-GTAW process is the sum of arc energy produced by gas tungsten arc and the heat due to HW addition by resistance heating method [2], [38], [42], [65] follow in Equation (3).

$$HI = (I_h^2 \times R_h)/V_w + (VI \times 0.6)/v \quad (3)$$

Where I = main current, I_h = hot wire current, V = voltage, v = welding speed (mm/min), V_w = wire feed rate (mm/min), R_h = resistance of wire (Ω). R_h depends on resistivity of filler material (ρ), filler extension length

(L) and cross sectional area of filler wire (A_w) follow in Equation (4).

$$R_h = \rho L/A_w \quad (4)$$

From the traditional heat input model, it looks that the heat input of HW-GTAW is higher than conventional TIG welding, as it is the sum of heat due to main arc and wire heat. However, practically the heat input of HW-GTAW should be less than the conventional CW-GTAW welding as the process is operating at very high welding speeds and under rapid cooling rates.

8 Advantages of HW-GTAW

HW-TIG welding process combines the production rates of GMAW with the quality of conventional GTAW. This process has several advantages, which include;

1) High deposition rates and high welding speeds, deposition rates are increased at least by factor 2.

2) Independent control of the arc current and deposition rate. This is useful to control the dilution to a large extent that directly reduces the undesirable alloy migration to the weld metal. Thus the chemistry will be much cleaner.

3) Exceptional weld soundness of weld metal is achieved due to the removal of surface contaminants and moisture content by heating the wire resulting in less chances of porosity.

4) Controlled or reduced heat input along with increased melting performance.

5) Lower heat input associated with increased melting rates are possible, which reduces residual

6) Increase the productivity, reduction in process times.

Limitations of HW-GTAW

A major limitation associated with this technique is the magnetic arc blow and arcing of wire with tungsten. The process is not advised for the low resistance filler wire materials such as aluminium and copper, which would be subjected to higher heating current resulting in excessive arc deflections and uneven melting.

9 Conclusions

Based on the literature survey (Table 1), it is observed that the performance of GTAW can be attempted beyond conventional welding parameters with increasing wire temperature and feed speed. HW-GTAW process has an elevated deposition rate of up to 6 kh/h in comparison with the conventional CW-GTAW process. Due to its high deposition rates and higher welding speed (1000 mm/min) it is possible to get MIG speed with TIG quality. The welding appearance and welding efficiency of HW-GTAW is superior to the CW wire process. The process has a capability to produce less defects in radiography along with improved weld finish resulting in increased productivity. Due to lower heat input, it is possible to achieve finer microstructure and faster cooling rates resulting in narrower HAZ. Weight of metal deposition can be enhanced significantly by increasing HW current 80 A and wire feed rate of 2000 mm/min as per the required geometry of weld bead. HW-GTAW can be used to weld a variety of materials including dissimilar metals to get defect-free and sound welds. This process has been used successfully for narrow gap welding technique and TIP-TIG technology to weld thicker sections. The problems associated with hot wire techniques like magnetic arc blow and acing phenomenon are avoided by using one of the techniques -heat conduction method, AC power supply, electromagnetic induction or high frequency induction technology. HW-GTAW has been successfully used for cladding and additive manufacturing to increase productivity. Due to various advantages of HW technique, this process is having many important industrial applications in joining of rocket motor cases and related aerospace components, nuclear vessels, stainless steel, heat resistance alloy piping, tanks and pressure vessels.

Future prospective of Hot Wire- Challenges

It is known that HW-GTAW is high speed, high deposition welding process maintaining TIG quality welds. Deposition rate somewhere between 1 kg/h to 8 kg/h is achievable at given circumstances. This technique shall not be limited to only the GTAW process, can be used beyond GTAW. The application of this technique for high power density processes like plasma and laser beam welding can be explored. Combination with HW and laser welding can give much faster welds with higher deposition at a lower cost compared to laser alone. In short, a heated wire has the potential to raise the productivity levels in many critical welding processes across the industry.

Table 1: Major recent literature survey on HW-GTAW techniques

Ref.	Remarks
[2]	Thorough visualization of hot wire GTAW process carried out. Evaluated the effect of HW-GTAW parameters by carrying out bead on trials of alloy 617. The cooling rate, heat input and weld bead characteristics were studied.
[5]	Twin Tungsten GTA welding studies along with HW and pulsed current were carried out and noticed that a combination of these techniques significantly increased the deposition rates.
[11]	The performance of GTAW was improved by implementing the A-TIG process. A-TIG process enhanced the penetration of 6mm thick carbon steel plates in a single pass by using the TiO_2 flux.
[12]	The microstructure and mechanical property relationships are brought out by A-TIG welds of dissimilar joints P91 and 316L dissimilar steel joint of 8mm thick in a single pass welding.
[22]	HW-GTAW welding studies were carried out on modified 9Cr 1Mo steel, for the nuclear reactor. A comparison of HW and CW weldments in terms of tensile, hardness and bend tests was done.
[25]	To avoid the magnetic arc, blow problem in the GW-GTAW process, wire heating by conduction method was adopted. Effect of wire temperature on weld bead profile and melting efficiencies were compared with HW and CW processes.
[26]	Indirect heating of filler wire by using an additional pre-heating unit was used to avoid magnetic arc blow and different metal transfer modes were studied.
[28]	Wire heating by electromagnetic induction method was developed, implemented and evaluated. The problem of magnetic arc blow was eliminated.
[29]	Oscillating laser hot-wire tungsten inert gas hybrid welding on 10mm thick SS316 steel was used to study the droplet transfer, molten pool and weld bead formation. Results showed that the larger molten pool area, more intense fluid flow, and better weld bead formation with oscillating laser joined to TIG as compared to TIG or normal laser-TIG hybrid welding.
[31]	Dissimilar joints of SS304H and T91 alloy were analyzed using the HW-GTAW process to assess the weldability & mechanical properties.
[54]	Study of Mechanical and Metallurgical Properties of Cold and hot wire GTA welded weldments were studied by using reciprocating wire TIG Welding.
[60]	Mechanical properties of super 304H tube welds were studied by manual and semiautomatic HW-GTA welding. Semi-automatic hot wire welded joint has higher yield strength, ultimate tensile strength and % elongation than manual weld joint.
[61]	Microstructure and Properties of Lean Duplex Stainless Steel weld joints were evaluated by Hot Wire TIG Welding. Microhardness of welds was higher and the microstructure was finer.
[65]	Advance welding & cladding methods were studied by using auxiliary cold & hot wires. Demonstrated the high speed welding up to 1000 mm/min for cladding operations.
[66]	Hot wire GTAW cladding on SS347 substrate by using Inconel filler wire has done. Continuous cladding can be achieved with a low current of 70A, lower heat inputs resulted in lower dilution and higher contact angles.
[68]	Application of additional HW to the GMAW process improved the characteristics of the GMAW process, and achieved the overlay welds with a dilution of 5% and deposition rates of 12 kg/h.
[70]	Hot wire GTAW process has been implemented for additive manufacturing of metallic components. The effects of welding parameters on bead geometry were studied.

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