INNOVATIONS IN ARC WELDING

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ABSTRACT

Developments in arc welding processes are strongly related with the need to increase productivity without losing quality of the welds performed. It is by targeting these aspects that can maintain their competitiveness in the world wide markets. Reduction of costs and competitive pricing are each day more strongly related with technological innovations.

MIG/MAG welding is one of the most used processes in industry both in manual and robotized welding. The search for higher productivity and better quality has led to the development of many variants of this process. Conventional TIG is known has a very controllable and precise welding process, to increase conventional TIG deposition rate other TIG variants have been developed in the latest years.

The present paper aims at outlining some of the recent innovations in MIG/MAG and TIG welding which represent steps ahead to achieve the objectives outlined above.

1. INTRODUCTION

Developments in arc welding processes are strongly related with the need to increase productivity without losing quality of the welds performed. Only targeting these aspects are companies competitive in the world wide markets. Reduction of costs and competitive pricing are each day more strongly related with technological innovations.

The transfer of production units from countries where labor costs are high and legislation against professional hazards strong has been a well know practice for many industries. This is nevertheless always a temporary solution to maintain competitiveness. Sooner or later the salaries in these countries will increase and the governments will create mandatory requirements for industry implement international standards (IIW, 2005; EN ISO15011-1, 2003)

The way forward is thus innovation – to produce better products at lower costs in working friendly environments, is the challenge any company needs to face.

Welding is a manufacturing process used in a large diversity of industrial sectors and it is estimated that in Europe more than two million jobs are related with welding technology. In what regards economic impact, welding is used in the production sector which generates an added value of approximately 1600 billion euros, per year, in Europe. It is estimated that approximately 5% of this value is related with joining technology – 8 billion euros.
The data refereed creates a solid base to think about welding and joining as technologies where innovation is important.

Arc welding, mainly MIG/MAG welding is a process widely used both in the manual and mechanized modes. The search in this process is mainly focusing two objectives:

- High productivity process, for thicker plates and long welds.
- Better penetration control for root passes and thin plates.

TIG welding, associated usually with high quality but low productivity process, can increase its potential if the productivity can be increased.

The present paper aims at outlining some of the recent innovations in MIG/MAG and TIG welding which represent steps ahead to achieve the objectives outlined above.

2. MIG/MAG WELDING

2.1. High productivity variants

2.1.1. Tandem Welding

Welding with the use of two electrode wires (Tandem) was applied for the first time for submerged arc welding. In the beginning of the nineties this solution was successfully transferred into gas shielded welding. The action of melted metal in two welding arcs, supplied from separate wire feeders, onto the common weld pool is applied in the Tandem method. Both welding current circuits are separated electrically, thus parameters can be set independently and individually for each welding wire. This results in the wide possibility to control melted weld pool and consequently the shape of the weld.

During the welding process with the Tandem method both welding electrodes are placed one after another towards welding direction. First electrode, called leading electrode, ensures required penetration depth, while second one, called following electrode, provides required filling up of the pool, prolongs the time of its degasification and provides proper face shape, free from porosity and undercutting. Usually the leading electrode is of larger diameter, as it ensures approximately 65% of the whole deposition efficiency obtained in the welding process. Second electrode, which is placed in the backside part of the weld pool, is usually loaded with lower current intensity and controls melted metal of weld pool.

Pulsed current welding in the Tandem method is used very often. When the background current is applied onto the leading electrode, current pulse occurs on the following one (see Fig.1). This way of current pulse synchronisation enables heat input to be controlled and this method can be applied for welding of relatively thin-walled elements, welding in different positions and materials sensitive to a high amount of input heat (high-resistant steels, duplex steels, aluminium alloys).

Welding station for Tandem welding consists of two, usually inverter, welding power sources, which allow optional adjustment of work characteristics of individual machines and two feed systems supplying electrode wires and welding torch, equipped with two contact tubes (Fig. 2) oriented in the required directions to be applied. A torch should be designed and cooled in such a way to withstand current load of 600 – 1200 A during long cycles of main arc burning (preferable 100 % duty cycle).

Application of Tandem welding instead of conventional MIG/MAG welding, especially on automated and robotised welding stations, allows travel speed to be increased even up to several meters per minute, depending on the thickness of welded elements and joint
configuration. Such welding speed is impossible to reach during semiautomatic welding, therefore Tandem welding is usually applied in mechanised or robotic processes. Tandem method is one of the most effective methods of improving welding productivity.

![Current diagram for Tandem pulsed welding](image1)

Fig. 1 - Current diagram for Tandem pulsed welding

![A torch for tandem welding produced by Lincoln Electric](image2)

Fig. 2 - A torch for tandem welding produced by Lincoln Electric

In figure 3 an example of a laboratory robotized cell for TANDEM Welding is presented and in figure 4 examples of weld macrographs obtained with this process in different joints are shown.
Fig. 3 - TANDEM robotic cell

3 mm throat thickness fillet weld

5 mm throat thickness fillet weld

Welding parameters

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Welding parameters

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Fig. 4 - TANDEM welds.  
a) T- joint with fillet weld of 3 and 5 mm throat thickness; b) 6 mm butt joint of plates; c) T- joint with fillet weld of 10 mm throat thickness (S690Q steel, plate thickness 25 mm); d) 20 mm butt joint of S690Q steel
Fig. 4 (continued) - TANDEM welds. a) T- joint with fillet weld of 3 and 5 mm throat thickness; b) 6 mm butt joint of plates; c) T- joint with fillet weld of 10 mm throat thickness (S690Q steel, plate thickness 25 mm); d) 20 mm butt joint of S690Q steel

### Welding parameters

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<td></td>
<td>2</td>
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2.1.2. TIME Welding

Research on the improvement of welding productivity through application of higher density of welding current as well as compound gas shielding resulted in new variant of metal active gas welding, called T.I.M.E (Transferred Ionised Molten Energy). Factors which determine high process productivity are the high current density and four-component Ar-He-CO₂-O₂ shielding mixture of precisely chosen composition (depending on the welded material grade, e.g. for mild steels: 65% Ar + 26.6% He + 8% CO₂ + 0.5% O₂). The process conducted with high current density and welding speed is flexible and allows for three methods of metal transfer as a result of alteration of the wire feeding speed:

- short arc – wire feed speed up to approximately 8 m/min (arc voltage 16-23.5 V),
- direct spray arc – wire feed speed up to approximately 25 m/min (arc voltage 28-46 V),
- rotational spray arc – wire feed speed up to approximately 30-40 m/min (arc voltage 47-56 V).

For each method of metal transfer spatter does not exceed 2%, the level of weld metal oxidation is also low. Rotational character of metal transfer ensures that fusion is wide and flat (Fig. 5), which provides uniform penetration into the joints walls, especially in fillet welds production. For wire feeding in the range of 20 to 25 m/min it is possible to acquire the deposition efficiency of 10-15 kg/h and for higher values even 26-27 kg/h.

![Fig. 5 - Shape of penetration for spraying transfer of metal in conventional MIG/MAG and rotational transfer in T.I.M.E processes](image)

The productivity of T.I.M.E. process has been shown in the form of deposition and surfacing rates for wide range of parameters with calculated losses for spatter. These losses are lower than in MIG/MAG, which helps to eliminate post-weld cleaning and improves significantly the welding productivity.

In figure 6 an example of a TIME power supply is presented and in figure 7 macrographs of TIME welds produced in different joints are shown.
Preparation and welding sequence:

Fig. 6 - TIME 540 from FRONIUS

Fig. 7 - TIME Welds: a) T-joint with fillet weld of 5 mm throat thickness, current intensities 165 and 230 A; b) T-joint with fillet weld of 5 mm throat thickness, current intensity 300 A; c) 6 mm butt joint of plates, current intensity 230 A and 300 A; d) 20 mm butt joint of plates
2.2. Low-energy MIG/MAG Welding Processes

2.2.1. Cold Metal Transfer

The CMT (Cold Metal Transfer) process (Fronius, 2004) is a revolution in welding technology, with respect to both, welding equipment and welding applications. The CMT-process is not only a completely new process, which is unknown until now, but it also opens a new field of application since it widens the limits of Gas Metal Arc Welding (GMAW), allowing the arc joining of steel to aluminum in a reproducible manner for the first time.

There are materials and applications that cannot withstand the constant heat of a welding process. In order to avoid weld-pool drop-through, to be spatter-free, and to be amenable to metallurgical joining, they need lower temperatures. With CMT, this is now possible. The term “cold” has to be understood in terms of a welding process, but when set against the conventional MIG/MAG process, CMT is indeed a cold process.

CMT can be described as a GMAW process where heat input is low as compared to the conventional dip arc process. The CMT-process is a dip arc process with a completely new method of the droplet detachment from the wire. In the conventional dip arc process the wire is moved forward until a short circuit occurs. At that moment the welding current rises, causing the short circuit to reopen, allowing the arc to ignite again. There are two main features of the MIG/MAG process: on the one hand the high short circuit current corresponds to a high heat input. On the other hand the short circuit opens in a rather uncontrolled manner, resulting in lots of spatters in the conventional dip arc process. In the CMT process the wire is not only pushed towards but also drawn back from the work piece – an oscillating wire feeding with an average oscillation frequency up to 70 Hz is used.

There are three features of the CMT process, which distinguish this process from a conventional GMAW process.
First of all, the wire movement is directly included into the welding process control. Until now the wire feed speed during welding was either fixed or had a predetermined time schedule (e.g. synchropulse). In the CMT process the wire is moved towards the work piece until a short circuit occurs. At that moment the wire speed is reversed and the wire is pulled back. When the short circuit opens again, the wire speed is again reversed, the wire moves towards the work piece again and the process begins again. There is no predetermined time schedule for the wire movement, but the occurrence and the opening of a short circuit determine the wire speed and direction. It can be said that there is an interaction between the processes in the welding pool and the wire movement. This is the reason why one can only speak of an average oscillation frequency of the wire, depending exactly on the occurrence of the short circuit. Therefore the oscillation frequency of the wire varies with time – averaging around 70 Hz.
The second feature which characterizes the CMT-process is the fact that the metal transfer is almost current-free, while the conventional dip arc process corresponds to a high short circuit current. In the CMT process the current is no longer responsible for the opening of the short circuit. When the wire is drawn back, the movement supports the metal transfer due to the surface tension of the molten material. Therefore the current during the short circuit can be kept very low and the heat input is also very small.

Finally the CMT-process is characterized by the fact that the wire movement supports the metal transfer as mentioned above.

Figure 10 presents a CMT unit for robotized welding, though the process is often used in the manual mode.

Typical areas of application for the CMT process are all thin and ultra-light gauge sheets, from as thin as 0.3 mm; for MIG brazing of galvanised sheets, and for joining steel to aluminium. Until CMT, applications like these were only possible under difficult and labour intensive conditions (e.g. weld-pool backing support), or users had to resort to different joining technologies altogether – which of course meant doing without all the advantages of a welded joint. With CMT, what used to seem impossible is now possible.

CMT sets brand-new standards in welding technology. This process is ideal for e.g. the automobile and allied vendor industries, the aerospace sector and for structural and portal work. Essentially, all automated or robot-assisted tasks are suitable. All customary base and filler metals can be used.

2.2.2. Surface Tension Transfer

Surface Tension Transfer – STT (Deruntz, 2003) welding is a GMAW, controlled short circuit transfer process. Unlike standard CV GMAW machines, the STT machine has no voltage control knob. STT uses current controls to adjust the heat independent of wire feed speed, so changes in electrode extension do not affect heat. The STT process makes welds that require low heat input much easier without overheating or burning through, and distortion is minimized. Spatter and fumes are reduced because the electrode is not overheated - even with larger diameter wires and 100% CO₂ shielding gas. This gas and wire combination lowers consumable costs.
In this process, the melting electrode material contacts the weld pool on the workpiece before detaching, creating a periodic short. Typical waveform cycle periods are 1/120 s and is presented in Fig. 12.

Explanation of each process phase is given below:

A. STT produces a uniform molten ball and maintains it until the "ball" shorts to the puddle.

B. When the "ball" shorts to the puddle, the current is reduced to a low level allowing the molten ball to wet into the puddle.

C. Automatically, a precision pinch current waveform is applied to the short. During this time, special circuitry determines that the short is about to break and reduces the current to avoid the spatter producing "explosion".

D. STT circuitry re-establishes the welding arc at a low current level.

E. STT circuitry senses that the arc is re-established, and automatically applies peak current, which sets the proper arc length. Following peak current, internal circuitry automatically switches to the background current, which serves as a fine heat control.

Table 1 summarizes the advantages of this process after MIG/MAG and TIG Welding.
### Table 1 – Advantages of STT

<table>
<thead>
<tr>
<th>Advantages of STT replacing short-arc MIG/MAG welding</th>
<th>Advantages of STT replacing TIG welding</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Significantly reduces lack of fusion.</td>
<td>• Four times faster than TIG.</td>
</tr>
<tr>
<td>• Good puddle control.</td>
<td>• Vertical down welding.</td>
</tr>
<tr>
<td>• Capable of producing consistent X-ray quality welds.</td>
<td>• Reduced training time.</td>
</tr>
<tr>
<td>• Reduced training time.</td>
<td>• Can use various compositions of shielding gas.</td>
</tr>
<tr>
<td>• Lower fume generation and spatter.</td>
<td>• 100% CO₂ (on mild steel).</td>
</tr>
<tr>
<td>• Can use various compositions of shielding gas.</td>
<td>• Welds stainless, nickel alloys and mild steel.</td>
</tr>
<tr>
<td>• 100% CO₂ (on mild steel).</td>
<td>• Consistent x-ray quality welds.</td>
</tr>
</tbody>
</table>

Figure 13 presents equipment for STT welding.

![Fig. 13 - Power Wave455M from Lincoln](image)

STT also ideal for, open root, pipe and plate welds, thin gauge material in automotive industry, silicon bronze, stainless steel and nickel alloy in the petrochemical utility and food industry, galvanized steel, semiautomatic and robotic applications.

### 2.2.3. Cold Arc

Development work with the aim of achieving a low-energy process without mechanical intervention in the wire feed process, resulted in a process variant in which all necessary interventions in the process take place in the power source alone. This variant of the MIG/MAG process, known as Cold Arc, is a short arc process, called as such due to the cyclical change between the arc and short circuit phases. As the electrical output during the re-ignition process is a critical criterion for successfully welding thin sheets, active intervention is carried out in the outline of the power intake for the overall process, however, in other words during the arc phase, in the short circuit phase and especially when re-igniting the arc, the voltage outline remains the same as in the normal short arc process. It is used as a guideline value when controlling the current. However, the continuous measurement of the voltage with the corresponding reaction to all changes in voltage is required to achieve this (highly dynamic instantaneous value regulation). A digital signal processor (DSP) can then be
used to extract the power from the arc immediately before re-ignition in a period of less than 1 µs, so that the reignition takes place very gently. So that, a sufficient quantity of molten material can be formed immediately on the electrode tip, however, there is an increase in the amount of energy required.

Immediately after the arc re-ignites, the current is therefore raised back up again for a defined short period to what is known as the melt pulse. Only then is the current lowered to an extremely low basic level to minimise further melting, and the next cycle begins. This melt pulse after each short circuit generates a melting cone of a constant size on the electrode which means that process continues very smoothly and evenly. This is the only way it has been possible to work at extremely low currents in the phases between the short circuits, without the wire melting further or the arc going out. All this goes to make up the very low-energy Cold Arc process. The next image shows a sequence of images from a high-speed film, which highlight the very even material transfer and the gentle ignition of the arc.

The outline of the arc output on arc re-ignition is shown below.
The advantages of the Cold Arc process in comparison to the standard short arc at the moment of re-ignition and immediately afterwards become very clear. Here the output at the moment of arc re-ignition is considerably lower not just as an absolute value. In fact, immediately after the arc ignites, the output is reduced in an exceptionally dynamic and controlled way, and then, after the arc has been stabilised, increased to the defined melting of the electrode tip in a pulsed way.

A process of this type can be used for many welding tasks, especially in vehicle construction where the normal short arc is no longer suitable. Even just a few years ago, it was assumed that the MIG/MAG process should be used for steel over a panel thickness of 0.7 mm and for aluminium over 3 mm. The panel thicknesses in vehicle construction today are becoming increasingly thin, however. They already go down to as low as 0.3 mm, and 0.2 mm is already being tested for composite construction work. The difficulties in achieving an even groove are even greater if there are larger air gaps to be bridged. This is a typical task for the Cold Arc process.

For some time now, different welding techniques have been used on surface-coated metal sheets, in other words, using copper-based filler material for arc brazing. This helps to preserve the zinc layer, but difficulties can arise if there is a larger air gap. With the Cold Arc process, on the other hand, even larger air gaps can be bridged with the filler material.

The main areas of application are:

- Joining of thinnest sheets from 0.3 mm thickness.
- Brazing and welding of zinc coated sheets.
- Heat-reduced brazing on basis of novel zinc wires as an alternative to Cu based alloys, such as CuSi3.
- Joining of mixed joints, such as steel-aluminum, steel-magnesium (St-Al, St-Mg).
- Welding of magnesium alloys.
3. TIG WELDING

The conventional TIG (Tungsten Inert Gas) is a very controllable and precise welding process which has been used since the beginning of the Second World War. It is possible to produce high quality welding joints in a wide range of parent materials (e.g. Carbon steels, stainless steels, Ni, Ti, Cu or Mg alloys), were the absence of defects, distortion, fumes and low hydrogen levels are required. For thinner sheets (≤ 3mm) manual TIG is normally performed in the manual variant were welding currents are lower. However, qualified operators are required. The most important drawback of the process is welding of thicker sections (> 3mm). In this cases “V” or “X” weld groove and filler metal are required, however, the associated lower deposition rate (less than 0.5 Kgh⁻¹) is the major disadvantage in what concerns to welding productivity. The associated multiple passes and thermal cycles (proportional to thickness) will also result in distortion and higher contamination levels.

MIG/MAG (Metal Inert Gas/Metal Active Gas), PAW (Plasma Arc Welding), LBW (Laser Beam Welding) or EBW (Electron Beam Welding) are suitable processes for thicker welding sections, nevertheless MIG/MAG welding quality is poorer in short circuit transfer mode, particularly in root passes. All other welding processes require higher initial investment costs, being PAW process sensitive to process parameters change with higher torch design complexity and normally requiring high maintenance.

To increase conventional TIG with flux rate, other TIG variants have been developed in the latest years. “Hot wire”, “narrow gap”, “high current” TIG techniques are examples of incoming technologies aiming deposition rate improvements which is the main disadvantage of conventional TIG. Although, “Hot wire” variant, brings in the hot wire through the trailing shroud and ensures its sufficient shielding protection can cause further problems. On the other hand, with “narrow groove” variant is difficult to have control on side wall fusion and ensure the right torch positioning to access the lower portions of the groove. “High current” melt-in-mode variant (“buried arc” or “immersed arc”) is generally automated and takes advantage of electromagnetic arc impingement force (> 300 A) which will cause a significant displacement of the weld pool resulting in deeper penetration.

This relatively deep weld pool is formed through the combined action of heat conduction and convection in the liquid metal, and depression of the pool surface by the arc pressure. In melt-in-mode (not fully penetrating) the process may become difficult to control, especially in what concerns to penetration degree. At currents beyond 350 A defects are common (hollow bead) and for currents above 500A the weld bead will become violently unstable. The high arc pressure will induce a cavity under the arc however the surface tension will tend to resist deformation becoming the pool rather unstable.

3.1. TIG Keyhole

TIG keyhole (K-TIG) mode (Jarvis, 2000; CSIRO) variant was first developed by the Australian industry in late 1997, regarding weld bead stability, depth welding profiles and significant production increase. The welding process has been jointly developed by CSIRO (Commonwealth Scientific and Industrial Research Organisation) and CRC-WS (Co-operative Research Centre for Welded Structures), which has introduced an unique and remarkable high productivity potential solution to joint ferrous, nickel and titanium alloys (plates and tubular products) from 3 – 12 mm thick. K-TIG welding is an automated welding process which operates at higher currents than conventional TIG in order to puncture a small
opening through the root face of the workpiece without need of backing bar. The electromagnetic force (Lorentz forces), which is dependent on the square of current, will induce a depression or cavity on weld bead surface.

![Fig. 17 - Electromagnetic force will have two components, radial compression \( \square \) and axial acceleration (a).](image)

This weld pool displacement must be formed as part of the welding process, allowing the generated welding energy to be delivered in depth from the surface through the liquid weld pool, as a result of combined action of highly localized energy and pressure (Fig. 17). The surface tension will be responsible to drive the opening cavity to a very stable keyhole geometry being the ruptured root surface an important root to allow the pressure within the cavity to be released. Finally, as part to dynamic mechanism it is important to keep the opening root surface small avoiding any loss of material in the training regions of the weld pool.

Due to physical mechanisms that support the dynamic keyhole force balance, K-TIG welding process is suitable for relatively low thermal conductivity parent materials, namely stainless steels, nickel and titanium alloys. A favorable keyhole surface geometry is achieved because the weld is much wider on the front face than on the root face. If the keyhole root bead becomes too wide the pool will not be supported and the process will fail.

One of the most important advantages of K-TIG technology is the particularly simple square-edge preparation needed. Filler metal can be used to compensate poor fit up, reduce undercuts, provide additional reinforcement, or modify the microstructure of the weld metal.

In figure 18 it is possible to compare features and respective depth welding profiles between conventional TIG and K-TIG for 10.5mm AISI 304 Stainless Steel.
Conventional TIG

- SS AISI 304 10.5 mm thick
- Single V or X60° preparation
- 1000 gm⁻¹ filler addition
- 7 passes at 200 mm min⁻¹
- Arc-on time 35ʹm⁻¹
- 320 Amps

TIG Keyhole

- SS AISI 304 10.5 mm thick
- Closed Square butt
- 50 gm⁻¹ filler addition
- 1 pass at 300 mm min⁻¹
- Arc-on time 3’20”sec min⁻¹
- 640 Amps

Fig. 18 - Penetration profile comparison between conventional TIG and K-TIG for 10.5 mm AISI 304 Stainless Steel.

4. CONCLUSIONS

1. Application of TANDEM welding process with the same current intensity as in the case of conventional MAG method make it possible to increase the welding speed and to reduce spatter both for butt welds and T-joints with fillet welds.

2. Application of TANDEM welding process allows reducing welding costs of 1 m long joints even by 35% in comparison to conventional MAG.

3. TANDEM welding assures good mechanical and plastic properties of welded joints made of non-alloyed steel and thermo mechanically treated steel.

4. Application of TIME process made it possible to increase welding speed by 20 to 90 % in comparison to traditional MAG technique. It depends on type of joint and first of all on welding current intensity. It reduces spatter.

5. Advantages of TIME process are more evident for high current intensities and spray arc.

6. Application of TIME process allows reducing welding costs of 1 m long joints by 20 % to 30 % in comparison to conventional MAG.

7. TIME process assures good mechanical and plastic properties of welded joints made of non-alloyed steel.

8. STT and Cold Arc are variants indicated for thin plates and penetration welds, thus it isn’t surprising that the productivities achieved weren’t very high, on the other hand
the quality (shape) of the welds is very good; STT and Cold Arc presented similar results.

9. The CMT variant allows achieving higher penetration welds than MIG/MAG with lower widths, thus leading to welds with shapes less prone to defects (lack of penetration).

10. Since productivities with STT, Cold Arc and CMT do not increase when compared with MIG/MAG welding, these would be with no cost reduction. The higher purchase costs of the equipment would make this difference even higher.

11. Another very important angle to address is the quality of the weld. The use of these variants for penetration welds will lead to root passes with lower defects, minimising re-work time which is expensive.

12. The correct balance between high productivity/high qualities needs to be addressed by the companies on a case by case basis. A combination of high quality root passes (STT, Cold Arc, CMT) with high productivity filling passes (Tandem, TIME) might be an interesting solution in some cases, namely in metal working companies where welding is a major production process.

13. The development of K-TIG technology, based on conventional TIG Process, has conducted to high quality final welds. Weld quality can be related to high productivity performance at relatively lower cost investments when compared with plasma and laser.

14. K-TIG has proved to be a high potential technology for production increase at lower cost guaranteeing however incomparable welding quality standards when compared with traditional welding processes.

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