Comparison of penetration profiles of different TIG process variations

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2003: Graduated at the Budapest University of Technology and Economics on the faculty of mechanical engineers from the department of material sciences and energetic.

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Keywords: TIG welding, ATIG welding, arc constriction, weld penetration depth, TIG welding penetration profile, TIG welding variations / versions / variants.

1. Abstract

The increasing productivity in industrial applications gets more and more into the focus of attention during the last decades. This intention is also present at the developments of welding technologies. TIG welding developments have also been parallel to the really heavy-duty welding processes (like MIG/MAG, SAW, Beam Weldings, etc.). Several TIG welding variants were developed due to these researches.

In spite of the fact that a very wide literature of TIG welding process is well known, the number of those publications which write down exact equations between the different parameters is very low. The situation is even worse for the new TIG variants.

Three TIG variant (using pure Argon, furthermore 70% Ar + 30% He as shielding gas, finally Activated TIG welding) are investigated and compared together in this paper. The comparison is executed from the penetration depth (D), the bead width (W), the penetration profile (D/W) and the weld bead cross section (A) point of view.

This work makes an attempt to create an overall picture, which evaluates the effects of the welding parameters to the above properties. All experiments were executed on different thick AISI 304 / W.Nr. 1.4301 type austenitic stainless steel plates from 2 mm up to 6 mm thickness. This paper is intended as an introduction part of a wider job which will investigate the advanced TIG variations and their properties with the strongly determined purpose of making more precise the existing models of the so called ATIG phenomenon.

2. Introduction

The TIG welding became a mass production welding procedure during the World War II. Later as the time changed and many more productive welding procedures were born TIG welding was continuously pushed into the background. In the last 4-5 decades TIG welding almost totally disappeared from mild steel and low alloyed steel welding (excluding pipes' root run welding and repair and maintenance works). The use of TIG welding is even frequent for stainless steels, aluminium, copper and nickel, but the process transfer to higher productive processes like MIG/MAG may be observed in case these base materials also.

Due to these historical changes many developments began to increase the productivity of the TIG welding and several TIG welding variations were elaborated as a result of these efforts. These TIG variations sometimes differ from each other only in the composition of the shielding gas, and sometime in the addition of something else like wire (Tip-TIG) or flux (Activated TIG = ATIG) (Table 1). Therefore the results of the welding are always different, but the hardware and the process don't change at all. This is why the different solutions may be called TIG variants.

	Process	Shielding gas	Method	Cold wire
1	TIG	100% Ar	CC-DCEN, CC-AC, P-DCEN, P-AC	with or without
2	TIG	Ar + He (30…90%)	CC-DCEN, CC-AC, P-DCEN, P-AC	with or without
3	TIG	~100% Ar + O_2 [11]	CC-DCEN, P-DCEN	with or without
4	TIG	~100% Ar + CO_2 [11]	CC-DCEN, P-DCEN	with or without
5	TIG	Ar + He (30…90%) + O_2 [12]	CC-DCEN, P-DCEN	with or without
6	TIG	Ar + He (30…90%) + CO_2 [12]	CC-DCEN, P-DCEN	with or without
7	TIG	Ar + H_2 (2…10%)	CC-DCEN, P-DCEN	with or without
8	TIG	Ar + N_2 (1…3%)	CC-DCEN, P-DCEN	with or without
9	ATIG	100% Ar	CC-DCEN	without
10	ATIG	Ar + He (30…90%)	CC-DCEN	without
11	FB-TIG	100% Ar	CC-AC	without
12	FB-TIG	Ar + He (30…90%)	CC-AC	without
13	KTIG	Ar, He, N_2 mixtures [14]	CC-DCEN	without

CC-DCEN	Direct Current Electrode Negative, Welding Current is Constant
CC-AC	Alternating Current, Welding Current is Constant
P-DCEN	Direct Current Electrode Negative, Welding Current is Pulsed
P-AC	Alternating Current, Welding Current is Pulsed
ATIG	Activated Tungsten Inert Gas welding
FB-TIG	Flux-Bonded Tungsten Inert Gas welding
KTIG	Keyhole TIG welding

Table 1. Some TIG welding variants.

Countless number of articles were published about the TIG welding both with pure argon and Ar-He shielding gas, nevertheless a really overall picture can be hardly founded in the technical literature which miss is tried to be filled by present results at least partially. The attempt to create an overview of all TIG process variations covering all the shielding gases, base materials and thicknesses and many other variables would have been impossible to execute, so the following TIG process variations were chosen for the comparison:

- Conventional TIG welding, using 100 % Argon as shielding gas
- Conventional TIG welding, 70 % Argon + 30 % Helium as shielding gas
- ATIG welding, using with activating flux and 100 % Argon as shielding gas

The main objective was to provide an as complete overall picture as possible about the chosen processes including the most important correlations of the penetration.

The most extensively used TIG process (when pure argon is the shielding gas) and the argon-helium mixed gas shielded version are compared with the ATIG process.

The ATIG process, which is the most interesting and lesser-known TIG process variation, has not a widely accepted common agreement in connection with the working mechanism. However the excellent penetration, which can be achieved by ATIG welding, made many scientists to carry out experiments and make attempts to create theories for the explanation of the so called “ATIG-effect”. At the moment four different well-detailed models exist in the literature.

The short statements of the four base theories are in the following:

- Theory of Simonik (1976) [1]: Simonik said that oxide and flourine molecules are present in the activating fluxes, which have affinity to chain the free electrons at the edge of the plasma of the arc. It is well known that ions formed this way have substantially lower mobility than the free electrons. This leads to increase current density in the centre of the arc by means of the higher movement of the free electrons. By resulting better focus of the arc the deeper penetration is achieved.
- Theory of Savitskii and Leskov (1980) [2]: This theory says that the activating fluxes decrease the surface tension of the weld pool which makes able the arc pressure to cause a deeper invading in the pool. This invading helps the arc pressure to reach a deeper penetration.
- Theory of Heiple and Roper (1982) [3]: This theory explains the high penetration with the reversed Marangoni-effect. The convective flowing of the molten metal from the center towards the edge is the phenomenon that is called Marangoni-effect. It is working when the gradient of the surface tension of the weld pool is negative. This theory says that the activating fluxes changes the gradient of the surface tension from negative to positive that results that the flowing of the molten metal turns in the opposite direction and flows towards the center. This is how the deep penetration obtained by the reversed Marangoni-effect.
- Theory of Lowke, Tanaka and Ushio (2005) [4]: The authors explain the deep penetration by the means of the higher electric insulation of the activating fluxes. Due to this, the arc is able to break through the surface (and the flux on it) only at a narrower area. This means that the focus of the arc increases which leads to higher current density in the arc spot resulting the deep penetration.

However besides these theories several other models were established recently the ATIG phenomenon is getting known wider. In the followings our experimental results are published.

3. Experimental work

AISI 304 type (1.4301) austenitic stainless steel plates were used as base material. During the welding no consumables were added to the weld pool. All the welds were carried out as bead-on-plate.

An AC/DC 3000 type power source was used to the welds which maximal welding current is 300 Amps (ESAB Origotig 3000 AC/DC). The power source can operate in CC (Constant Current) and pulsed mode where the frequency can be varied from 0,1 to 500 Hz. The plates were fixed to a 20 mm thick table with manual clamps. It means neither ceramic nor gaseous backing was applied. The close clamping to the table proved enough safety against burning (heavy oxidation) of the root side. Naturally the table was always cooled to “hand-temperature” after every weld.

Welding speed was provided by a welding tractor (ESAB Railtrac 1000 FW) which could have been set by 1 cm/min steps from 1 to 150 cm/min maximal speed. In case of the Argon/CO_2 mixed shielding gas a gas-mixer (WITT KM20-3DI) was used to set precisely the required composition.

The cross section of the welds were photographed and evaluated by the help of a picture analyser program (JMicroVision 1.2.7). The experiments were executed on 2, 3, 4, 5 and 6 mm thick plates with all the three technology versions. This range provided sufficiently lot results to make a correct and satisfactorily wide evaluation of the penetration profiles.

During the welds 10 Amps up to the current increased the welding current where the penetration became complete at most of the plates. Welding speed was 15 cm/min (2,5 mm/s) and the arc length was 2 mm. The flowing rate of the shielding gas was 7 litre/min below 100 Amps, 10 litre/min from 110 to 180 Amps and 12 litre/min from 190 Amps. In case of the He containing shielding gas 2 litre/min more gas flow was applied than the previous values.

Gray colour coded (ceriated) tungsten electrode was used for the welds with diameter 2,4 mm and sharpened to 90°.

The welding tests were executed according to schedules that included every important parameter and value. The welding current was fixed value, while the voltage, the penetration depth (D), the bead width (W) and the joint cross section (A) were measured. Heat input (Q) and penetration profile (D/W) was calculated.

4. Results and discussion

4.1. Penetration depth (D)

The values of the schedules were the base material of the diagrams (Figure 1…5) which present the penetration values of the mentioned three TIG welding variants on the 2…6 mm thick 304 type stainless steel plates.

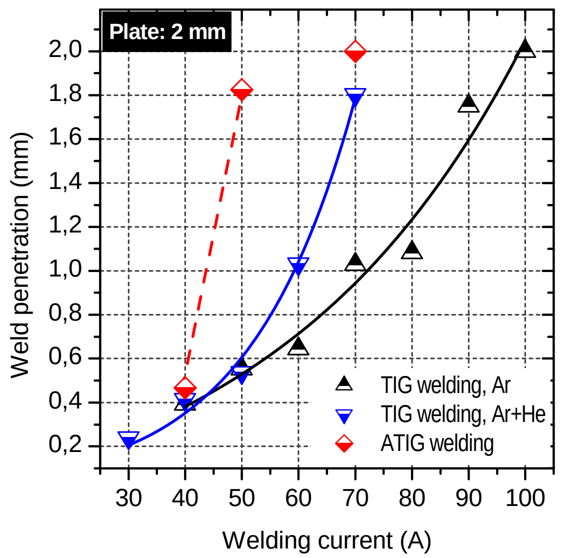

Figure 1. Weld penetration in function of welding current and welding process variants for 2 mm thick plate.

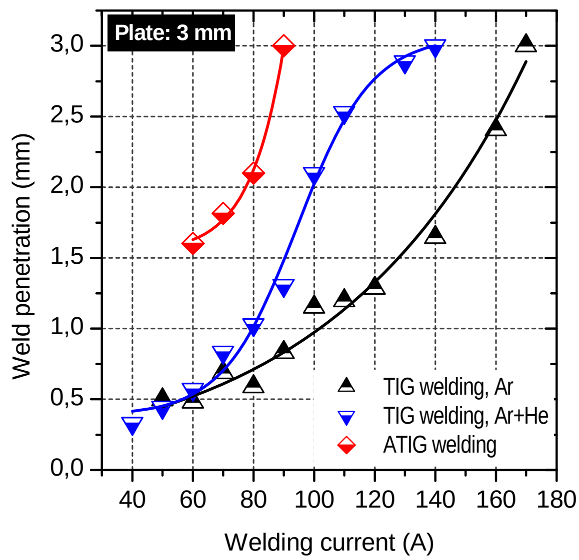

Figure 2. Weld penetration in function of welding current and welding process variants for 3 mm thick plate.

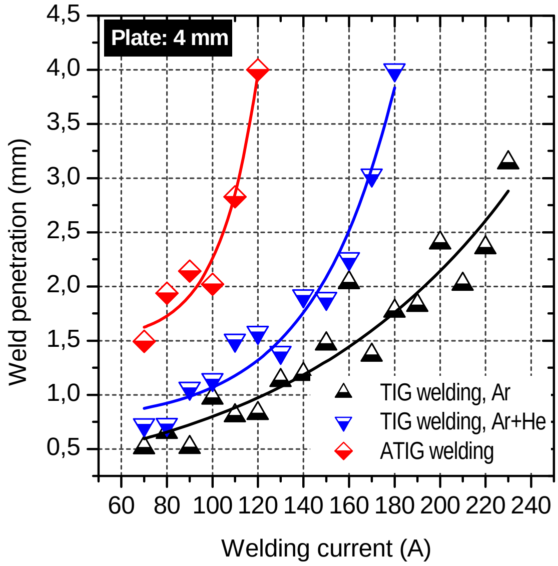

Figure 3. Weld penetration in function of welding current and welding process variants for 4 mm thick plate.

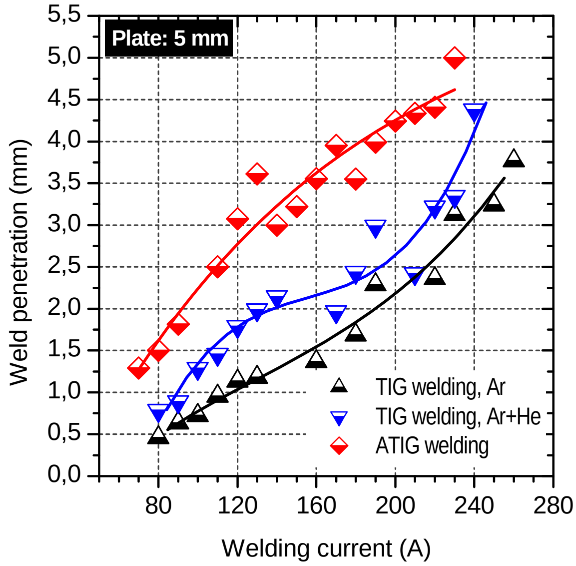

Figure 4. Weld penetration in function of welding current and welding process variants for 5 mm thick plate.

The figures represent perfectly the trends what could be expected. Pure argon TIG has the weakest penetration depth. The 70% Ar + 30% He mixed shielding gas improved the penetration, however this beneficial effect reduced by increasing the plate size up to 6 mm thickness. At this point the penetration improvement effect of He may be regarded neutral.

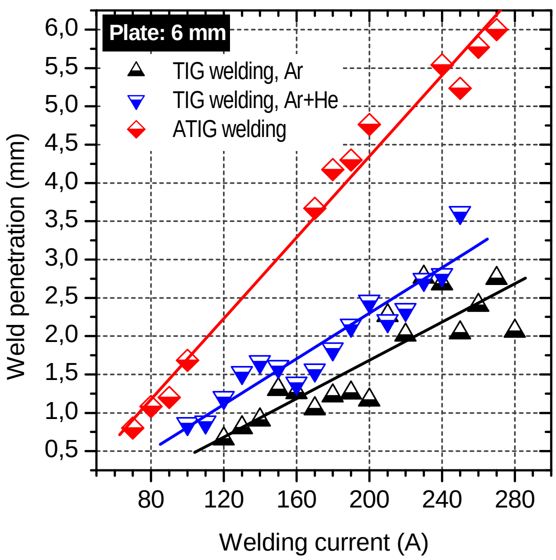

Figure 5. Weld penetration in function of welding current and welding process variants for 6 mm thick plate.

This is a really interesting phenomenon and needs to be investigated deeper. Moreover it also has importance from industrial point of view. Our recommendation is not to use He-containing gas above 4 mm thickness with deeper penetration requirements. Naturally the other beneficial effects of the He are not considered here.

According to many authors' works ([5], [6], [7], [8], [9]) the expectations were satiated. ATIG welding provided significantly deeper penetration, (Figure 6) than the previous TIG variations. Nevertheless a new problematic property of the ATIG welding got to our sight. This problem is namely the effect of the portioning method's reproducibility. Most of the authors presented that the flux was applied manually, usually with a simple brush. The effect of the improper brushing method is observable on Figure 1, where unacceptable deviation occurred within the penetration results.

However many limits of the volume of the activating flux can be found in the different publications an easily applicable and reproducible portioning method is still missing.

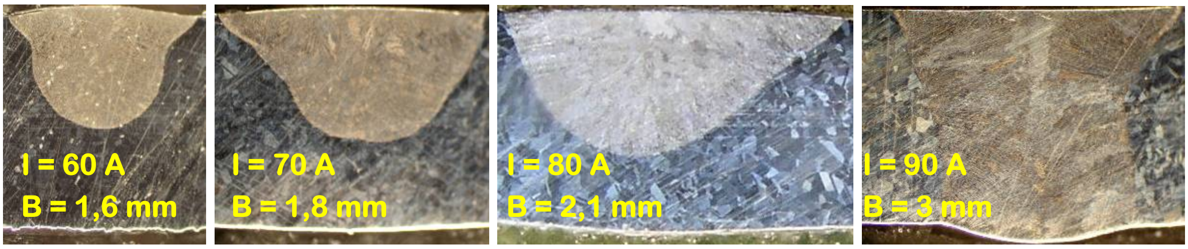

Figure 6. Bead-on-plate weld cross section carried out by ATIG welding (thickness is 3 mm).

In contrast with the He-containing shielding gas the ATIG effect is not reduced by the increasing plate thickness. A new recognition was that the ATIG welding has a lower limit from the welding current point of view. Below 40 Amps the arc stability was suddenly lost. The arc did not have enough power to break/melt continuously the activating flux, so the arc “sticked” to the anode spot and while the torch persistently moved the arc was elongating. When the arc elongated to 8-10 mm (!) it re-striked again at the nearest point below the electrode and here a new arc column was formed, then the described process started again. The result was not a bead but a series of welded spots (Figure 7).

Reducing the electrode gap at lower currents can shift this phenomenon, but it cannot be evaded. In case of 2 mm electrode gap 40 Amp is the applicable minimum welding current.

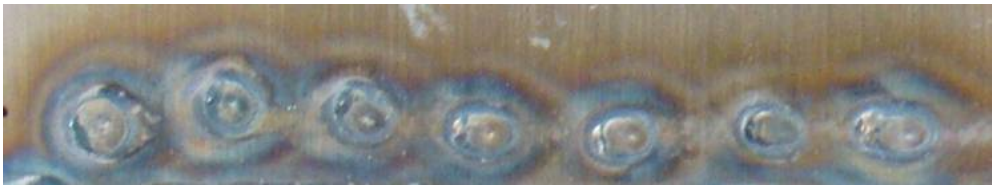

Figure 7. The surface of a 2mm thick plate welded with 40 Amps; note the arc restriking points.

This property is depending on several factors like on the flux type, on its grain size, on the electrode type, on its sharpening profile, etc., which factors are not considered here, only the fact that a minimally applicable welding current limit was observed in case of ATIG welding. The relatively high electric insulation of the activating flux ([4], [10]) that can resist the arc to break through the flux layer is the unambiguous explanation of this observation. As general rule can be stated that ATIG welding provides 2,5…3,5 times deeper penetration than TIG welding with 100 % Ar shielding gas and 1,5…2,5 times deeper than TIG with 70 % Ar + 30 % He at the same current.

4.2. Width of the weld beads (W)

Another interesting feature of the welded joint is the width of the joints. The width strongly influences the deformation of the base material, consequently the whole welded structure. The explanation of this phenomenon can be found in the solidification process. The bigger volume of molten metal, the bigger contraction occurs during the solidification. Consequently if a weld bead is narrower than another one bead (while the penetration depth is the same) then the narrower joint will cause less deformation to the structure (Figure 8). Based on this idea the narrower joint is more beneficial from deformation point of view.

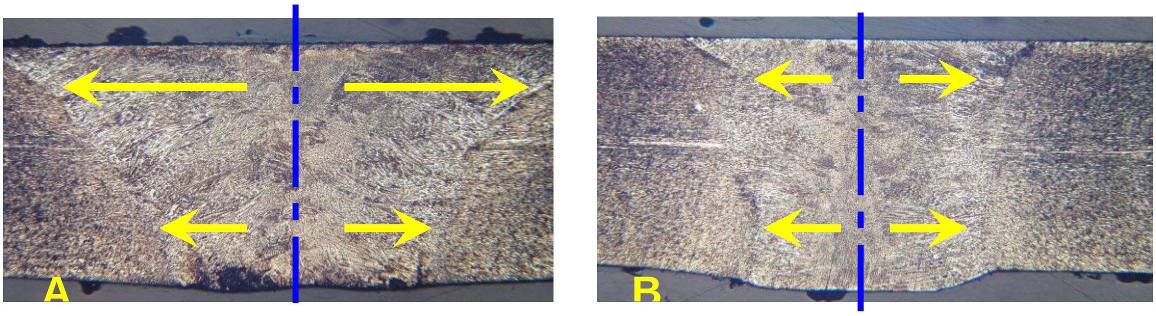

Figure 8. The working stresses which develop during the solidification in the conventional TIG (A) and ATIG welded joint (B); (arrows represent the contracting forces)

The diagrams of Figure 9… Figure 13 represent the bead width of the welded beams carried out on 2… 6 mm thick plates.

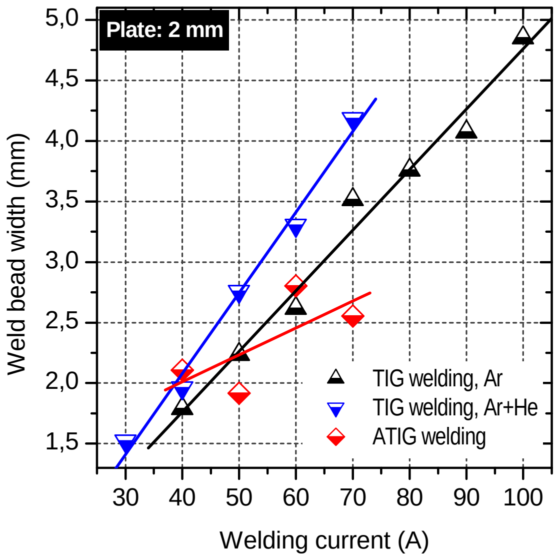

Figure 9. Weld bead width in function of welding current on 2 mm thick plate.

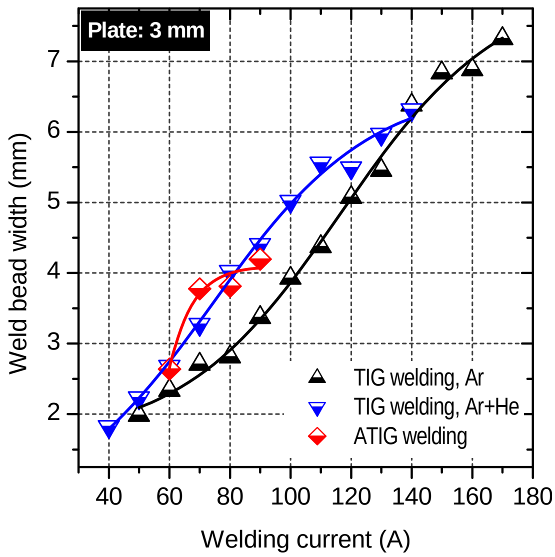

Figure 10. Weld bead width in function of welding current on 3 mm thick plate.

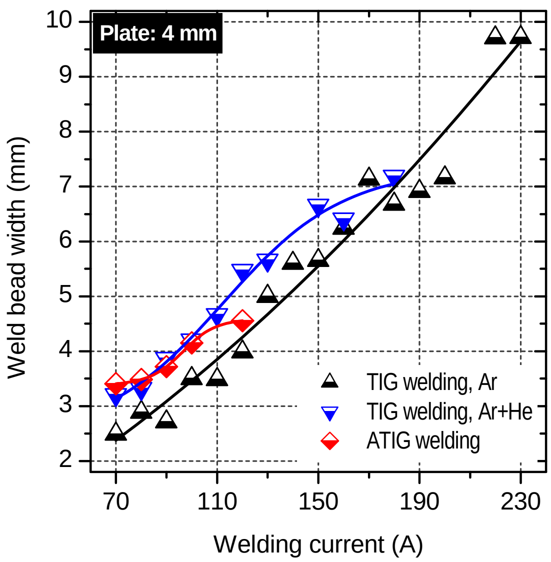

Figure 11. Weld bead width in function of welding current on 4 mm thick plate.

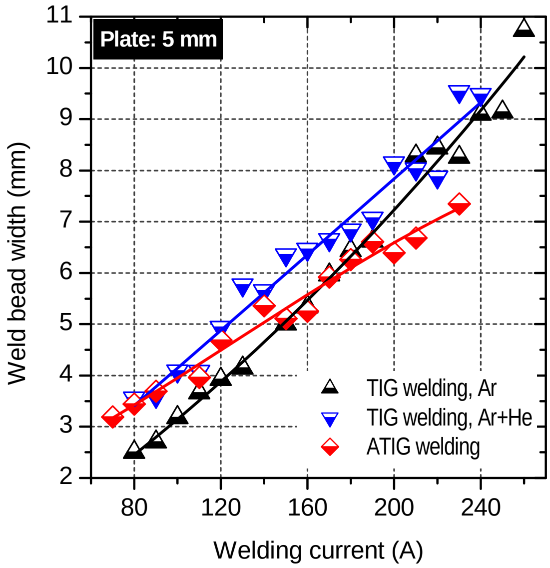

Figure 12. Weld bead width in function of welding current on 5 mm thick plate.

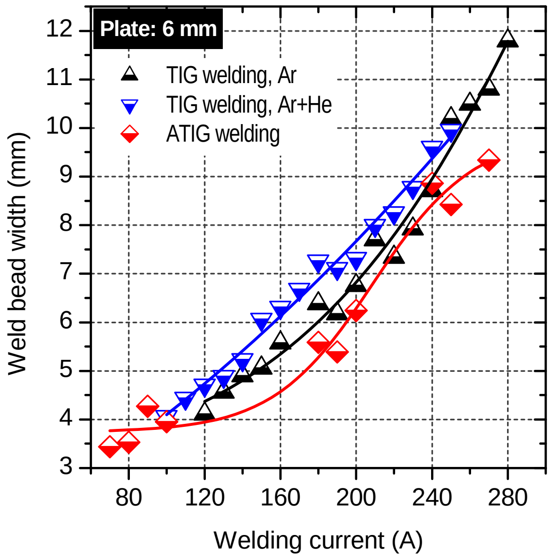

Figure 13. Weld bead width in function of welding current on 6 mm thick plate.

The difference is obvious. In case of TIG with 100% Ar on 3 mm thick plate, the width is 7,3 mm (Figure 14/A) when the penetration is complete. This value is 6,3 (Figure 14/B) mm when the shielding gas is 70% Ar + 30% He. ATIG welding's width is 4,2 mm (Figure 14/C).

Figure 14. Cross section of characteristic weld beads: (A) TIG with 100 % Ar, (B) TIG with 70 % Ar + 30 % He shielding gas and (C) ATIG welding on 3 mm thick plates. Note the differences between the bead widths.

The difference is bigger in case of the 4 mm thick plates (10 mm / 7,2 mm / 4,6 mm) and increasing dramatically with the thickness, however the diagrams may cause confusion at this point. It seems at first sight that the difference decreases at 5 and 6 mm thick plates. The reason is that while ATIG welding could provide complete penetration at all thicknesses (at 5 and 6 mm too), the TIG could not (check Figure 4 and Figure 5) consequently the comparison is not exact, because the achieved penetration depth is not the same, so the reader has to consider this confusing factor.

If the base of the comparison is only the welding current then the diagrams represent that both TIG welding result narrower beads, than ATIG, especially at lower currents. This is fact, but these figures are incomparable on their own. The comparison can be correct only correlated to penetration depth. To avoid further confusion and to clarify this disturbing phenomenon the diagrams are created to represent the bead with correlated to the penetration depth.

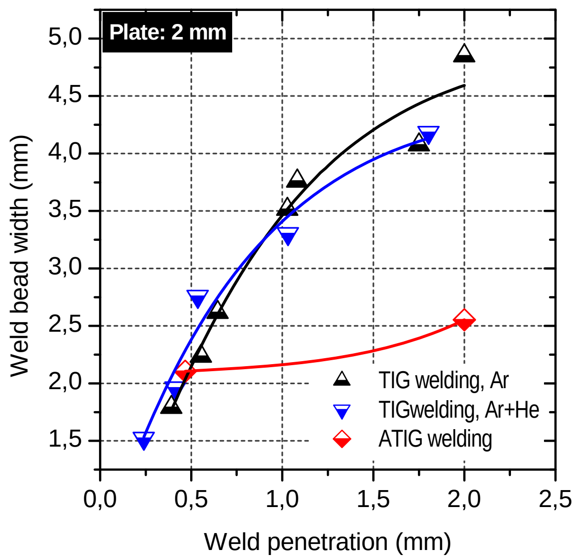

Figure 15. Comparison of the bead widths correlated to the penetration depths on 2 mm thick plate

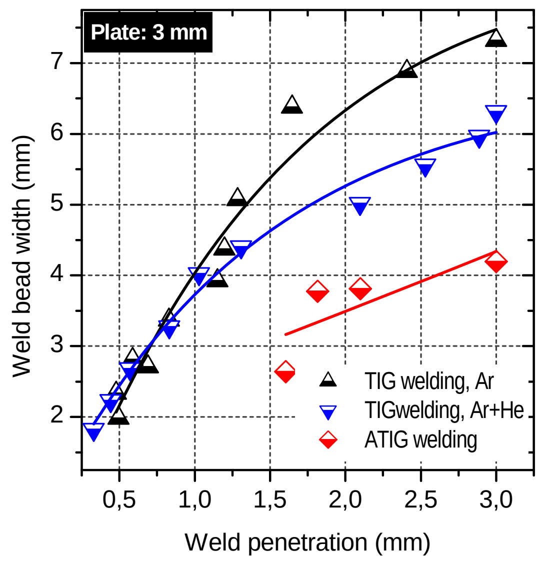

Figure 16. Comparison of the bead widths correlated to the penetration depths on 3 mm thick plate

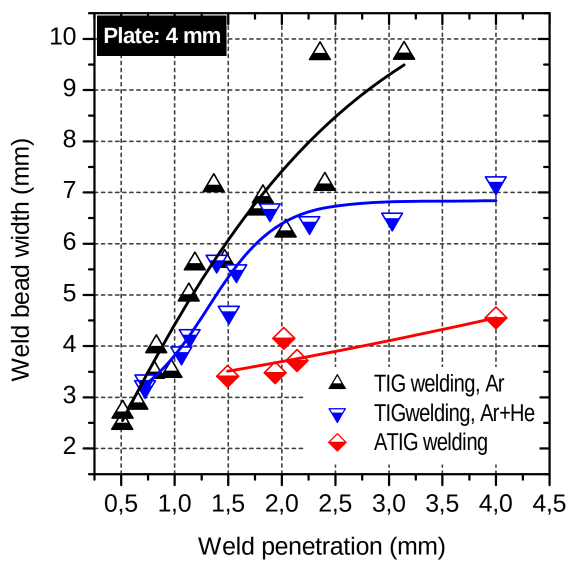

Figure 17. Comparison of the bead widths correlated to the penetration depths on 4 mm thick plate

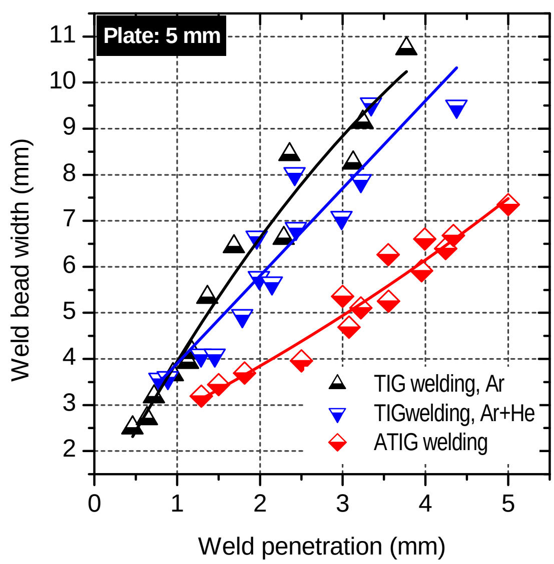

Figure 18. Comparison of the bead widths correlated to the penetration depths on 5 mm thick plate

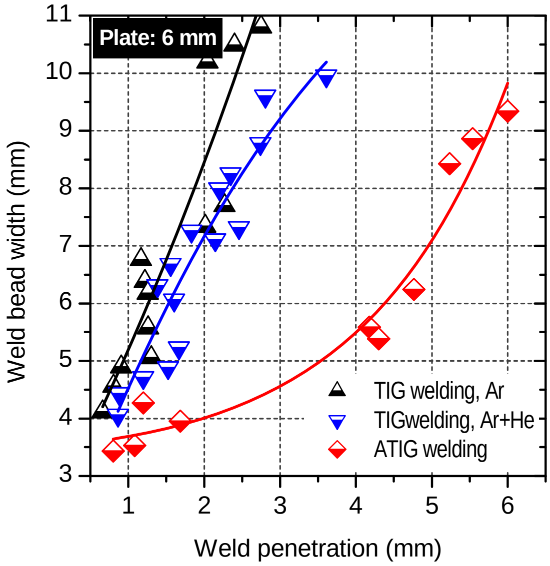

Figure 19. Comparison of the bead widths correlated to the penetration depths on 6 mm thick plate welded with TIG (100 % Ar and 70 % Ar + 30 % He) and ATIG

It may be stated as a consequence that the bead width will be narrower at a given penetration depth by applying the ATIG welding.

So the required depth and the relevant welding current must be selected properly from Figure 1…Figure 5 according to the welding process and only then may be compared the widths of the beads.

The narrower bead attainable by the use of the ATIG welding (at a given current) is formed in spite of the higher welding voltage what is caused by the SiO_2 based activating flux. This is remarkable, because the higher welding voltage widens the bead. Notwithstanding the flux has an arc constriction effect too, what however restricts the bead width [4]. The reaction of these opponent effects (increasing voltage induced bead widening versus flux caused arc constriction) resulted the diagram what is shown on Figure 20.

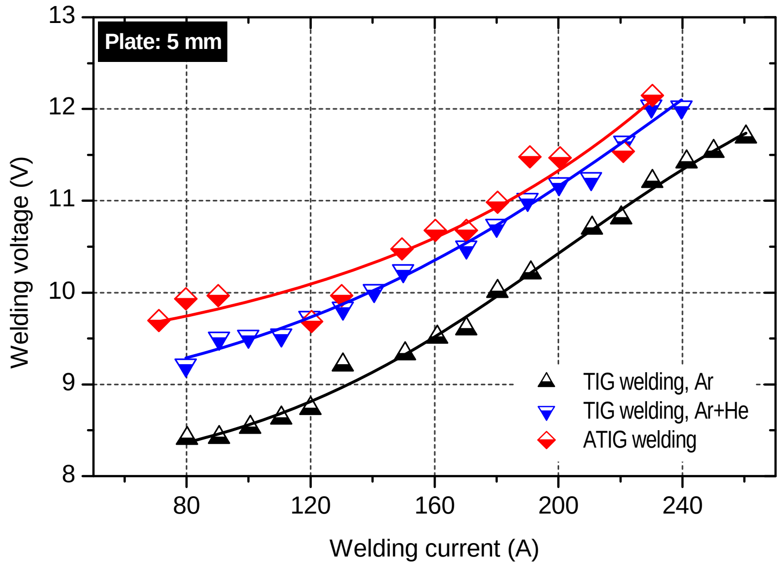

Figure 20. Welding voltage correlated to the welding current and to the welding process.

In case of ATIG welding the welding voltage increase approximately equals to that what occurs when pure argon shielding gas is replaced by the 70%Ar + 30% He mixture (Figure 20).

The results prove that the arc constriction effect is more powerful than the voltage increasing induced bead widening. By completing this statement with the penetration depth values the conclusion can be made easily that the arc efficiency is better in case of ATIG than in case of the conventional TIG versions. The question is the ratio of this better efficiency.

4.3. Penetration profiles (D/W)

By using the figures of the penetration depth (D) and bead width (W) may be calculated the penetration profile (D/W). The penetration profile is a characteristic feature of the joint or bead and consequently it indicates well the arc efficiency. We found the followings after summing up all the values of the beads:

- In case of 100 % Ar shielded TIG welding P/W converged from 0,15… 0,2 up to 0,35… 0,4.
- In case of 70 % Ar + 30 % He shielded TIG welding P/W converged from 0,15… 0,2 up to 0,45… 0,5.
- In case of ATIG welding P/W converged from 0,25… 0,3 up to 0,7… 0,9.

As a consequence of the arc efficiency improving feature of the 70 % Ar + 30 % He shielding gas and the activating flux may be ascertained. It also can be declared that this enhancing effect is more powerful (approximately 2 times) in case of ATIG welding.

4.4. Bead cross sections

The cross section differences of the beads are considered as final aspect of this paper. The formed cross section represents very well the arc efficiency since the cross section is the final result of the heat process that worked during the welding.

Consequently it can be said if at a given welding current a cross section is larger with one welding procedure than with another one then the first one’s arc efficiency is better.

The bead cross sections of the subjected TIG variations of this paper are appraised separately for all the five plate thicknesses in the following diagrams (Figure 21…Figure 25).

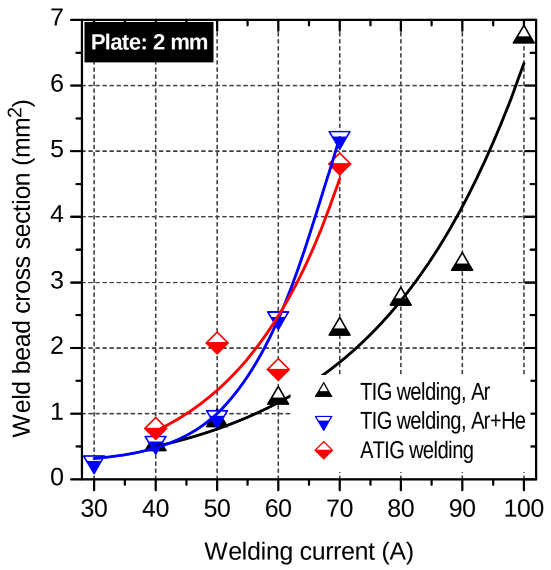

Figure 21. Effect of welding current to the weld bead cross section at 2 mm thick plate

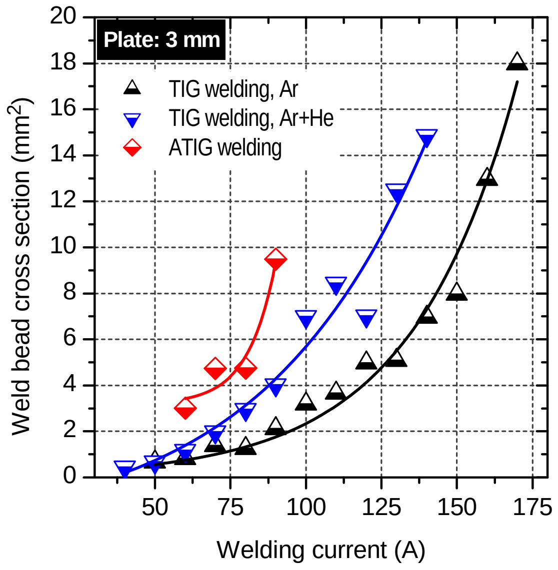

Figure 22. Effect of welding current to the weld bead cross section at 3 mm thick plate

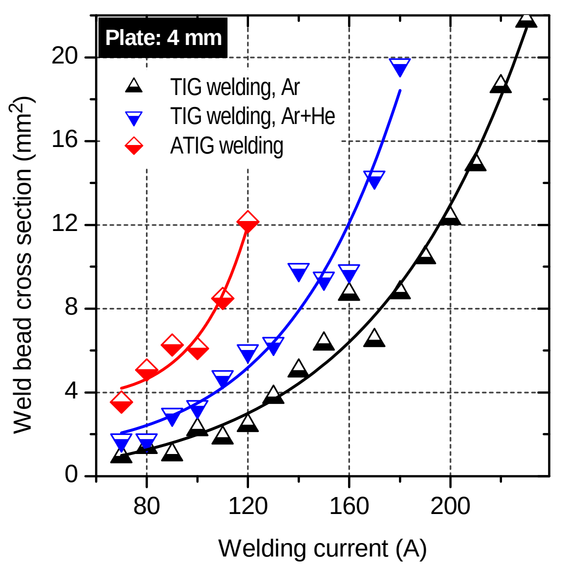

Figure 23. Effect of welding current to the weld bead cross section at 4 mm thick plate

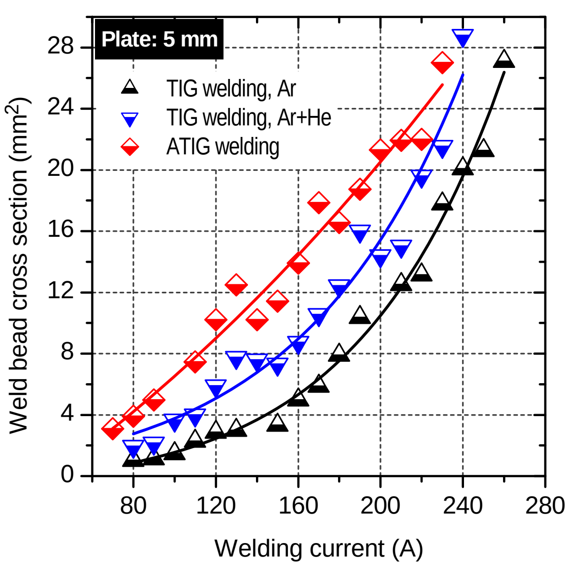

Figure 24. Effect of welding current to the weld bead cross section at 5 mm thick plate

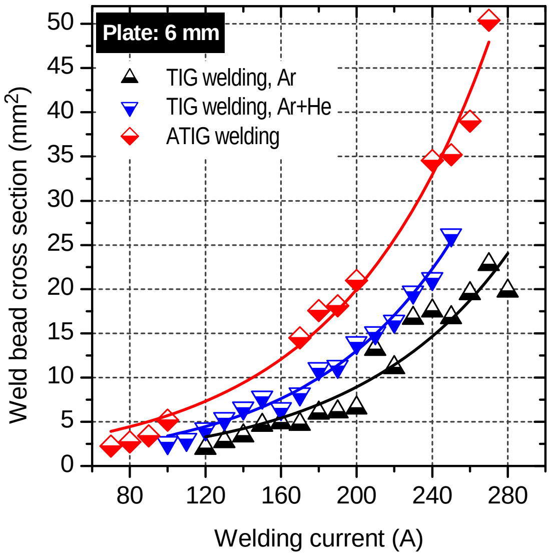

Figure 25. Effect of welding current to the weld bead cross section at 5 mm thick plate

The presented results confirm our previous statement in connection with the arc efficiency that the efficiency improves with the He content gas and improves better with the activating flux. Generally it can be ascertained that parallel with the deeper penetration values for both TIG with 70 % Ar + 30 % He shielding gas and ATIG welding the bead cross sections are also larger by the same ratio.

The exponential increasing of the bead cross sections correlated to the welding current is a remarkable observation. It harmonises with the Rykallin model. The explanation is that the heat conduction is three dimensional with low currents (while the penetration does not reach the one third of the plate thickness) then 2,5 dimensional with medium currents (penetration is between one third and two third of the plate thickness) and finally 2 dimensional with high currents (when the penetration is above two third of the plate thickness).

The bead cross sections demonstrate how the He addition and the activating flux application enhance the arc efficiency, consequently these factors improves the heat transfer into the base material.

5. Conclusions

Based on the experiments of present paper the following conclusions were stated:

- The 30 % He content of the Ar-He mixed gas improves the penetration, but this enhancing effect is getting lower with the plate thickness increasing. This penetration depth improving effect disappears above 6 mm thickness, but may be kept insignificant from 5 mm in case of 304 type austenitic stainless steels.
- The activating flux result deeper penetration than the other two TIG variations by the same welding currents. Moreover the deeper penetration is not reduced at thicker plates. It does not have dependence on the thickness up to 8 mm (based on our preliminary researches).
- The ATIG welding has a minimal application limit from welding current point of view. This value is 40 Amps in case of 2 mm electrode gap.
- There is not significant difference between the examined TIG variations from bead width point of view if the base of the comparison is the applied welding current. However the difference is significant and remarkable when the bead widths are correlated to the penetration depths.
- The application of the activated flux results approximately so much voltage increasing like 30 % helium mixing to the argon.
- Both the He-addition to the shielding gas and the application of the activating flux improves the arc efficiency and/or the heat transfer to the base material.

6. Acknowledgements

The Hungarian Research Found and National Office supported this work for Research and Technology, the project number is: NKTH-OTKA K69122.

7. References

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