NUMERICAL AND EXPERIMENTAL STUDIES OF THE INFLUENCE OF PROCESS GASES IN TIG WELDING

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ABSTRACT

This paper presents extensive investigations about the influence of He-additions to argon TIG-arc properties. Results of diagnostic methods, numerical simulations and welding trials are combined to improve the comprehension about the mode of action of gas mixtures. Additionally, selected results of the investigation with H_2- and N_2-additions are summarized. The investigations show that all gas additions cause an increase of the heat input into the workpiece. However, the stagnation pressure depends on the gas composition: He-additions result in a decrease of the stagnation pressure which depends on the arc length, whereas H_2- and N_2-additions increase the pressure. By a systematic choice of the gas mixture the weld depth and also the maximum feed speed can be influenced.

IIW-Thesaurus keywords: Argon; GTA welding; Helium; Hydrogen; Mixtures; Nitrogen; Shielding gases.

1 Introduction

Tungsten inert gas welding is a widely used process for welding of stainless steels, aluminium or other non-ferrous materials. The arc is established between a non-melting tungsten electrode and the workpiece. The separate control of power input and metal feed rate in TIG welding compared to MIG welding induces welding seams with a very high quality. But a disadvantage of this welding process is the relatively low welding speed. The enlargement of the process efficiency and therefore the increase of the application range have been the aim of many analyses in the recent years.

One possibility to influence the arc process is the gas used. The standard gas is Ar due to its inert gas properties and its low costs. But also additions of He, H_2 and N_2 are common practice for the welding of stainless steels [1].

On the one hand, there are metallurgical reasons for the use of shielding gas mixtures, especially for Ar+N_2 for welding duplex steels. It is well-known that these gas additions assure the austenitic microstructure in the weld. In contrast to this, H_2-additions are just usable for austenitic steels [2]. H_2 leads to a reduction of O_2 and therefore discolorations are reduced. However, too high quantities of H_2 cause pores. In addition to these metallurgical correlations, which are well established in practice, there is also an influence on the arc properties, especially on the heat input and the arc pressure. Thus, He-additions are often used in practice [3].

Nestor [4] and, Tsai and Eagar [5] analysed the heat and current flux density of TIG-arcs. They investigated the influence of the arc length (distance between the electrode tip and the workpiece), the tip angle and the current for pure Ar-arcs. Additionally, there are some measurements for ArHe (98 % He), ArH_2 (8.6 % H_2) and ArN_2 (17.06 % N_2) with different arc lengths but only for one welding current.

Lin and Eagar [6] investigated the influence of the shielding gas composition on the arc pressure. Again the influence of different tip angles, arc lengths and welding current were examined for pure Ar-arcs. The influence of He-additions with different arc lengths was also analysed but just for one welding current and one tip angle.

These researches have produced knowledge about the behaviour of 100 % Ar arcs with different geometrical and welding parameters. But there are no comprehensive studies and therefore no extensive knowledge about the interactions between the shielding gas composition, the arc length and the welding current for gas mixtures. General tendencies for the welding parameter cannot be derived.

For the last years numerical simulation has been used for a better understanding of the cause-and-effect-chain in the

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arc. Different gas mixtures were analysed by Murphy [7-9] and Lowke [10]. The diffusion effects have one important influence on the arc properties. These effects were studied in [7] and [9]. With the help of these analyses the general arc behaviour regarding the stagnation pressure and the heat input can be simulated. However, it is unfavourable that all calculations are done for a fixed geometry and only one welding current. Additionally, these simulation results of the stagnation pressure and heat flux and current distribution were not validated or compared with experimental measurements. Therefore, there are uncertainties about the reliability of the results.

This paper presents a comprehensive study of the interaction between the process gas, the arc properties and also the weld pool. This shall support a systematic choice of the gas in practice.

The main part of the paper consists of an extensive study about the influence of He-additions to the process gas. Therefore measurements about the arc properties at the intersection between the arc and the weld pool (e.g. heat input and stagnation pressure) are presented in Section 2. Besides the variation of the He-quantity, the arc length and the welding current are also varied, because the former experimental analyses show a significant influence of these two parameters.

In Section 3 the common TIG-simulation models of Sansonnens *et al.* [11] and Lowke *et al.* [12, 13] are implemented and validated with the diagnostic results. Furthermore, a simplified contact resistance model is presented. This model is able to predict the stagnation pressure and total heat input especially for ArHe-mixtures. Thus, this model is subsequently used for sensitive analyses, which give an increased understanding of the influence of the He-additions on the arc properties.

In Section 4, the identified influences of the He-additions on the arc properties are applied in welding trials. Firstly, the weld penetration is investigated for varying He-contents, arc lengths and welding currents. Secondly, the advantage of He-additions is shown by determining the maximum welding speed for a weld seam without any visible irregularities (e.g. humping effects and penetration cut) depending on the shielding gas composition.

According to the analyses for ArHe-mixtures the influence of H_2- and N_2-additions are also summarized in Section 5. The conclusions are presented in Section 6.

2 Diagnostic analyses of ArHe-mixtures

The stagnation pressure and the total heat input are the two important measurable arc properties. They have an effect on both of the size and the deformation of the weld pool. Stagnation pressure measurements were done according to the principle of Lin and Eagar [6] and [14]. Thereby the arc is moving over a hole with a diameter of 0.5 mm in a water-cooled copper plate. The stagnation pressure is measured by a piezoresistive pressure sensor which is located at the backside of the copper plate. The electrical and heat flux density was measured with the help of the divided anode principle according to Nestor [4] and [14]. Thereby the arc is again moving over a gap of 0.1 mm between two water-cooled copper plates. While the arc is moving, the current as well as the temperature and the mass flow of the cooling water of both plates are measured depending on the arc position to the gap. With the help of the Abel inversion the measured data are converted in the radial electrical and heat flux density.

The tests were conducted with a lanthanide tungsten electrode (1.5 % La_2O_3+W) with a diameter of 3.2 mm and a tip angle of 30°. The process gases used included contents of 0, 15, 30, 50 and 70 % helium. Besides the shielding gas composition, the arc length (2 mm, 5 mm, 8 mm) and the welding current (100 A, 200 A and 300 A) were also varied.

The measurement of the stagnation pressure and the total heat input demonstrate a high reproducibility and clearly show tendencies depending on the process gas composition, whereas the electrical current as well as the heat flux density do not show significant tendencies. Thus, we use primarily the stagnation pressure and the total heat input for the interpretation of the shielding gas influence.

An increasing He-content in the shielding gas causes a decrease of the stagnation pressure and an increase of the total heat input, see Figure 1. It has to be emphasized, that the decrease of the stagnation pressure is proportional to the He-concentration of the gas.

Furthermore, the maximum of the electrical current density increases due to the He-additions. This gain does

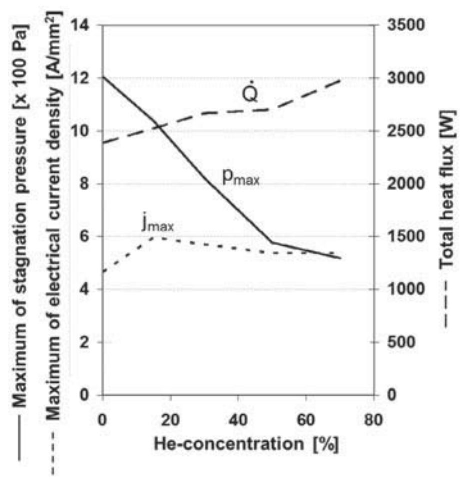


Figure 1 – Arc properties (max. stagnation pressure p_{max}, max. electrical current density j_{max} and total heat input $\dot{Q}$) for 200 A and an arc length of 5 mm and varying He-concentrations

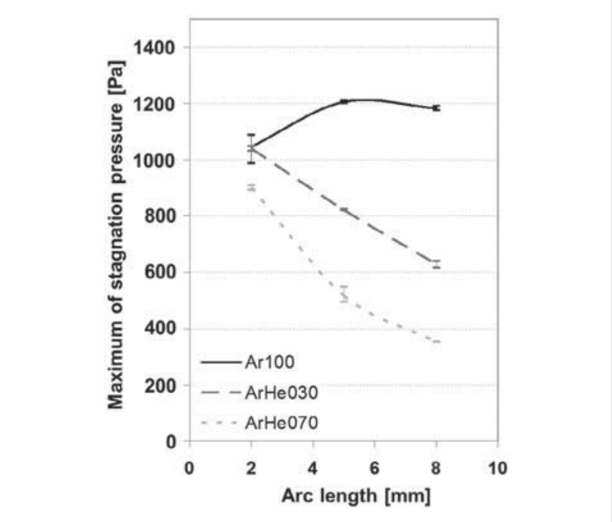


Figure 2 – Influence of the arc length on the maximum stagnation pressures for Ar 100 %, ArHe30 (with 30 % He) and ArHe70 (with 70 % He)

not depend on the percentage of He. Thus, the heat input and also the stagnation pressure can be chosen specifically to meet the welding task (e.g. material, sheet thickness, ...).

As mentioned above, the influence of different arc lengths as well as welding current on the arc properties is known to have a high significance. In Figure 2 the influence of the arc length is displayed. For pure Ar, there was measured a minimum of the stagnation pressure at 2 mm arc length. An increase of the distance between the electrode tip and the workpiece induces a gain from 10.5 mbar to 12 mbar.

Due to He-additions the stagnation pressure decreases. This effect increases according to the arc length: At 2 mm ArHe-arcs have similar pressures as pure Ar-arcs. But with an increase of the arc length the stagnation pressure decreases continuously. In contrast to the stagnation pressure, the heat input increases with the enlargement of the arc length. The heat input, as well as the stagnation pressure, increase with increasing welding currents.

3 Simulation model and sensitive analyses

In the previous chapter the principle behaviour of the arc was described depending on the gas composition. To get a better understanding of the cause-and-effect-chains between the gas composition and the arc properties sensitive analyses were used. Therefore, it is necessary to have a simulation model which represents arc properties and behaviour. Due to the non-melting electrode, TIG-models are relatively easy to simulate. In order to be able to describe the thermodynamic and transport properties of the plasma as functions of temperature, pressure and mixture, LTE-conditions are assumed for the arc column, which may lead to inaccurate results for pure He-arcs [15]. Hence in the later part of the paper only ArHe-mixtures were investigated.

However, the simulation of the sheath regions is more complicated due to the low temperatures near the electrodes. Therefore, the current transfer has to be realized due to the diffusion of the ions and electrons. In addition to diffusion there are also the electron emissions from the cathode and recombination processes which take place in these layers. There are two common approaches published, which models the processes in the sheath layers:

1. Consideration of the electron diffusion due to the ambipolar diffusion according to Sannsonnens, Haidar and Lowke [11, 12], considering a finite value for the electron density at the anode as proposed by [13].
2. Use of relatively large mesh sizes at the electrode surface using the 'LTE Diffusion approximation' [13].

Both approaches were tested in the present project. The calculated as well as the measured values for the stagnation pressures [a)] and the electrical current densities [b)] are compared in Figure 3.

The simulation results of pure Ar-arcs with a current of 200 A are within an acceptable range in both approaches. However, in this project gas mixtures of ArHe have also to be investigated. Considering this requirement, only the

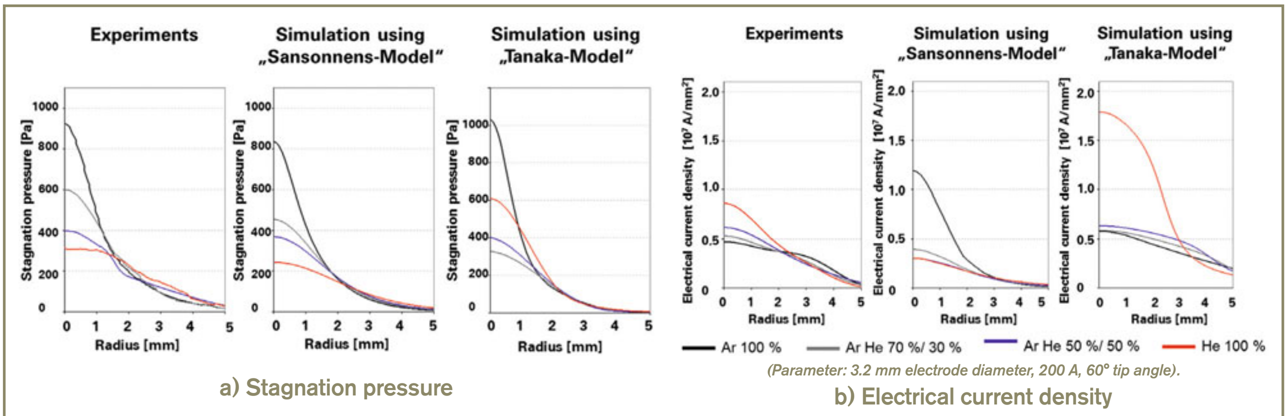


Figure 3 – Measured and calculated values for stagnation pressure and electrical current density for different shielding gases (Ar 100 %, ArHe 70/30 %, ArHe 50/50 %, He 100 %)

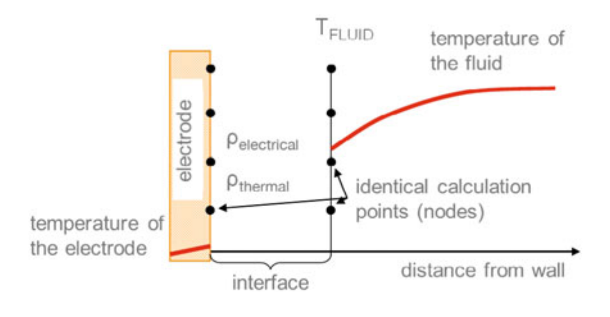


Figure 4 – Contact resistance model of the sheath layer for the electrical current and the heat transfer between the fluid and the workpiece

complex Sansonnens-model displays the measured stagnation pressure regarding the tendencies as well as the maxima. The electrical current density cannot be reproduced by either approach.

The named differences arise due to simplifications used in the respective models, namely the mesh size at the electrodes for the 'LTE-diffusion approximation' and plasma data like the 'electron-ion-cross-section' for the model according to Sansonnens. These values would need an increased effort to be adapted when carrying out calculations with different shielding gases, since the values given in [11, 13] where evaluated for pure Ar-arcs. In order to ease this effort a different approach was used, where the processes in the sheath layers are modelled as thermal and electrical contact resistances, Figure 4. The electrical resistance R_e characterizes the voltage drop in the sheath layer, which results from the decreased electrical conductivity in these regions. Additionally, a resistance regarding the heat transfer R_h is implemented which represents the temperature decline.

These resistances R_e and R_h follow the equation R = l / conductivity, where the conductivities are the

Table 1 – Values for l from 'resistance model'

	Ar 100 %	ArHe 30/70 %
Cathode	0.25 mm	0.075 mm
Anode	0.4 mm	1.17 mm

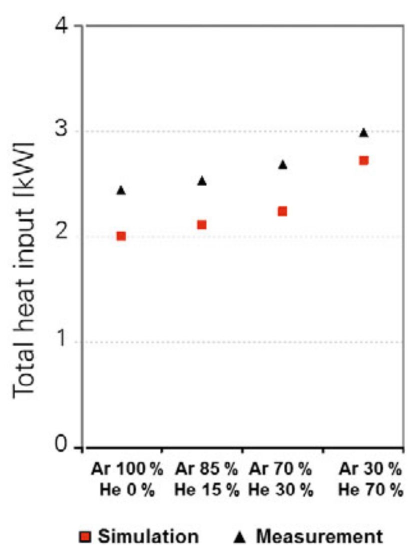
calculated material properties of the used gas mixtures assuming LTE. The parameter l is a length and can be interpreted as the distance from the electrode surface in which the resistance is effective, hence the assumed sheath length. In this work the parameter l has been fitted to experimental results for two different ArHe-mixtures, namely Ar 100 % and ArHe 70/30 %. For calculations using other ArHe-mixtures the parameter was inter-, respectively extrapolated linearly from the two fitted points. For consistency the same values of the parameter l have been used for R_e and R_h. The found values for l are summarized in Table 1.

With the help of these resistances a fine grid resolution can be used, where the grid resolution at the electrodes was about 0.01 mm. Therefore, the heat transfer between the fluid and the workpiece is displayed sufficiently.

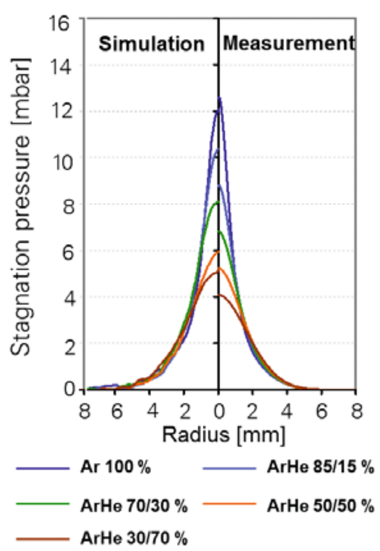
Also, the tendencies and maxima of the stagnation pressure show satisfactory results for the different ArHe-mixtures, Figure 5. Hence, this model is used for further analyses, e.g. sensitive analyses, which shall increase the understanding of the influence.

First numerical investigations are presented for pure Ar and also for a gas mixture containing 70 % He, Figure 6. In each illustration the flow velocity (left) and the temperature distribution (right) in the arc are displayed.

There are significant differences in the flow profile. He-additions cause a broadening of the flow profile and temperature distribution as well as a decrease of the

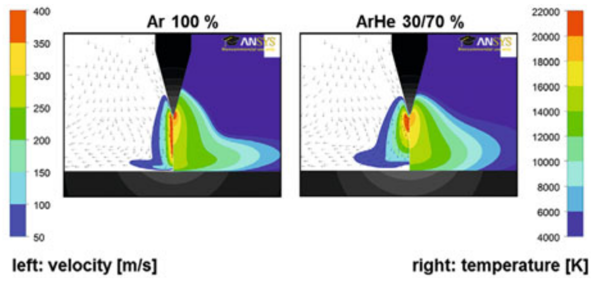


a) Total heat input



b) Stagnation pressure

Figure 5 – Comparison of measured and calculated values for developed contact resistance model



(200 A, 5 mm arc length, 3.2 mm electrode diameter, 30° tip angle).

a) Ar 100 % b) ArHe 30/70 %

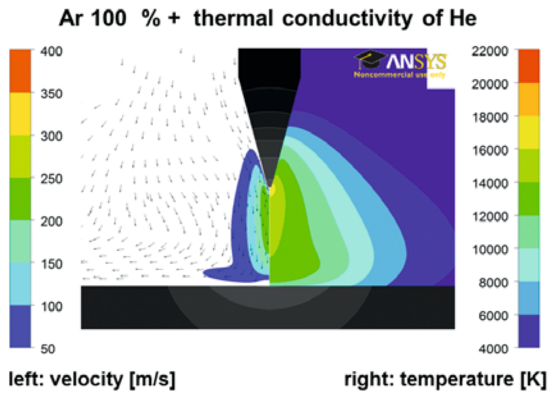
Figure 6 – Numerical modelling

fluid velocity and the fluid temperature. Due to the minor velocity inside ArHe-arcs the decrease of the stagnation pressure can be explained, but with these investigations, it is not possible to explain the reasons for the effects of He-additions.

To understand these mechanisms sensitive analyses are done. In these analyses an arc with Ar-properties is used as basic gas and just one physical property is used from He. This is a method which is made possible by using numerical simulation, but it enhances the systematic investigation in the influence of each material property.

The decrease of the stagnation pressure by He-additions is mainly caused by the gas properties: viscosity, thermal conductivity and density. However, the electrical and the higher thermal conductivity, as well as the lower radiation emission, excite the increased heat input. All material properties are depending on the temperature. Figure 7 displays the thermal conductivity and viscosity for different ArHe-mixtures. It is obviously that the thermal conductivity is increased significantly by the addition of He. Concerning the viscosity there is an increase for He-containing gases for temperatures above 11 000 K.

As a result of the increased thermal conductivity a heat transfer in the outer regions of the arc occurs. Therefore, the maximum temperature decreases, but the temperature distribution is broadened, Figure 8.



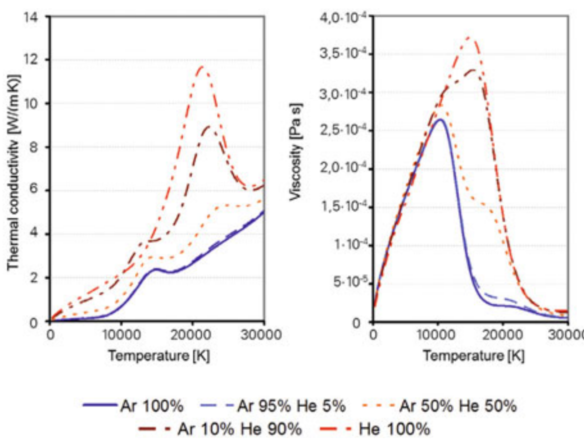
(200 A, 5 mm arc length, 3.2 mm electrode diameter, 30° tip angle).

Figure 8 – Influence of thermal conductivity of He on flow velocity (left) and temperature (right)

Additionally, the heat transfer in the workpiece is enhanced, so the temperature of the workpiece rises. Due to the lower arc temperatures, the current has to be conducted across an expanded area, so a decrease of the current density and thereby of the Lorentz-force is caused. Hence, the acceleration of the flow is lowered, which induces the decreased flow velocity.

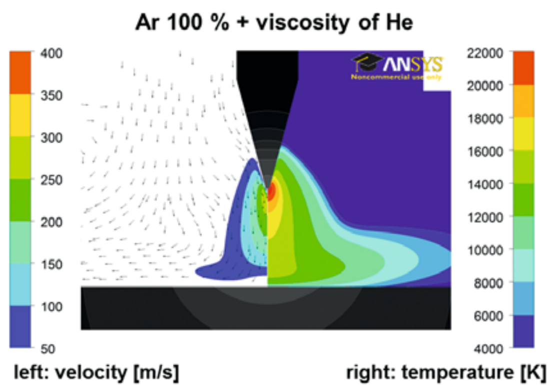
The higher viscosity of He at temperatures above 11 000 K is important for the fluid flow inside the arc, Figure 9. Due to the increased viscosity the flow is decelerated and the fluid velocity decreases. Therefore the flow profile is broadened but flat. At the workpiece, the velocity of the fluid flow and, hence, the stagnation pressure are lower.

Based on the already described analyses it is obvious that He-additions cause an increase of the heat input. The stagnation pressure depends on the arc length: for low arc lengths the pressure corresponds to the pressure for pure Ar-arcs. An enlargement of the arc length results in a decrease of the stagnation pressure.



a) Thermal conductivity b) Viscosity

Figure 7 – Thermal conductivity and viscosity for ArHe-mixtures [7]



(200 A, 5 mm arc length, 3.2 mm electrode diameter, 30° tip angle)

Figure 9 – Influence of viscosity of Heon flow velocity (left) and temperature (right)

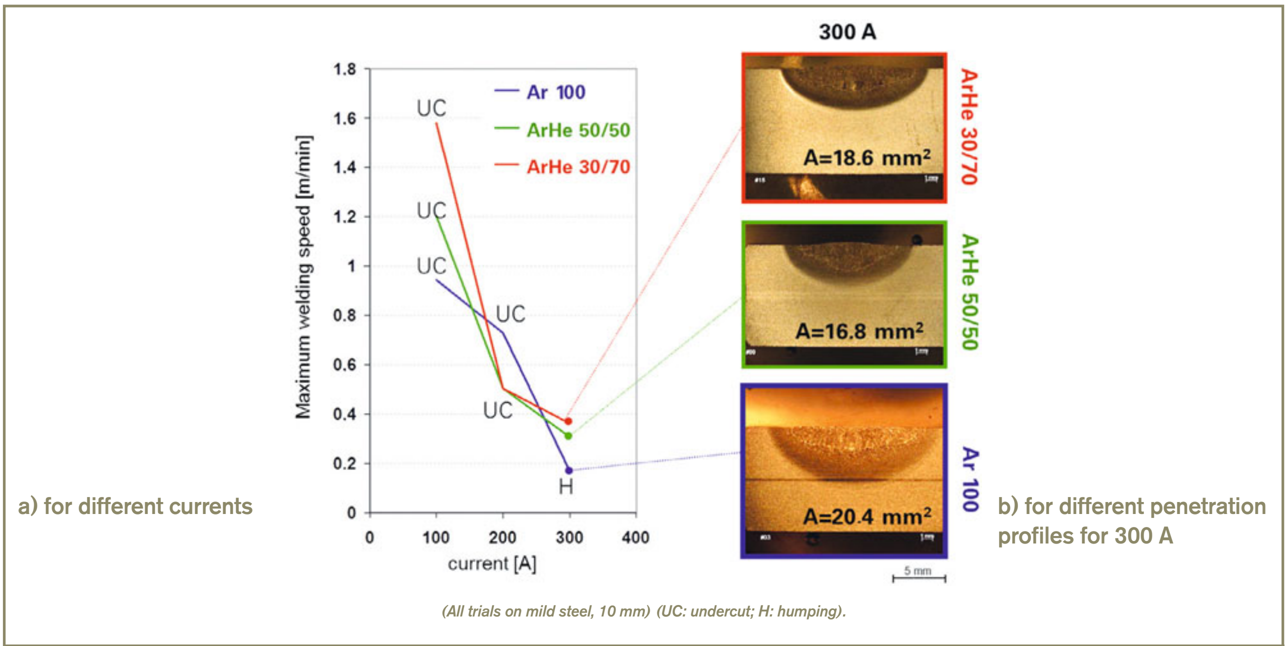


Figure 10 – Maximum welding speed for Ar 100 %, ArHe 70/30 % and ArHe 30/70 %

4 Practical application

In this chapter suggestions will be given for a purposeful selection of the gas mixture according to the welding task. He-additions cause an increase of the width and of the depth of penetration due to the higher heat transfer and the thereby caused heat thermal conduction. With an arc length of 2 mm the penetration depth is deeper than that with higher arc length. It has to be assumed that this effect is caused by the increased stagnation pressure.

One possibility to use these specific properties of He is the increase of the welding speed. Figure 10 summarizes the maximum welding speed for different ArHe-mixtures and currents.

Due to the higher heat transfer into the workpiece, the welding speed can be increased without welding irregularities. Figure 10 shows that there is a significant increase for the maximum welding speed for 100 and 300 A just because of the use of ArHe-mixtures. At 100 and 200 A undercuts are the limiting irregularities, for 300 A humping effects occur for further increasing of the welding speed. In the polished cross-sections, it can be seen that the doubling of the welding speed from Ar 100 % (0.18 m/min) to ArHe 30/70 % (0.38 m/min) induces almost constant penetration areas although the energy input unit per length was halved.

5 Influence of H_2 - and N_2 -additions

First, the non-inert gas compositions H_2 and N_2 are used in contrast to the inert gas He, mostly because of metallurgical reasons. Secondly, they also have an influence on the arc properties because of their thermophysical properties. Diagnostic investigations were done for H_2 (2 %, 5 % and 10 %) as well as for N_2 (2 %). Both gas additions cause an increase of the heat input and, in contrast to He-addition, also an increase of the stagnation pressure. With the help of sensitive analyses the importance of the viscosity and the thermal and electrical conductivity on the stagnation pressure is indicated. The viscosity of H_2 is less compared to Ar. Therefore, the fluid flow is not decelerated as much as for Ar and so, an increase of the fluid velocity and stagnation pressure occurs. The thermal conductivity is higher than for Ar. The behaviour of this property of H_2 is similar to the behaviour of He. This is the reason for the higher heat input into the workpiece.

These arc properties can be used again to increase the weld pool. First investigations are summarized in Figure 11. It has to be emphasized that 5 % H_2-addition causes similar weld depths and widths to those with 70 % He-addition. For higher arc lengths, where ArHe-gases have lower stagnation pressures, ArH_2 have a deeper penetration. This point proves again the influence of the stagnation pressure on the formation of the penetration.

6 Summary and conclusions

This paper presents investigations into the influence of the process gases on the arc properties, e.g. the stagnation pressure and the heat input. The work was done using diagnostic methods, numerical simulation and welding trials. The results can be summarized as follows:

1. He-, H_2- and N_2-additions cause an increased heat input into the workpiece.

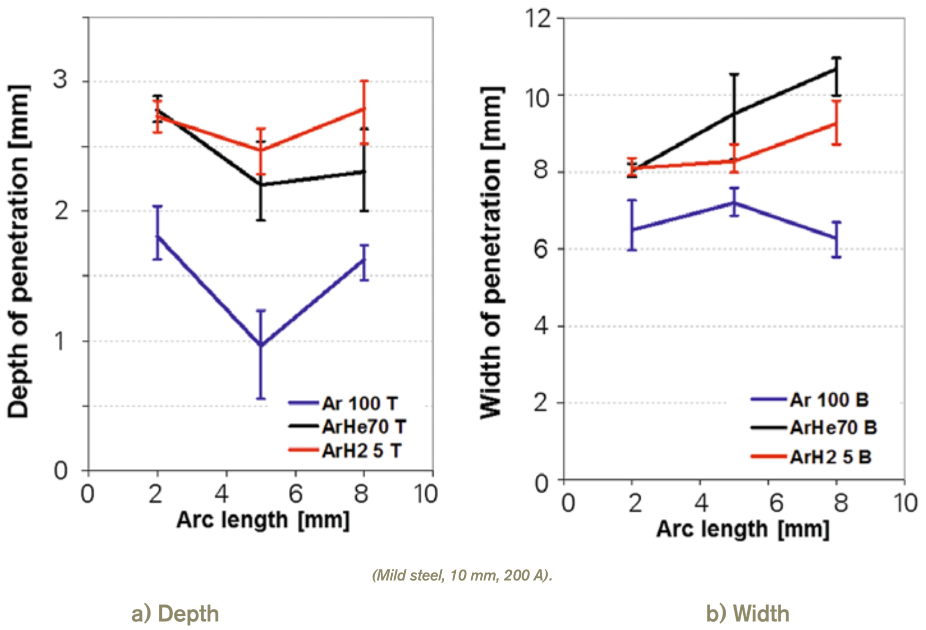


Figure 11 – Depth and width of penetration

2. H_2-additions especially have a high influence also with small concentrations.
3. H_2- and N_2-additions cause an increase in stagnation pressure, compared to pure Ar-arcs, whereby He-additions cause a decrease.
4. The influence of He-additions on the stagnation pressure depends on the arc length: for small arc lengths a pressure similar to pure Ar is existent, while the stagnation pressure decreases for higher arc lengths. The decrease depends on the He-content of the gas mixture.

These results can assist the choice of the gas mixture in practice and allow a suitable adjustment of the process parameters. Besides the metallurgical constrictions, one should consider the influence of the arc on the formation of the weld pool, whereby the welding speed or the penetration depth can be increased. An increase of heat input can be achieved by using He-, H_{2-} as well as N_2-additions. Furthermore, the stagnation pressure can be adjusted. He-additions can be used for the welding of materials with a low viscosity to lower the risk of humping effects especially with high arc lengths. An increase of the stagnation pressure can cause an enlargement of the weld pool depth. Therefore, H_2- and N_2-additions with small arc lengths are usable.

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