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RESEARCH PAPERS

JUKKA MARTIKAINEN

ON THE EFFECTS OF WELDING PARAMETERS ON WELD QUALITY OF PLASMA ARC KEYHOLE WELDING OF STRUCTURAL STEELS

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ABSTRACT

The possibility and the usefulness of applying plasma keyhole welding to structural steels with different compositions and material thicknesses, and in various welding positions has been examinated. Single pass butt welding with I-groove in flat, horizontal-vertical and vertical positions and root welding with V-, Y- and U-grooves of thick plate material in flat position have been studied and the welds with high quality has been obtained.

The technological conditions for successful welding are presented. The single and interactive effects of welding parameters on weld quality, especially on surface weld defects, geometrical form errors, internal defects and mechanical properties (strength, ductility, impact toughness, hardness and bendability) of weld joint, are presented. Welding parameter combinations providing the best quality welds are also presented.

PREFACE

This study has been carried out between 1985 and 1988 in the Department of Mechanical Engineering of Lappeenranta University of Technology.

I would like to thank Professor Tapani Moisio for suggesting this interesting and practically relevant research topic and for his positive interest in my work, and for constructive discussions.

I would also like to thank all the persons who have helped me with this study, especially Mr Antti Heikkinen and Mr Esko Reinikainen for their contributions during the experimental work. Further, I am grateful to Mr Markku Ala-Outinen, Mr Pekka Nevasmaa and Mr Kyösti Nokka for preliminary experimental work. Thanks are due Dr David Porter for correcting my English.

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Lappeenranta, December 1989

Jukka Martikainen

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

A	cross sectional area of plasma gas flow, mm^2 (Eq. 3)
Ar	argon gas
A_5	elongation, short proportional test specimen (tensile test), %
B	weld width, mm
BM	base material
c	crack in specimen
CO_2	carbon dioxide gas
d_o	diameter of keyhole crater outlet, mm
d_n	nozzle diameter, mm
D_p	pressure spot diameter, mm
D_{cr}	pool crater diameter, mm
E	energy required to vaporise 1 kg of the workpiece (Eq. 3)
EB	Electron Beam
f	failure in specimen
fl	flaw in specimen
Fe 37B	unalloyed structural steel, quality grade B,
FL	fusion line
Fo	nitrogen-12 % hydrogen mixing gas
g	acceleration due to gravity, m/s^2 (Eq. 4)
h_c	height of the column of liquid metal, mm (Eq. 4)
h_{rf}	height of root face, mm
HAZ	heat-affected zone
HV10	Vickers hardness with 98.1 N (10 kp) intending load
I	welding current, A
IIW	International Institute of Welding
KV 5/^{0}C	Charpy V-notch impact test, width of test specimen/test temperature, J
l	distance from nozzle to workpiece, mm
LB	Laser Beam

MIG/MAG	Metal Inert Gas/Metal Activ Gas welding
NDT	Nondestructive Testing
N_2	nitrogen gas
OK Autrod xx.xx	filler material wire
OK Flux xx.xx	powder in Submerged Arc Welding
OX-xxx-x	quenched and tempered high strength microalloyed steel
p_b	parameter in equation (1)
p_r	parameter in equation (1)
p_v	parameter in equation (1)
p_g	parameter in equation (1)
p_γ	parameter in equation (1)
P	power of plasma jet, kW (Eq. 3)
PC A	unalloyed shipbuilding steel, grade A, in accordance with Register of Shipping of the USSR
Q	welding energy
Q_{pg}	flow rate of plasma gas, l/min
Q_{sg}	flow rate of shielding gas, l/min
Q_{bg}	flow rate of backing gas, l/min
r	radius of keyhole, mm (Eq. 5)
R	root of weld
RAEX xxx, RAEX HSF xxx	high strength microalloyed and strong formable microalloyed steel
R_{eH}	upper yield stress, MPa
R_m	ultimate tensile strength, MPa
S	surface of weld
SAW	Submerged Arc Welding
SFS	Finnish Standards Association
SH5	argon-5 % hydrogen mixing gas
SH10	argon-10 % hydrogen mixing gas
SK20	argon-20 % carbon dioxide mixing gas
t	material thickness, mm
T	temperature, K, ^{0}C

TIG	Tungsten Inert Gas welding
v	welding speed, cm/min
v_f	feeding rate of filler wire
W	weld
WA, WB, WC, WD	
	weld classes by standard SFS 2379(1983)
Z	reduction of area (tensile test), %

α	angle of groove, angular distortion, ^{0}
ρ_m	density of metal, kg/m^3 (Eq. 4)
ρ_{pg}	density of plasma gas (Eq. 2)
$\rho_{pg, v}$	vapour density of plasma gas (Eq. 3)
γ	surface tension, N/m (Eq. 5)
Ø	diameter of filler material wire, nozzle diameter, mm

1. INTRODUCTION

In welding, as well as in other industrial activities, quality, productivity and economy improvements are crucial for survival. In practice these factors are nearly always interconnected. New welding methods and new applications of conventional methods create the necessary conditions for making high quality products economically. With this in mind plasma arc welding, especially in the keyhole mode, has been studied and developed for structural steels.

Plasma arc welding is a welding method that can be classified together with conventional gas shielded arc welding methods like TIG and MIG/MAG welding or high power density welding methods like electron beam (EB) and laser beam (LB) welding, according to whether fusion or keyhole modes are employed. Generally plasma arc welding has been regarded as a constricted form of TIG welding. Plasma arc fusion welding is very similar to conventional TIG welding in the sense that the plasma jet is used as a source of intense heat to melt the material to be welded. Plasma arc keyhole welding (later in the text is used the shorter form 'plasma keyhole welding') is a combination of plasma arc fusion welding and plasma arc cutting. In this mode of process the arc power density is essentially higher than in those common TIG and MIG/MAG processes or in the plasma arc fusion process, and so keyhole welding is possible. Plasma arc welding in keyhole mode is always mechanized or automated because of difficulties in manually maintaining a consistent welding speed, torch position, gas protection, filler material addition etc.

In industrial fabrication plasma arc welding is used successfully for welding high alloyed steels and titanium and its alloys. The melts of unalloyed and low alloyed structural steels differ from the melts of high-alloyed steels and titanium in that they have a significantly lower viscosity and lower surface tension, such that control of keyhole stability and the weld pool is difficult (Drews and Böhme, 1975). When the keyhole is achieved, it must be maintained and it doesn't close. The melt must be held together. In keyhole welding the final quality of the weld depends directly on the keyhole stability which itself depends on a large number of different factors, especially the welding parameters.

Some research workers, Drews and Böhme (1975), Böhme (1977), Larue and Thomsen (1980), Messager and Cuny (1982), Engfeldt and Fager (1984), Nielsen (1984), Cuny (1986), Moisio (1986) and Bakarjiev and Varbenova (1987), have shown by single experiments that even structural steel can be welded in a flat position without weld defects using the plasma keyhole technique, but the plasma welding conditions have not been systemised. The qualities of the welds have been very variable and the welding has been unreliable. The single and interactive effects of welding parameters on weld quality have not been precisely elucidated. It has been said that the plasma keyhole welding of structural steels in horizontal-vertical and vertical positions is quite impossible.

The most important limitations of plasma keyhole welding lie in the need for close control of the welding parameters to maintain the keyhole and, when required, the difficulty of feeding filler material into the keyhole without disturbing its stability. Because of its unreliability and lack of knowledge the use of plasma keyhole welding has been relatively uncommon in the industrial welding of structural steels.

2. KEYHOLING IN PLASMA ARC WELDING

2.1 The invention of plasma

A plasma - the fourth state of matter - is a gas which has been heated to a condition where it is at least partially ionised and is therefore capable of conducting an electric current. The ionised plasma column consists of positively charged atoms (ions), an essentially equal number of electrons together with neutral atoms or molecules.

Plasma like invention was mentioned in the early 1900's for iron ore treatment and high intensity arc development. Plasma use as a heat source was described by E.Mathers in a 1911 patent. In the 1920's, I.Langmuir carried out theoretical research on the process and is credited with calling the process plasma. In the middle of 1950's in the United States, R.Gage from Union Carbide (Linde) discovered that the properties of an open arc, i.e. TIG welding arc, could be considerably altered by constricting the arc. Further research and development indicated that the plasma column could be adapted for welding and so the plasma arc welding, first in fusion mode, was devised for the first time in 1956. Since then, the process has been constantly developed for e.g. in West Germany, France, Japan, Sweden and the USSR.

2.2 The utilization of plasma in connection with welding

For welding plasma is produced by an electric arc passing through a gas separating two electrodes. Arc heat ionizes some of the gas molecules to produce a plasma stream of positively charged atoms, electrons, and neutral atoms or molecules. Forcing the arc through a small orifice and consricting the jet between electrode and workpiece increases the level of ionization and concentrates the heat. Arc temperatures in the range of 14000 to 27000 ^{0}C are typical. Constriction also stabilizes the plasma jet, making it less likely to be warped by e.g. misalignment and magnetic fields.

A plasma torch has nozzle gas (i.e. plasma gas) flowing so as to surround the electrode. There the gas ionizes to form the plasma jet. The characteristics of the plasma jet can be altered greatly by changing the gas type, flow rate, arc current and nozzle shape and size. Another flow of gas, the shielding gas, comes down through an outer gas cup. The electrode is recessed within the nozzle, and the arc is aligned and focused on the workpiece as it passes through the orifice. The welding is possible to perform with or without backing gas, but the use of backing gas makes the welding often more reliable. The construction of the plasma arc torch is shown schematically in Fig. 1.

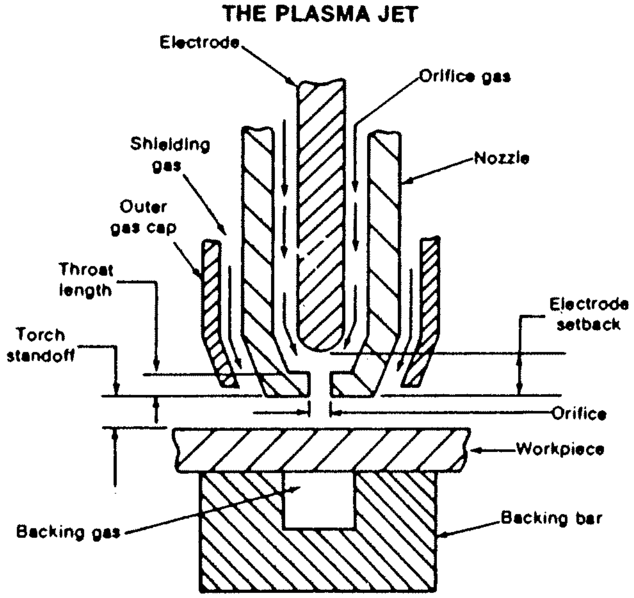


Fig. 1. The construction of the plasma arc torch in plasma arc process. The electrode strikes an arc that heats the orifice gas enough to ionize it, forming a plasma. The nozzle constricts the jet stream, focusing the heat on the workpiece.

Plasma occurs in all welding arcs to varying degrees. In plasma arc welding the plasma arises after a series of events:

* Inert gas passes through the torch.
* High frequency arc is generated between the electrode (cathode) and torch nozzle (anode). The high frequency breaks down the air insulation between the electrode and workpiece.
* The low-current pilot is fired, providing an ionized path from the electrode to the workpiece.
* A plasma current is generated.

This sequence of steps provides the ionized path to the workpiece for the plasma current. Without the pilot arc, the current could arc from the electrode to the nozzle, causing extensive torch damage.

2.3 The conditions for keyhole welding

In keyhole welding the penetration is deep and narrow. Keyhole welding is generally used when making single-pass welds requiring increased and 100 % penetration , narrower weld beads, a minimized heat-affected zone (HAZ) and minimal distortions. Besides these the advantages of the keyhole mode of welding are an increased possibility using an I-groove, less need for filler material, and most importantly the quality, productivity and economy of the welding.

Keyhole welding is possible if the power density of the arc is at about 10^{10} W/m^2 or more. Figure 2 shows the ranges of power density employed in conventional arc welding and the various high power density processes (EB, LB and plasma). The relative importance of the various thermal processes change with power density to produce marked differences in behaviour. Four regions can be identified:

* Power density over 10^{13} W/m^2; vaporisation is faster than conduction of heat, welding is impossible.
* Power density between 10^{10} W/m^2 and 10^{13} W/m^2; vaporisation and conduction are present, keyhole welding is possible.
* Power density between about $3x10^6$ W/m^2 and 10^{10} W/m^2; conduction is dominating, fusion welding is possible.
* Power density lower than $3x10^6$ W/m^2; there is insufficient melting because of high conduction of heat, welding is impossible.

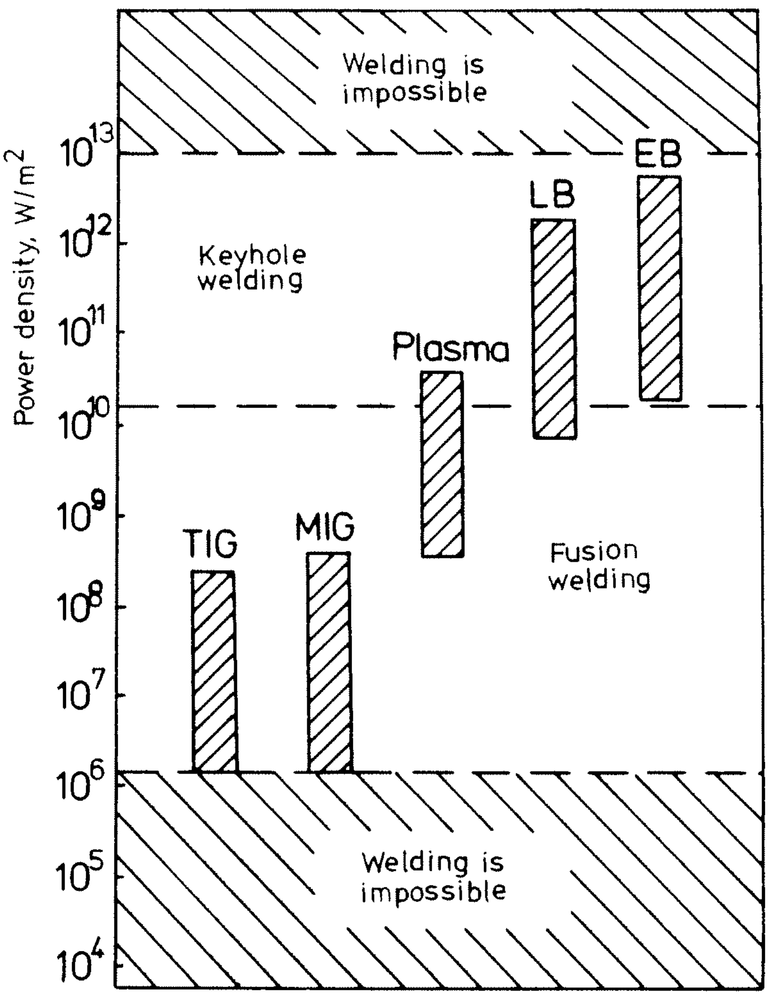


Fig. 2. Power density for various welding processes (Quigley, 1984).

When the power density is between 10^{10} and 10^{13} W/m^2 (keyhole region) the relative importance of conduction and vaporisation depend on the power and spot size, but they are both present to a considerable extent. According to Quigley (1984) in plasma arc welding the power density is of the order of 10^9 W/m^2 to 3 x 10^{10} W/m^2. In the lower part of this region welding occurs in a fusion mode, and in the upper part in a keyhole mode.

2.4 The keyhole in plasma welding

The great heat and the force of the plasma jet produces a keyhole effect - the arc passes completely through the workpiece, making a hole. As the torch moves, molten metal flows in and solidifies behind the keyhole to solidify, forming the weld bead.

In plasma keyhole welding a high velocity gas strikes the workpiece over an area of a few mm^2. A typical plasma keyhole in 6 mm structural steel is about 3.5 mm wide at the top and about 1,5 mm wide at the bottom end (Fig. 3 and 4). Plasma welding is a more diffuse process than electron beam or laser beam processes and the keyholes are thereby much wider than produced by those processes.

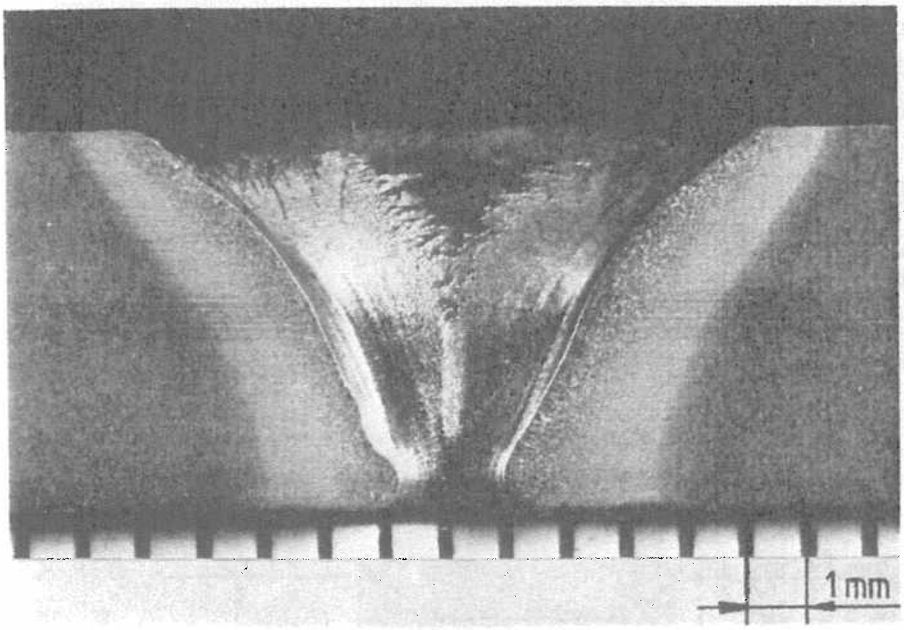


Fig. 3. The plasma keyhole in 6 mm structural steel. The width of the keyhole is 3,5 mm at the top and 1,5 mm at the bottom.

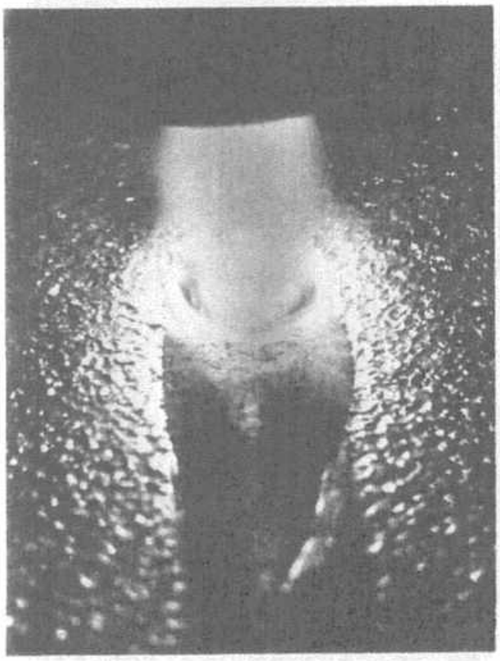


Fig. 4. The plasma arc and the keyhole looking from the top. The keyhole is 3,5 mm wide at the top (Moisio, 1984, not published).

The forces affecting the keyhole and its stability can be classified to two groups: forces tending to form and maintain the keyhole and forces tending to close the keyhole. The forces tending to form and maintain the keyhole in plasma keyhole welding are beam pressure (p_b), recoil pressure (p_r) and vapour pressure (p_v). Forces tending to close the keyhole are gravitational pressure (p_g) and surface tension pressure (p_γ). These pressure forces are illustrated in Fig. 5 for a closed keyhole condition.

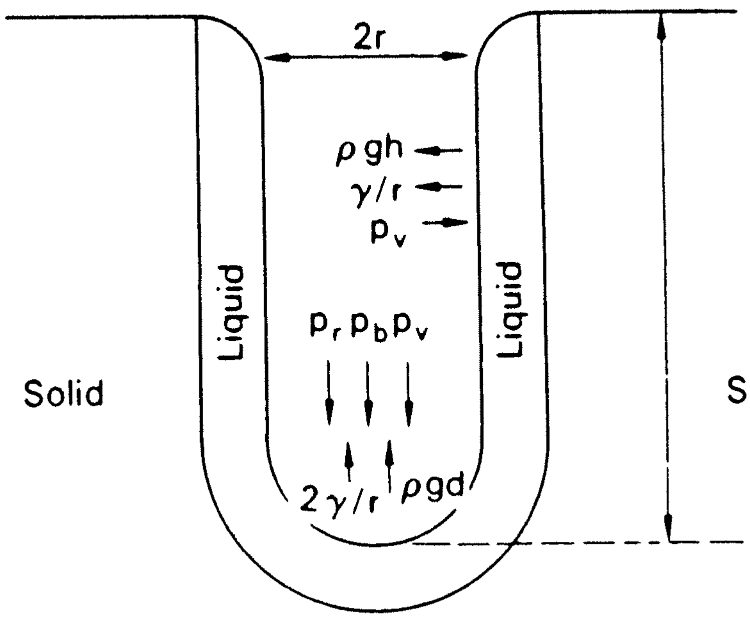


Fig.5. The pressure forces in a closed keyhole (Quigley, 1984).

Beam pressure (p_b) is caused by the impact of plasma gas against workpiece. The axial force of the plasma jet caused by beam pressure increases when the welding current rises. This is due to the increased flow rate of plasma in the nozzle.

Recoil pressure (p_r) is exerted on the workpiece due to the velocities of the evaporating particles leaving the surface. This will act in the same direction as the beam pressure and will tend to deepen a closed keyhole and maintain an opened keyhole. Vapour pressure (p_v) is due to vaporisation of metal on the bottom of the opened keyhole, where the weld pool temperature is at its highest. The vapour pressure tends to push the walls of the keyhole open.

Gravitational pressure (p_g) at any point in the liquid surrounding the keyhole is directly proportional to the density and height of the metal above it. Surface tension pressure (p_γ) tends to minimise the surface area of the liquid and close the keyhole if the material thickness is greater than the keyhole diameter. If the material thickness is thinner than the keyhole diameter, surface tension tends to pull the molten metal back to the parent material, overcoming the force tending to close the keyhole and so producing a cut.

According to Quigley (1984) the balance between pressure forces may be written:

$$p_b + p_r + p_v = p_g + p_\gamma , \qquad (1)$$

where

$$p_b = 1/2 \times \rho_{pg}(T) \times Q^2_{pg} , \qquad (2)$$
$$p_r = P^2 / A^2 \times \rho_{pg,v} \times E^2 , \qquad (3)$$
$$p_v = \rho_m \times g \times h_c , \qquad (4)$$
$$p_\gamma = 2 \times \gamma / r . \qquad (5)$$

In Eq. (2) to (5)

ρ_{pg} = density of the plasma gas
T = temperature
Q_{pg} = flow rate of the plasma gas
P = power of the plasma jet

A = cross-sectional area of the plasma gas flow
(P/A = power density)
$\rho_{pg,v}$ = vapour density of plasma gas
E = energy required to vaporise 1 kg of the workpiece
ρ_m = density of the metal
h_c = height of the column of liquid metal
γ = surface tension
r = radius of keyhole

As seen in Eq. (1)...(5) the high beam pressure (p_b), recoil pressure (p_r) and vapour pressure (p_v) increase the depth of the keyhole, or in other words high power densities with associated high pool temperatures and vapour pressures lead to the greatest weld penetrations.

The keyhole is produced in plasma arc keyhole welding mainly by the pressure of the impinging gas and by the high concentration of heat input. The effect of vaporisation is not dominant, however the vapour pressure has a significant effect on the plasma welding process as compared with conventional TIG welding. The welding parameters must be carefully balanced to maintain the stability of the keyhole and the weld pool. Instabilities can easily result in weld defects such as excessive penetration, lack of penetration and undercutting.

The mentioned balance does not take into account the fact that the workpiece is moving, resulting in decreased pool temperature and size, and hence decreased vapour pressure. Another effect of the workpiece motion is to cause the geometry to be non-cylindrical and introduce instabilities which may cause closure of the keyhole before maximum penetration has been achieved.

3. WELDING PARAMETERS IN PLASMA WELDING

Plasma keyhole welding is characterised by a large number of welding parameters. The most important welding parameters are:

- welding current
- welding gases (incl. plasma, shielding and backing gases)
- welding speed.

The combinations of these parameters have essential effects on the weld quality of plasma welding. On the practical side such parameters as the torch design, the location of the nozzle, groove preparation, weld joint design, joint fixtering and tolerances also have important influences on the success of welding. Base material and filler material must also be taken into account, of course.

The weld pool of structural steels is very fluid (low viscosity and low surface tension) and therefore particular consideration must be given to the risk of weld defects. Because of many welding parameters and material characteristics, the control of plasma keyhole welding in the case of structural steels must be closer than when welding with conventional methods or when welding highly alloyed stainless steels or titanium for example.

In the following the results of previous studies of the plasma keyhole welding of structural steels concerning the effects of welding parameters on weld quality are presented.

3.1 Welding current

In plasma welding the welding current together with nozzle gas (later plasma gas) produces the fourth state of matter - plasma. When a current is passed between two electrodes through a gas, the gas molecules accelerate and collide with each other. As the energy increases, it exceeds the binding force between the atom nucleus and electrons. The electrons are released from the nucleus. The gas now consists of neutral molecules, positively charged atoms and negative electrons. The gas is now ionized, capable of conducting current.

The welding current affects weld quality through the arc pressure and the arc temperature. Studies by Bethlehem (1987) and ME Technical Report (1986) show that increased welding current widens the weld on both the surface and root sides. An inadequate current level causes lack of penetration and slight undercutting in the toe area of the weld. Excessive current levels cause electrode damage either immediately in the starting stage of welding or later.

In plasma keyhole welding the welding current is over 100 A, typically 200...300 A, and the corresponding material thicknesses about 3...8 mm in a single pass. To prevent the formation of a so-called dual arc and destruction of the nozzle, the welding current needs to be restricted to below about 500 A.

3.2 Welding gases

The selection of plasma and shielding gases and their flow rates are critical to the success of the welding. In many applications backing gas is also necessary. The effects of the welding gases on the welding process are interconnected. The choice and combinations of these gases affect the results, particularly bead width, melted zone shape and welding speed.

Plasma gas and its flow rate has essential and direct effects through the plasma jet on the results of welding. Pure argon and mixtures based on argon and hydrogen are used as plasma gas. Argon is a preferred and reliable plasma gas, but it does not necessarily produce optimum results for all cases. The addition of small amounts of hydrogen (about 5 %) to the argon is sometimes recommended [Böhme (1977), Nielsen (1984), Cuny (1986) and Moisio (1986)]. Argon-hydrogen mixtures provide a higher power density with a hotter arc, assisting in both penetration and weld-puddle fluidity. A too low plasma gas flow rate causes electrode damage and lack of penetration. Porosity in welds and undercutting are a result of too high a plasma gas flow rate.

The shielding gas, in addition to protecting the molten metal, penetrates into the plasma stream, and depending on its physical properties, affects arc and weld properties. Argon and mixtures of argon and hydrogen are used for shielding gases, as are mixtures of argon and carbon dioxide.

Backing gas, the shielding gas of the weld root area, is necessary in most cases [Böhme and Drews (1975), Engfeldt and Fager (1984) and Nielsen (1984)]. This is particularly important to ensure uniform solidification of high fluid materials like structural steels. Argon is used as backing gas.

Drews and Böhme (1975) used a separate focusing gas (a separate gas situated between the plasma jet and the shielding gas) and found that the addition of hydrogen to the argon focusing gas is suitable. At higher welding speeds undercutting was avoided and a smoother weld surface was achieved.

For material thicknesses of 3 and 4 mm, Larue and Thomsen (1980) found that it is impossible to obtain butt welds with both regular penetration and a smooth and uniform appearance when using argon as plasma and shielding gas. The best results were obtained by using argon-5 % hydrogen for the plasma gas and argon-20 % carbon dioxide for the shielding gas. For thicknesses of 6 mm argon is suitable both as plasma and shielding gases.

Nielsen (1984) recommends that with pure argon as plasma and shielding gas both Si and Al de-oxidized structural steels can be welded without weld defects. By Nielsen, with 3,5 % hydrogen in the plasma gas there is little difference to pure argon, but with 7 % hydrogen in plasma gas the weld pool is unstable and it is very difficult to achieve a stable keyhole without burning through. With 3,5 % hydrogen in the shielding gas the weld pool is a little more unstable than with pure argon, and with 7 % hydrogen in the shielding gas the weld pool is very unstable and there is local porosity. With 20 % carbon dioxide in the shielding gas the weld pool is a little unstable but there is no porosity. With hydrogen in the plasma gas and carbon dioxide in the shielding gas the weld pool is very unstable, and it is difficult to get a stable keyhole without burn through, there are many pores and a high tendency for undercutting and sagging.

Studies by Cuny (1986) show that with argon-5 % hydrogen plasma gas and argon-20 % carbon dioxide shielding gas pore formation is prevented and there is a smoother surface and less tendency to undercutting than with pure argon gas.

By Moisio (1986) the chemistry of welding gases and the method of deoxidation of base metal affect the behaviour of the weld pool. In deoxidized steels aluminium occurs mainly as a high melting oxides. It forms a solid slag film on top of the solidifying weld. The surface tension between the slag film and the melt makes bulges to form on the weld bead. Besides this, according to Moisio, in calsium-silicon treated silicon-aluminium deoxidized steels, aluminium exists as a low melting aluminates and slag on top of the melt forms droplets on the solidifying weld. The surface is smooth. The choice of plasma gas has a detrimental effect on the weld quality.

3.3 Welding speed

The optimum welding speed is determinated by other welding parameters, like welding current, type of plasma gas and gas flow rate. If welding speed is too high in relation to the other parameters, especially to welding current, undercutting and lack of penetration occur. With regard to welding economy it is sensible to weld as fast as possible.

3.4 Other parameters

Welding current, welding gases and welding speed have important effects on the weld quality, but other parameters must also be taken into consideration to fully optimize weld quality.

Nozzle dimensions, shape and constriction affect the nature of plasma jet and thereby also the welding process. With mechanical constriction of the arc, the keyhole is only steady for currents less than 250 A. Above this the outer layers of cold gas that normally isolate the plasma from the nozzle are destroyed and there are erratic double arcs.

Using pneumatic constriction avoids this problem and allows the use of plasma arcs of up to 500 A without any instability or nozzle erosion. Such currents which are impossible to obtain with mechanical constriction, are necessary for welding structural steels because of their high thermal conductivity, [Messager and Cuny (1982)].

Larue and Thomsen (1980) recommend that the mechanical constriction of the plasma gives a very confined arc (precious for position welding), but limited in intensity to about 200...250 A. The pneumatic constriction of the plasma allows an increase of the arc power and an increase of the thicknesses that can be welded.

The investigations by Sosnin (1988) show that an increase of the concentration of heat input in plasma welding is possible especially with an increasing I/d_n ratio. However, to prevent the formation of a dual arc, it is necessary to restrict the current. Reliable welding is ensured at

$$d_n = 1 + 0{,}01 \times I, \qquad (6)$$

where
d_n = nozzle diameter, mm
I = welding current, A.

Thus, according to Sosnin, the increase of plasma welding rate, associated with increasing current, increases the minimum permissible nozzle diameter d_n.

Sosnin and Shemonaev (1981) have demonstrated that the extent of restriction of the maximum value of d_n is determinated by the increase of the pressure spot diameter D_p to the dimensions of the pool crater $D_{cr} = 0{,}9B$ (Fig. 6.), where B is the weld width. At $D_p \to D_{cr}$ the liquid metal flow rate on the crater sidewalls rapidly increases and the extend of undercutting of the welded joint becomes greater. In addition to this the diameter of the crater outlet orifice d_0 and the probability of burntrough increase. Taking the above ratios into account the maximum possible nozzle diameter is $d_{n\ max}$ = 0,64...0,69B. If a reduction of welding speed is allowed or it is necessary to reduce the extent of undercutting it is convenient to reduce d_n. According to Sosnin and Shemonaev (1981) the minimum possible nozzle diameter $d_{n\ min}$ = 0,32...0,35B. Thus, the optimum range of d_n is 0,4...0,6B.

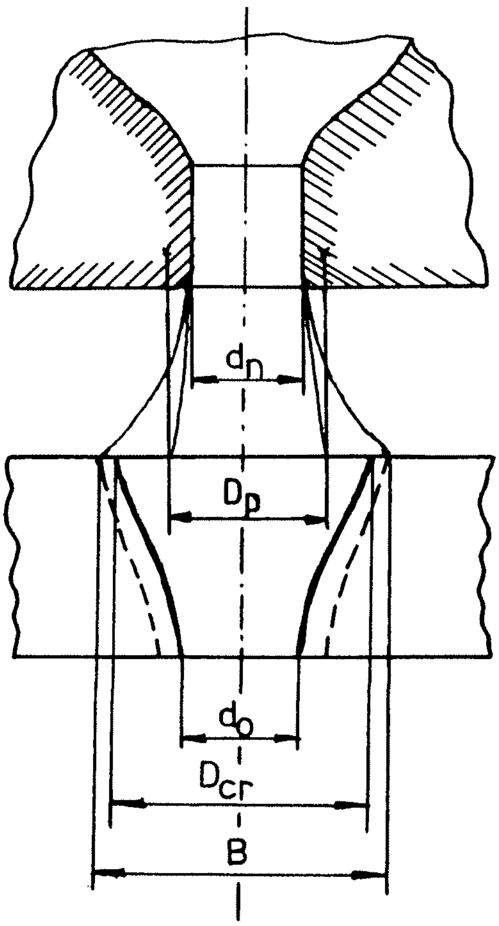


Fig. 6. A transverse section through the molten pool crater [Sosnin (1988)].

From a practical point of view groove preparation and weld joint design are very significant. The tolerances of groove preparation and joint gap are smaller for plasma welding than for TIG welding for example. For instance, according to Messager and Cuny (1982) the maximum acceptable gap between plate edges increases from 0,5 to 2 mm, when the thickness increases from 3 to 12 mm. In this range, the maximum height difference between the plates is from 0,8 to 2 mm. Bakardjiev and Varbenova (1987) have arrived at the following result: the gap in the I-groove welding changes from 0 to 1 mm, when the thickness increases from 2 to 5 mm. In root welding the gap of a V-groove increases from 0 to 1 mm, when the thickness changes from 6 to 15 mm. At the same time, the maximum difference in the level of the plates can increase from 0 to 1 mm.

4. THE AIM OF THIS STUDY

Industrial plasma keyhole welding is used today to join high alloyed steels and titanium. Plasma keyhole welding of structural steels is unusual and it is not much dealt with even in the literature. Some research workers (mentioned in Section 1 Introduction) have shown by single experiments that even structural steels can be welded using plasma key-hole technique, but the conditions have not been characte-rized widespreadly or systemised. It is considered that the behaviour of the structural steel weld pool is uncontrolab-le compared with high high alloyed steel or titanium weld pool.

The aim of this study is to reveal the possibilities of welding unalloyed and microalloyed structural steels repro-ducibly and with a high quality using plasma keyhole wel-ding method. The study consists butt welding with I-groove in flat, horizontal-vertical and vertical positions and root welding of thick plates in flat position. The study evaluates the technological conditions for successful wel-ding structural steels with different compositions and ma-terial thicknesses and in various welding positions, and investigates the individual and interactive effects of the welding parameters on weld quality.

5. EXPERIMENTAL PROCEDURE

The experimental part of this study was performed in the Department of Mechanical Engineering of Lappeenranta University of Technology. In the following the experimental equipment, materials and welding and testing schedules are presented.

5.1 Experimental equipment

The experimental equipment was composed of plasma welding equipment, weld positioner and plate fasteners, and measuring instruments for the welding parameters.

5.1.1 Plasma welding equipment

The plasma welding experimental equipment was made up of the following items:

- power sources (UCAR Plasma Weld 300 and UCAR TIG 404 AC DC),
- plasma torches (AGA PTW 300 and Thermal Arc PWM-6A),
- control unit for ignition and gas control (AGA PW 300),
- plasma sequence control (AGA Plasma Sequence Control),
- wire feeder (AGA CW 6C).

The equipment is shown in Fig. 7.

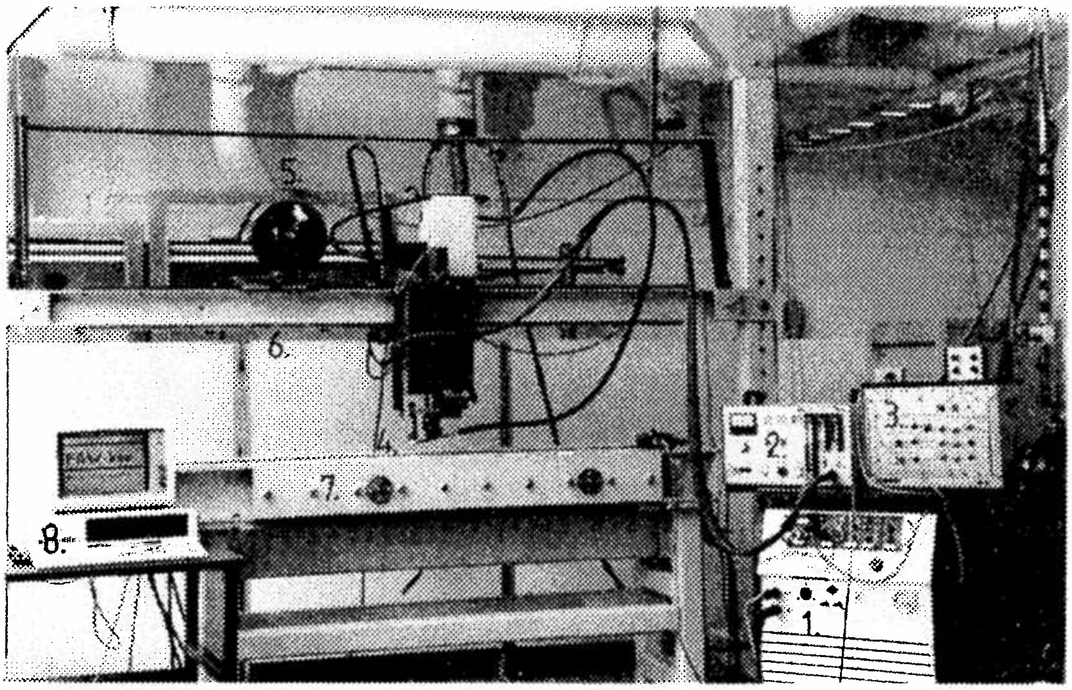


Fig. 7. The plasma welding equipment. 1. power source, 2. control unit for ignition and gas control, 3. plasma sequence control, 4. plasma torch, 5. wire feeder, 6. weld positioner, 7. plate fastener, 8. data logging (PC).

5.1.2 Weld positioner and plate fastener

The welding experiments were performed using mechanized welding in a weld positioner and two plate fasteners. The weld positioner used was equipped with copper jaws operated by compressed air for the clamping of the plates. The welding table was fitted with a copper backing bar with a groove of 15x17 mm cross section for the backing gas. The groove must be sufficiently deep to avoid any disturbance of the arc jet. Backing gas was fed into the groove through holes of 1 mm diameter drilled in the side of the groove.

For welding experiments in the horizontal-vertical and vertical positions the plate fastener was attached to a rotating fastener. Whereby all welding positions were possible.

5.1.3 Measuring instruments

The welding parameters (welding current and voltage, welding speed and wire feed speed) were measured with Arc Data Analyzer-equipment (CRC Automatic Welding). An oscilloscope (Gould 20) was also used for measuring welding current and voltage.

5.2. Experimental materials

The experimental materials can be classified into three groups according to chemical composition and mechanical properties: five conventional unalloyed structural steels (Steels 1-1, 1-2, 1-3, 1-4 and 1-5), four high strength, microalloyed steels (Steels 2-1, 2-2, 2-3 and 2-4) and two strong, formable microalloyed steels (Steels 3-1 and 3-2). One typical steel was chosen from each three groups for more extensive experiments. The steels chosen were conventional unalloyed structural steel Al-deoxidized Fe 37B (Steel 1-1), high strength microalloyed steel RAEX 384 (Steel 2-1) and strong, formable microalloyed steel RAEX HSF 640 (Steel 3-2). The other experimental steels were used in supplementary experiments for the study of the effects of deoxidation, alloying and strength on the weldability of structural steels.

All plates were hot-rolled. The microalloyed steels 2-1, 2-2 and 2-3 were normalized and steel 2-4 was quenched and tempered. The strong and formable special steels' (Steels 3-1 and 3-2) high strength and formability have been brought about by optimizing the alloying and rolling process.

The chemical compositions of the experimental steels with plate thicknesses 6 mm are presented in Table 1. The chemical compositions of the other plate thicknesses are not presented because of insignificant differences in values of compositions.

Table 1. Chemical compositions of the experimental steels. Plate thickness 6 mm.

STEEL	CHEMICAL COMPOSITION														
	C	Si	Mn	P	S	Cu	Cr	Ni	Mo	V	Ti	Nb	Al	N	B
1-1 Fe 37B, Al-deoxid.	0.09	0.02	0.37	0.017	0.020	0.025	0.04	0.02	-	-	0.001	-	0.036	0.006	-
1-2 Fe 37B, Si-deoxid.	0.11	0.20	0.50	0.017	0.021	0.030	0.03	0.02	-	-	0.001	-	0.001	0.007	-
1-3 Fe 37B, Si+Al-deoxid.	0.08	0.22	0.31	0.012	0.020	0.028	0.03	0.02	-	-	0.001	-	0.043	0.006	-
1-4 Fe 37B, Si+Al-deoxid. and CaSi-injected	0.09	0.20	0.47	0.017	0.008	0.028	0.03	0.02	-	-	0.001	-	0.035	0.009	-
1-5 FC A, Si+Al-deoxid.	0.10	0.19	0.89	0.026	0.042	-	-	-	-	-	-	-	0.041	-	-
2-1 RAEX 384, normalized	0.121	0.373	1.36	0.016	0.015	0.040	0.03	0.04	0.008	0.012	0.003	0.034	0.036	0.005	-
2-2 RAEX 385, -"-	0.140	0.333	1.31	0.030	0.016	0.030	0.03	0.04	0.005	0.032	0.003	0.028	0.044	0.008	-
2-3 RAEX 425, -"-	0.168	0.362	1.36	0.018	0.009	0.033	0.03	0.05	0.005	0.085	0.003	0.034	0.026	0.008	-
2-4 OX-812-E, quenched and tempered	0.130	0.52	1.36	0.014	0.005	-	0.02	-	0.008	0.060	0.035	0.027	0.048	0.010	0.002
3-1 RAEX HSF 560	0.115	0.191	1.42	0.022	0.009	0.030	0.04	0.04	0.004	0.078	0.002	0.026	0.038	0.008	-
3-2 RAEX HSF 640	0.122	0.250	1.53	0.016	0.011	0.034	0.03	0.04	0.006	0.152	0.002	0.040	0.048	0.010	-

All unalloyed steels were fully deoxidized, either by Si-, Al- or Si+Al. Besides Si+Al deoxidation Steel 1-4 was also calcium-silicon (CaSi) treated.

The carbon (C) content of all unalloyed steels are low (0.08-0.11 wt-%) compared to the high strength microalloyed steels (0.121-0.168 wt-%). The high strength microalloyed steels also have higher manganese (Mn) contents (1.31-1.36 wt-%) than the unalloyed steels (0.31-0.89 wt-%).

Steels 2-1, 2-2, 2-3 and 2-4 contain different quantities of aluminium (Al), ranging from 0.026 to 0.048 wt-%. Other microalloying elements are molybdenium (Mo), niobium (Nb), titanium (Ti) and vanadinium (V). The levels of Mo, Ti and V are low except for Steel 2-4 with a Ti content of 0.035 wt-%. and for Steel 3-2, which has a V content of 0.152 wt-% Steel 2-4 has also a boron (B) content of 0.002 wt-%. The Nb content varies between 0.026-0.040 wt-%. The nitrogen (N) contents vary from 0.005-0.010 wt-%.

Small amounts of the residuals copper (Cu), nickel (Ni) and chromium (Cr) are present in the steels with the exception of Steel 2-4 which contains no copper and nickel.

In this study the effect of sulphur (S) on the plasma weldability of structural steels was also examined. Steel 1-5 has high S content. For all other steels the S contents are low (S 0.005-0.021 wt-%).

The mechanical properties of the experimental steels with plate thickness 6 mm are shown in Table 2.

Table 2. Mechanical properties of the experimental steels. Plate thickness 6 mm.

STEEL	MECHANICAL PROPERTIES			
	Strength		Ductility	Toughness
	R_{eH} [MPa]	R_m [MPa]	A_5 [%]	KV 5/-20^{0}C * [J]
Steel 1-1	246	382	30	85
Steel 1-2	238	378	30	79
Steel 1-3	244	388	32	74
Steel 1-4	246	388	29	82
Steel 1-5	252	399	22	44
Steel 2-1	428	550	30	80
Steel 2-2	425	548	31	82
Steel 2-3	498	597	31	74
Steel 2-4	794	815	15	78
Steel 3-1	602	682	22	46
Steel 3-2	680	764	20	42

* longitudinal specimens 5 x 10 mm

The unalloyed steels have similar tensile test values: upper yield stress (R_{eH}) 238...252 MPa; tensile strength (R_m) 378...399 MPa; elongation (A_5) 29...32 % (except Steel 1-5) and toughness (KV/5/-20^{0}C) 74...85 J (except Steel 1-5).

The normalized high strength, microalloyed steels (Steels 2-1, 2-2 and 2-3) have R_{eH} values 425...498 MPa, R_m values 548...597 MPa and A_5 values 30...31 %. Steel 2-4 is very strong: R_{eH} value is 794 MPa and R_m value 815 MPa. Toughness values are equal to the other high strength steels.

The strong, formable microalloyed steels (Steels 3-1 and 3-2) have R_{eH} values 602...680 MPa, R_m values 682...764 MPa and A_5 values 20...22 %. The toughness is about a half of that of the unalloyed or microalloyed steels.

With conventional welding methods the weldability of all the steels studied as measured by freedom from defects is good or at least reasonable (Steels 1-5 and 2-4).

The filler material wires were chosen according to base materials. Three types of filler material wires were used: filler material wires for unalloyed and microalloyed steels (Types A and B) and filler material wire for quenched and tempered steel (Type C). The chemical compositions of the filler material wires and mechanical properties of the deposited (undiluted) weld metals of filler material wires are presented in Tables 3 and 4.

Table 3. Chemical compositions of the filler material wires.

FILLER MATERIAL	CHEMICAL COMPOSITION														
	C	Si	Mn	P	S	Cu	Cr	Ni	Mo	V	Ti	Nb	Al	N	B
Type A OK Autrod 12.51	0.09	0.71	1.12	0.015	0.022	0.035	0.04	0.03	-	-	-	-	0.002	0.005	-
B OK Autrod 12.64	0.09	0.74	1.37	0.017	0.019	0.035	0.05	0.02	-	-	-	-	0.001	0.005	-
C OK Autrod 13.12	0.12	0.78	1.11	0.010	0.019	0.025	1.22	0.02	0.51	-	-	-	0.007	0.006	-

Table 4. Mechanical properties of the deposited (undiluted) weld metals of the filler material wires. Welded with MIG welding according to standard SFS 3328.

FILLER MATERIAL	MECHANICAL PROPERTIES			
	Strength		Ductility	Toughness
	R_{eH} [MPa]	R_m [MPa]	A_5 [%]	KV 5/-20^{0}C * [J]
Type A OK Autrod 12.51	482	529	29	78
B OK Autrod 12.64	495	548	26	72
C OK Autrod 13.12	756	770	23	45

* specimens 5 x 10 mm

5.3 Experimental schedule

The effects of welding parameters on the weld quality of plasma keyhole welding have been studied by many kinds of experiments. The technical and metallurgical suitability of plasma keyhole welding for welding of unalloyed and microalloyed structural steels has been experimentally demonstrated.

The thicknesses of experimental plates were 3, 4, 6, 7, 8, 10, 12, 16 and 20 mm and the length of each test piece was 400 to 500 mm.

5.3.1 Welding schedule

The performed welding experiments can be classified into three groups: butt welding experiments with I-groove in the flat, horizontal-vertical and vertical positions and root welding experiments and complementary experiments in the flat position.

Butt welding experiments with I-groove

The aim of these studies was to determine the effects of welding current, welding gases and welding speed on the success of welding and weld quality.

One steel from each three material groups were chosen (Steels 1-1, 2-1 and 3-2). The experimental plates were mainly 6 mm thick. That was selected to ensure penetration by the plasma keyhole such that the effects of welding parameters on weld quality could be studied reliably. Thinner (3, 4 and 5 mm) and thicker (8 mm) plate thicknesses were also studied. The experiments were performed in the flat, horizontal-vertical and vertical positions. The welding schedule of butt welding experiments with I-groove are indicated in Table 5.

Table 5. Welding positions and plate thicknesses (mm) used in butt welding experiments with I-groove.

POSITION \ STEEL	1-1 Fe 37B	2-1 RAEX 384	3-2 RAEX HSF 640
Flat	3 4 5 6 8	4 6 8	4 6 8
Horizontal-vertical	4 6 8	4 6 8	4 6 8
Vertical	4 6 8	4 6 8	4 6 8

Root welding experiments

When the plate thickness is beyond the range of I-groove preparation a groove with or without a root face is necessary. Welds were made in a single V-groove and in a single V-groove with a root face (Y-groove) in the flat position. Also single U-groove was studied. The welding schedule of root welding experiments are presented in connection with results of these experiments.

Complementary experiments

The possibilities and conditions of plasma keyhole welding for the welding of unalloyed and microalloyed structural steels were studied by butt welding experiments with I-groove and root welding experiments. In this part of the study the effects of some additional welding parameters on weld quality were established greater detail.

In separate experiments the following effects were studied:

- the effect of deoxidation of the base metal on plasma arc welding with different plasma and shielding gases,
- the effect of sulphur on plasma weldability of structural steels,
- the effect of plasma gas hydrogen content on mechanical properties of weld joint,
- the solubility of hydrogen in weld metal with different plasma and shielding gases,
- the effect of backing gas on weld quality,
- the solubility of nitrogen from the backing gas on weld metal,
- the effect of the surface quality of the base metal on weld quality,
- the effect of nozzle on weld penetration and

welding speed, and
- weld distortion in plasma keyhole welding.

5.3.2 Testing methods

All welded joints were tested by both nondestructive and destructive testing. Visual testing and measurement of geometrical form errors were performed for all experimental welds. Internal defects were tested radiographically according to standard SFS 3207 (1979) "Nondestructive testing. Radiographic examination. Steel welds" and by ultrasonic testing according to standards SFS 3290 (1983) "Ultrasonic examination of welded joint" and SFS 3294 (1982) "Ultrasonic examination of steel plates".

The classification criteria of welding joints was based on the standard SFS 2379 (1983) "Welding. Fusion welded joints in steel. Classification". This standard classifies the welded joints according to results of nondestructive testing into four classes: WA (most exacting), WB, WC and WD. The standard shows the acceptance limits for surface weld defects, geometrical form errors and internal weld defects.

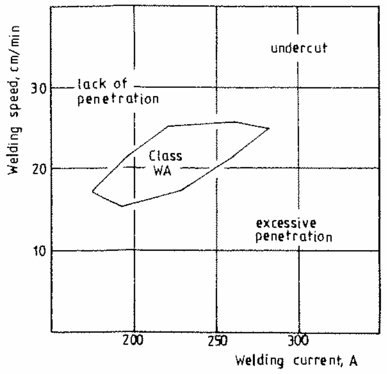
The mechanical properties of plasma welded joints were tested according to gas metal arc welding procedure test standard SFS 3326 (1975) "Welding of pressure vessels. Welding procedure test". The standard covers tensile testing, bending testing, and hardness and toughness tests. Each of the tests were performed according to the relevant standards: tensile test SFS 3173 (1974) "Tensile testing of metals", bending test SFS 2001 (1967) "Bend testing of metal material", hardness test SFS 3214 (1976) "Testing of materials. Vickers hardness test" and toughness test SFS 2853 (1973) "The Charpy V-notch impact test". Besides these mechanical tests the macro- and microstructures were characterized.

6. RESULTS

6.1 Butt welding experiments with I-groove

The results obtained in the butt welding experiments with I-groove have been stored on an Oracle -database using IBM PC/XT and written out as separate parameter window. The parameter windows ("quality boxes") show the acceptable welding parameter combinations for which specific weld class (class WA in flat and horizontal-vertical positions and WC in vertical position) are obtained and combinations leading to typical weld defects.

The parameter windows of the three base materials studied (Steels 1-1, 2-1 and 3-2) are shown in Figs. 8 to 16 for flat, horizontal-vertical and vertical welds. In the figures the vertical axis indicates the welding current and the horizontal axis the welding speed. In these experiments the plasma gas and its flow rate were chosen so that the welding was reliable and the welds were acceptable with wide tolerances. Argon-5% hydrogen gas (SH5) was used as plasma gas. The other parameters, i.e. filler material, shielding gas, backing gas and type of nozzle, are shown beside the corresponding diagrams. Two cross-sections and the mechanical properties (strength, ductility, impact toughness, hardness and bendability) of the corresponding weld joints are also presented in the figures. The cross-sections represent two different combinations of welding current and welding speed. However both examples are situated inside the same parameter window.



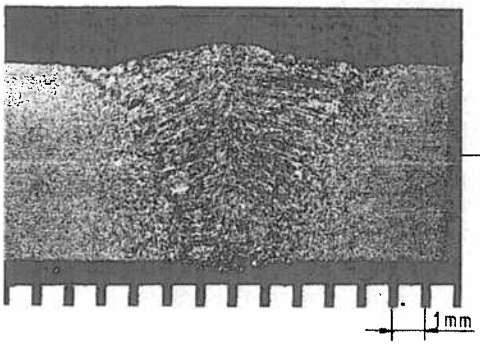
Fe 37 B
- 6 mm
- Flat position
- I-groove
- Filler metal: OK 12.51
- Plasma gas: SH5 3,0 l/min
- Shielding gas: Ar 15 l/min
- Backing gas: Ar 5 l/min
- Nozzle: restr. ø 3,5 mm
- Class WA

STEEL 1-1, Fe 37 B

Strength and ductility:
- R_{eH}: 246 MPa
- R_m: 382 MPa
- A_5: 30 %

Toughness: 85 KV 5/-20°
Hardness: 144 HV 10

Mechanical properties of weld joints:

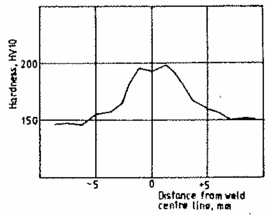


I=200 A, v=17 cm/min

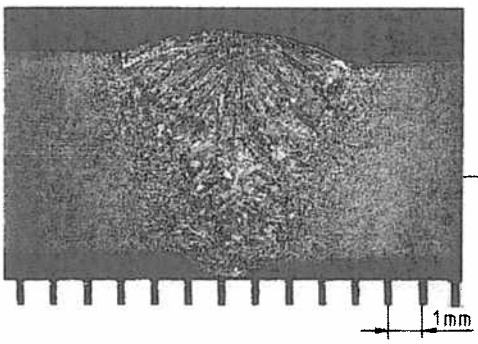
R_{eH}: 248 MPa, R_m: 382 MPa, A_5: 32 %
Toughness: KV 5/° C

	0°C	-20°C	-40°C
Weld	59	59	38
Fusion line	74	76	73
Coarse grain HAZ	74	80	72
Part.transf.zone	80	78	80
Base metal	85	80	80

Hardness:



Bending 120°: no cracks

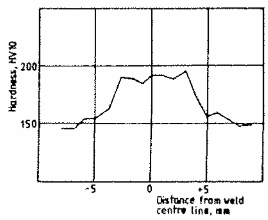


I=255 A, v=24 cm/min

R_{eH}: 240 MPa, R_m: 380 MPa, A_5: 31 %
Toughness: KV 5/° C

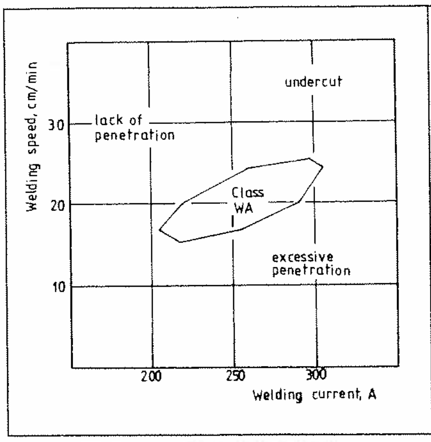
	0°C	-20°C	-40°C
Weld	65	60	36
Fusion line	82	79	80
Coarse grain HAZ	84	78	80
Part.transf.zone	80	72	80
Base metal	81	84	83

Hardness:



Bending 120°: no cracks

Fig. 8. Welding parameters and mechanical properties of weld joint of plasma keyhole welding of unalloyed structural steel. I-groove and flat position.



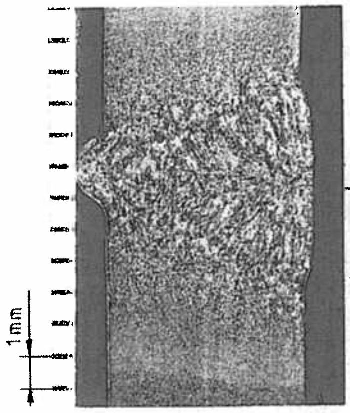
Fe 37 B
- 6 mm
- Horizontal-vertical position
- I-groove
- Filler metal: OK 12.51
- Plasma gas: SH5 3,0 l/min
- Shielding gas: Ar 15 l/min
- Backing gas: Ar 5 l/min
- Nozzle: restr. ø 3,5 mm
- Class WA

STEEL 1-1, Fe 37 B

Strength and ductility:
- R_{eH}: 246 MPa
- R_m: 382 MPa
- A_5: 30 %

Toughness: 85 KV 5/-20°
Hardness: 144 HV 10

Mechanical properties of weld joints:

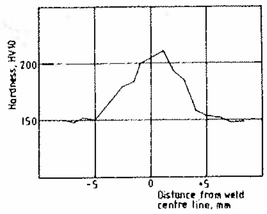


I=215 A, v=16 cm/min

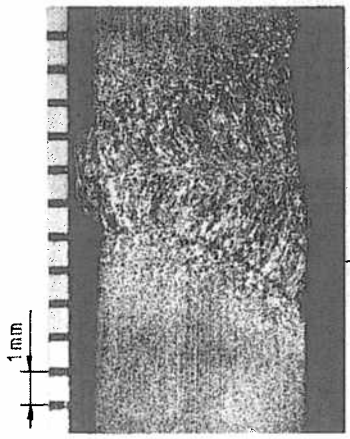
R_{eH}: 250 MPa, R_m: 388 MPa, A_5: 30 %
Toughness: KV 5/° C

	0°C	-20°C	-40°C
Weld	62	56	41
Fusion line	77	72	72
Coarse grain HAZ	80	74	70
Part.transf.zone	80	76	68
Base metal	84	80	78

Hardness:



Bending 120°: no cracks

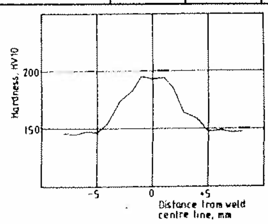


I=280 A, v=24 cm/min

R_{eH}: 249 MPa, R_m: 390 MPa, A_5: 28 %
Toughness: KV 5/° C

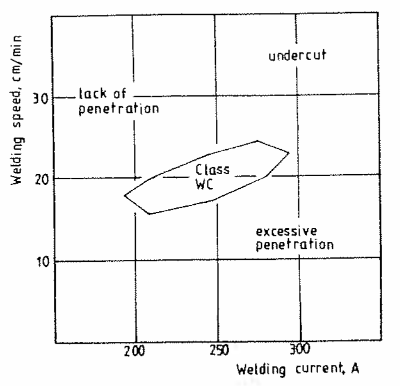
	0°C	-20°C	-40°C
Weld	64	60	44
Fusion line	78	74	74
Coarse grain HAZ	80	82	72
Part.transf.zone	80	78	72
Base metal	84	80	80

Hardness:



Bending 120°: no cracks

Fig. 9. Welding parameters and mechanical properties of weld joint of plasma keyhole welding of unalloyed structural steel. I-groove and horizontal-vertical position.



Fe 37 B

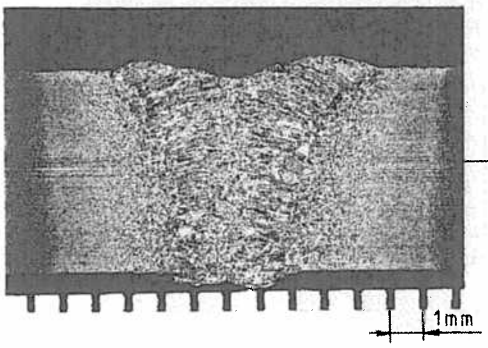
- 6 mm
- Vertical position (from top to down)
- I-groove
- Filler metal: OK 12.51
- Plasma gas: SH5 3,0 l/min
- Shielding gas: Ar 15 l/min
- Backing gas: Ar 5 l/min
- Nozzle: restr. ø 3,5 mm
- Class WC

STEEL 1-1, Fe 37 B

Strength and ductility:
- R_{eH}: 246 MPa
- R_m: 382 MPa
- A_5: 30 %

Toughness: 85 KV 5/-20°
Hardness: 144 HV 10

Mechanical properties of weld joints:

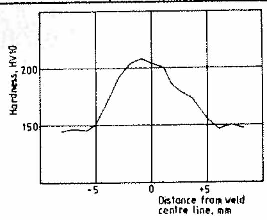


I=210 A, v=18 cm/min

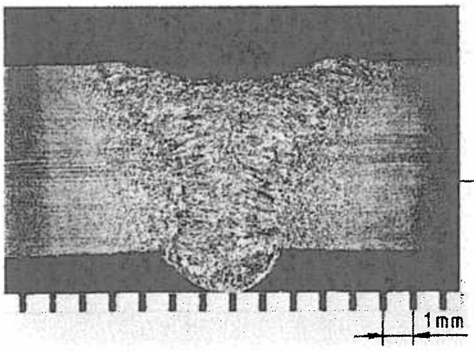
R_{eH}: 238 MPa, R_m: 368 MPa, A_5: 27 %
Toughness: KV 5/° C

	0°C	-20°C	-40°C
Weld	62	54	38
Fusion line	69	60	51
Coarse grain HAZ	80	71	74
Part.transf.zone	82	80	80
Base metal	84	78	80

Hardness:



Bending 120°: no cracks

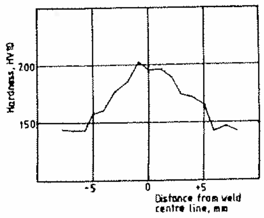


I=265 A, v=23 cm/min

R_{eH}: 232 MPa, R_m: 368 MPa, A_5: 28 %
Toughness: KV 5/° C

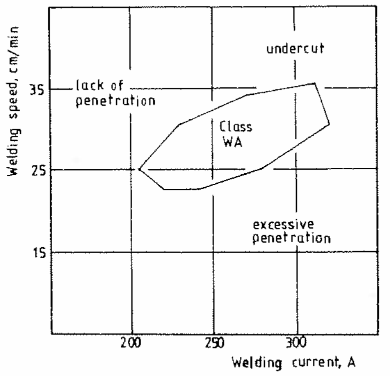
	0°C	-20°C	-40°C
Weld	52	40	38
Fusion line	70	70	62
Coarse grain HAZ	78	78	72
Part.transf.zone	80	80	72
Base metal	81	80	80

Hardness:



Bending 120°: no cracks

Fig. 10. Welding parameters and mechanical properties of weld joint of plasma keyhole welding of unalloyed structural steel. I-groove and vertical position.



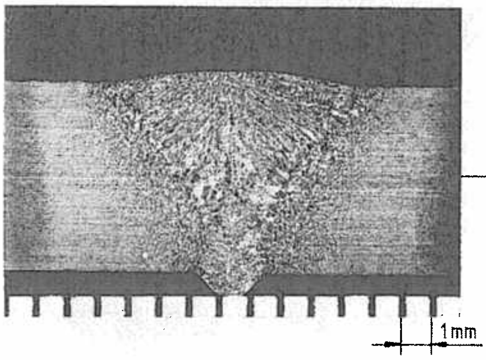
RAEX 384
- 6 mm
- Flat position
- I-groove
- Filler metal: OK 12.64
- Plasma gas: SH5 3,0 l/min
- Shielding gas: Ar 15 l/min
- Backing gas: Ar 5 l/min
- Nozzle: restr. ø 3,5 mm
- Class WA

STEEL 2-1, RAEX 384

Strength and ductility:
- R_{eH}: 428 MPa
- R_m: 550 MPa
- A_5: 30 %

Toughness: 80 KV 5/-20°
Hardness: 182 HV 10

Mechanical properties of weld joints:

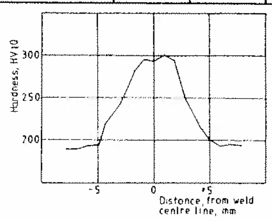


I=230 A, v=25 cm/min

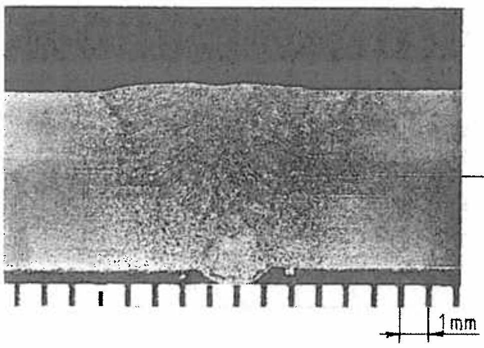
R_{eH}: 438 MPa, R_m: 568 MPa, A_5: 30 %
Toughness: KV 5/° C

	0°C	-20°C	-40°C
Weld	35	26	24
Fusion line	48	42	25
Coarse grain HAZ	67	59	54
Part.transf.zone	80	81	82
Base metal	85	81	82

Hardness:



Bending 120°: no cracks

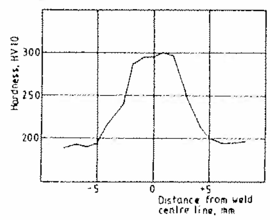


I=305 A, v=34 cm/min

R_{eH}: 439 MPa, R_m: 558 MPa, A_5: 28 %
Toughness: KV 5/° C

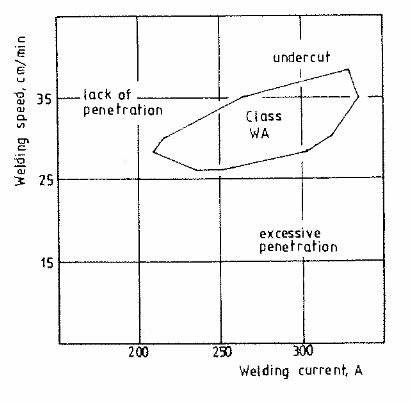
	0°C	-20°C	-40°C
Weld	40	29	24
Fusion line	46	44	28
Coarse grain HAZ	72	70	59
Part.transf.zone	82	80	78
Base metal	85	81	82

Hardness:



Bending 120°: no cracks

Fig. 11. Welding parameters and mechanical properties of weld joint of plasma keyhole welding of high strength microalloyed steel. I-groove and flat position.



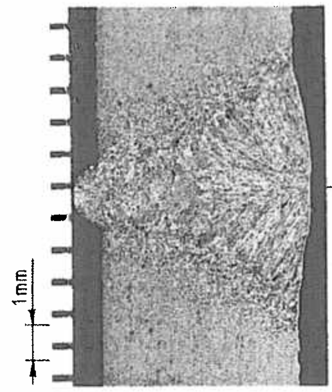
RAEX 384
- 6 mm
- Horizontal-vertical position
- I-groove
- Filler metal: OK 12.64
- Plasma gas: SH5 3,0 l/min
- Shielding gas: Ar 15 l/min
- Backing gas: Ar 5 l/min
- Nozzle: restr. ø 3,5 mm
- Class WA

STEEL 2-1, RAEX 384

Strength and ductility:
- R_{eH}: 428 MPa
- R_m: 550 MPa
- A_5: 30 %

Toughness: 80 KV 5/-20°
Hardness: 182 HV 10

Mechanical properties of weld joints:

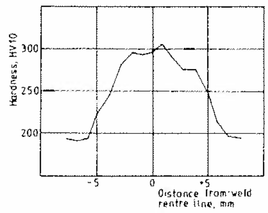


I=245 A, v=27 cm/min

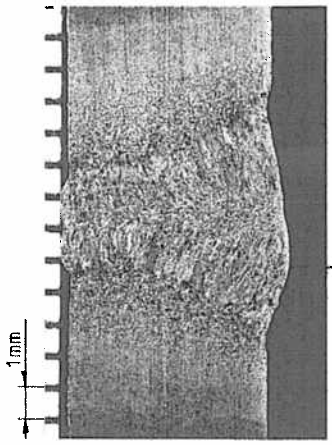
R_{eH}: 417 MPa, R_m: 548 MPa, A_5: 28 %
Toughness: KV 5/° C

	0°C	-20°C	-40°C
Weld	28	30	22
Fusion line	32	30	30
Coarse grain HAZ	66	62	51
Part.transf.zone	72	70	64
Base metal	82	80	80

Hardness:



Bending 120°: no cracks

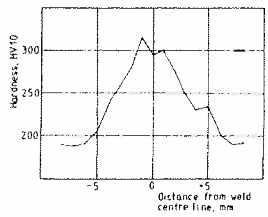


I=320 A, v=37 cm/min

R_{eH}: 420 MPa, R_m: 552 MPa, A_5: 30 %
Toughness: KV 5/° C

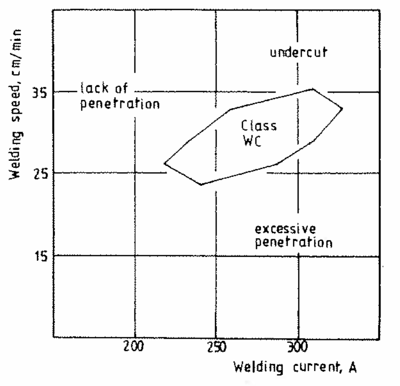
	0°C	-20°C	-40°C
Weld	38	28	28
Fusion line	47	40	34
Coarse grain HAZ	60	60	51
Part.transf.zone	68	52	50
Base metal	81	75	78

Hardness:



Bending 120°: no cracks

Fig. 12. Welding parameters and mechanical properties of weld joint of plasma keyhole welding of high strength microalloyed steel. I-groove and horizontal-vertical position.



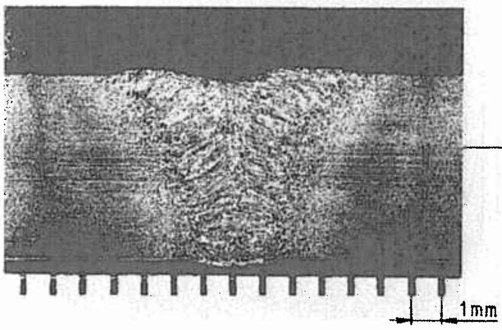
RAEX 384
- 6 mm
- Vertical position (from top to down)
- I-groove
- Filler metal: OK 12.64
- Plasma gas: SH5 3,0 l/min
- Shielding gas: Ar 15 l/min
- Backing gas: Ar 5 l/min
- Nozzle: restr. ø 3,5 mm
- Class WC

STEEL 2-1, RAEX 384

Strength and ductility:
- R_{eH}: 428 MPa
- R_m: 550 MPa
- A_5: 30 %

Toughness: 80 KV 5/-20°
Hardness: 182 HV 10

Mechanical properties of weld joints:

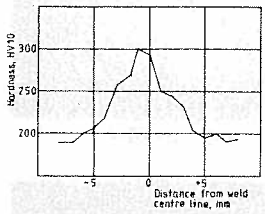


I=245 A, v=26 cm/min

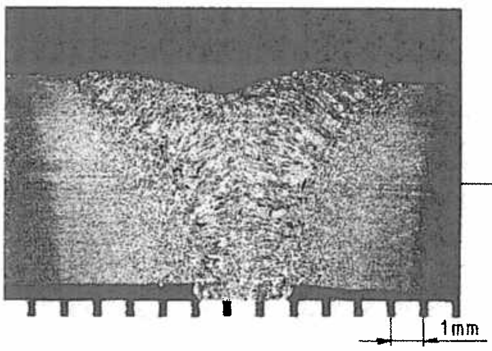
R_{eH}: 435 MPa, R_m: 561 MPa, A_5: 28 %
Toughness: KV 5/° C

	0°C	-20°C	-40°C
Weld	32	28	27
Fusion line	39	30	26
Coarse grain HAZ	49	42	44
Part.transf.zone	68	70	66
Base metal	78	80	72

Hardness:



Bending 120°: no cracks

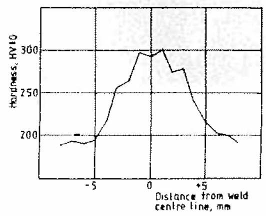


I=310 A, v=34 cm/min

R_{eH}: 435 MPa, R_m: 555 MPa, A_5: 30 %
Toughness: KV 5/° C

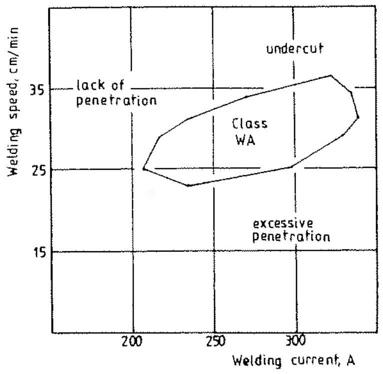
	0°C	-20°C	-40°C
Weld	28	25	25
Fusion line	36	28	26
Coarse grain HAZ	56	48	44
Part.transf.zone	64	67	63
Base metal	81	77	74

Hardness:



Bending 120°: no cracks

Fig. 13. Welding parameters and mechanical properties of weld joint of plasma keyhole welding of high strength microalloyed steel. I-groove and vertical position.



RAEX HSF 640

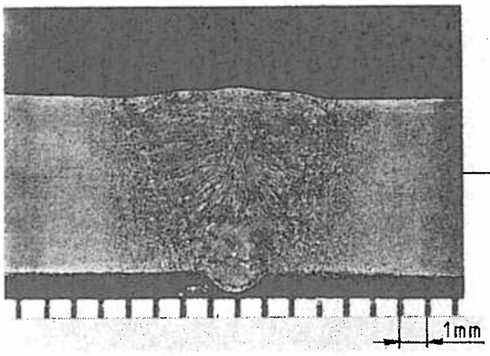
- 6 mm
- Flat position
- I-groove
- Filler metal: OK 12.64
- Plasma gas: SH5 3,0 l/min
- Shielding gas: Ar 15 l/min
- Backing gas: Ar 5 l/min
- Nozzle: restr. ø 3,5 mm
- Class WA

STEEL 3-2, RAEX HSF 640

Strength and ductility:
- R_{eH}: 680 MPa
- R_m: 764 MPa
- A_5: 20 %

Toughness: 42 KV 5/-20°
Hardness: 268 HV 10

Mechanical properties of weld joints:

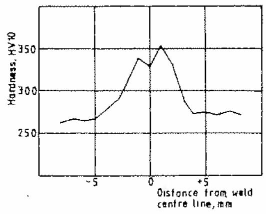


I=240 A, v=24 cm/min

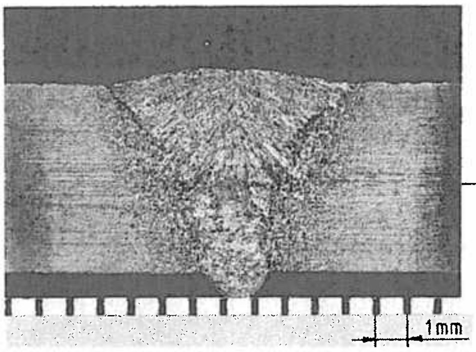
R_{eH}: 674 MPa, R_m: 765 MPa, A_5: 18 %
Toughness: KV 5/° C

	0°C	-20°C	-40°C
Weld	25	25	24
Fusion line	45	25	30
Coarse grain HAZ	52	41	40
Part.transf.zone	68	63	64
Base metal	43	42	41

Hardness:



Bending 120°: no cracks

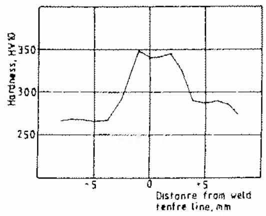


I=320 A, v=35 cm/min

R_{eH}: 689 MPa, R_m: 765 MPa, A_5: 18 %
Toughness: KV 5/° C

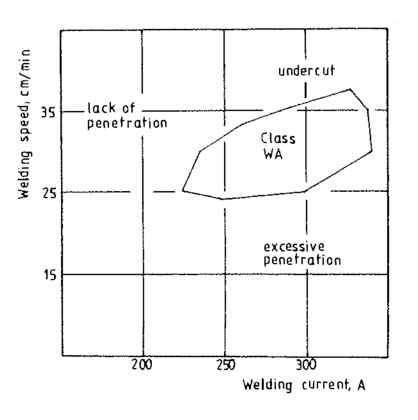
	0°C	-20°C	-40°C
Weld	22	22	20
Fusion line	38	25	26
Coarse grain HAZ	47	45	38
Part.transf.zone	59	60	60
Base metal	41	40	42

Hardness:



Bending 120°: no cracks

Fig. 14. Welding parameters and mechanical properties of weld joint of plasma keyhole welding of strong formable microalloyed steel. I-groove and flat position.



RAEX HSF 640

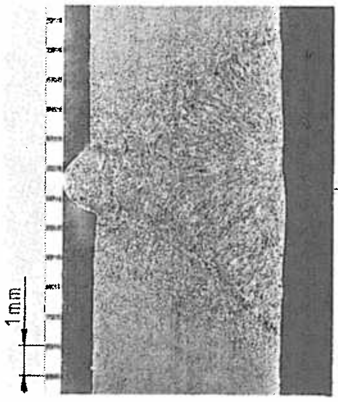
- 6 mm
- Horizontal-vertical position
- I-groove
- Filler metal: OK 12.64
- Plasma gas: SH5 3,0 l/min
- Shielding gas: Ar 15 l/min
- Backing gas: Ar 5 l/min
- Nozzle: restr. ø 3,5 mm
- Class WA

STEEL 3-2, RAEX HSF 640

Strength and ductility:
- R_{eH}: 680 MPa
- R_m: 764 MPa
- A_5: 20 %

Toughness: 42 KV 5/-20°
Hardness: 268 HV 10

Mechanical properties of weld joints:

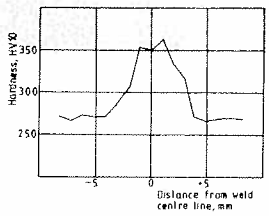


I=245 A, v=25 cm/min

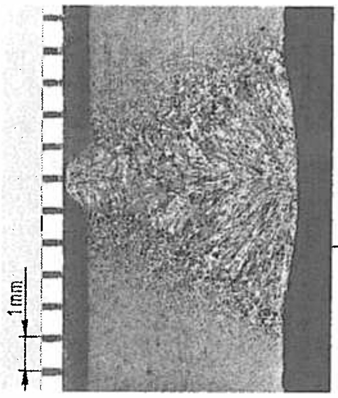
R_{eH}: 689 MPa, R_m: 765 MPa, A_5: 18 %
Toughness: KV 5/° C

	0°C	-20°C	-40°C
Weld	19	30	28
Fusion line	41	30	45
Coarse grain HAZ	55	41	38
Part.transf.zone	71	66	65
Base metal	41	39	40

Hardness:



Bending 120°: no cracks

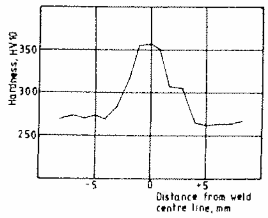


I=330 A, v=36 cm/min

R_{eH}: 682 MPa, R_m: 770 MPa, A_5: 18 %
Toughness: KV 5/° C

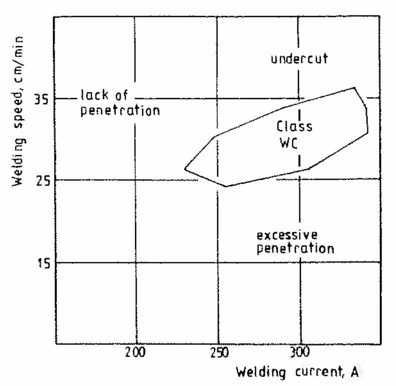
	0°C	-20°C	-40°C
Weld	30	19	20
Fusion line	50	20	26
Coarse grain HAZ	50	40	42
Part.transf.zone	69	60	64
Base metal	41	39	40

Hardness:



Bending 120°: no cracks

Fig. 15. Welding parameters and mechanical properties of weld joint of plasma keyhole welding of strong formable microalloyed steel. I-groove and horizontal-vertical position.



RAEX HSF 640

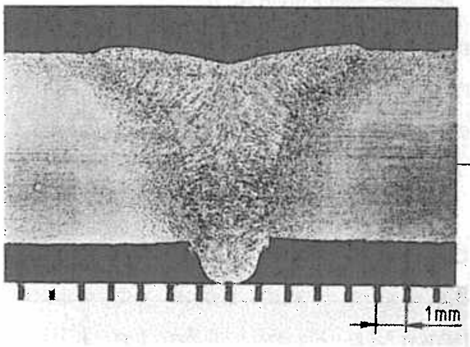
- 6 mm
- Vertical position (from top to down)
- I-groove
- Filler metal: OK 12.64
- Plasma gas: SH5 3,0 l/min
- Shielding gas: Ar 15 l/min
- Backing gas: Ar 5 l/min
- Nozzle: restr. ø 3,5 mm
- Class WC

STEEL 3-2, RAEX HSF 640

Strength and ductility:
- R_{eH}: 680 MPa
- R_m: 764 MPa
- A_5: 20 %

Toughness: 42 KV 5/-20°
Hardness: 268 HV 10

Mechanical properties of weld joints:

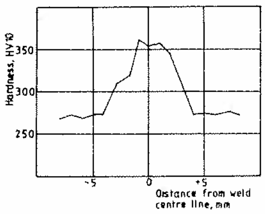


I=250 A, v=26 cm/min

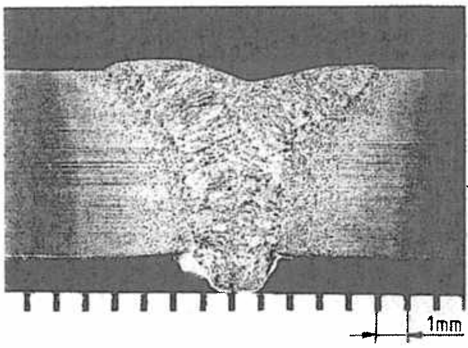
R_{eH}: 682 MPa, R_m: 770 MPa, A_5: 17 %
Toughness: KV 5/° C

	0°C	-20°C	-40°C
Weld	19	17	14
Fusion line	31	32	30
Coarse grain HAZ	47	40	41
Part.transf.zone	59	55	55
Base metal	40	39	35

Hardness:



Bending 120°: no cracks

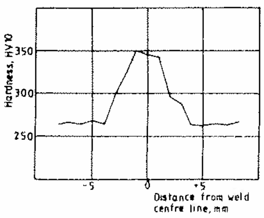


I=330 A, v=35 cm/min

R_{eH}: 691 MPa, R_m: 769 MPa, A_5: 18 %
Toughness: KV 5/° C

	0°C	-20°C	-40°C
Weld	20	16	15
Fusion line	33	30	29
Coarse grain HAZ	49	44	39
Part.transf.zone	64	57	58
Base metal	43	42	35

Hardness:



Bending 120°: no cracks

Fig. 16. Welding parameters and mechanical properties of weld joint of plasma keyhole welding of strong formable microalloyed steel. I-groove and vertical position.

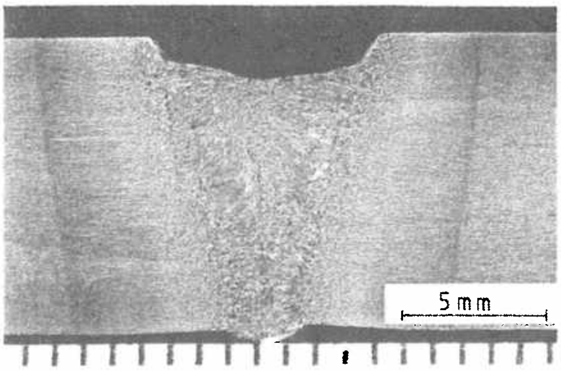
6.2 Root welding experiments

The root welding experiments were performed in the flat position without filler material. The pneumatically constricted nozzle was used in all experiments. The gap between the plates to be welded was closed. The effects of the main welding parameters (welding current, welding gases and welding speed) on weld quality were studied for different base materials and material thicknesses. Besides these main welding parameters the most important parameters affecting the quality of root welds are the height of root face and the groove angle. One object of the root welding experiments was to determine the combination of root face and groove angle for which the root face in as high as possible and the groove angle as narrow as possible for four different material thicknesses.

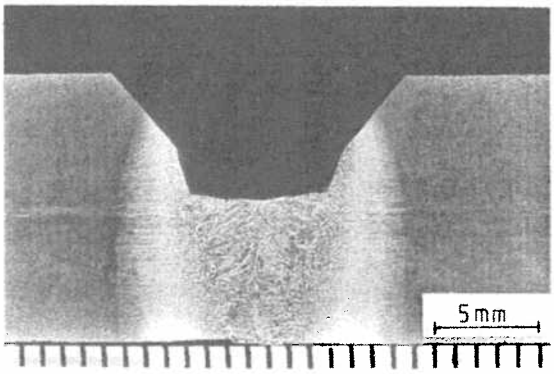
The welding parameters used in the root welding experiments are presented in Table 6. Typical cross-sections of each welded material thickness are shown in Figs. 17a to 17d. The connection between root face$_{max}$ (root face as high as possible) and groove angle$_{min}$ (groove angle as narrow as possible) is presented in Table 7.

Table 6. The root welding experiments.

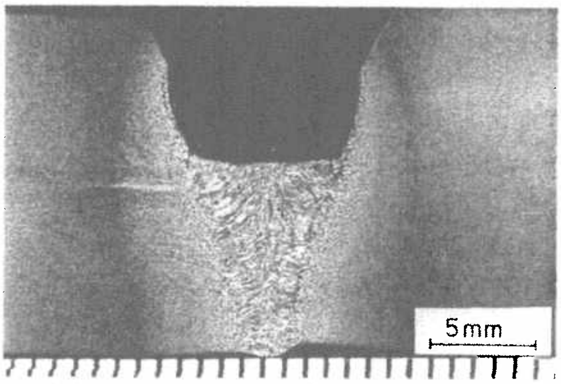
Material thickness and preparation	Welding current I [A]	Welding speed v [cm/min]	Plasma gas flow rate Q_{pg} [l/min]		Shielding gas flow rate Q_{sg} [l/min]		Backing gas flow rate Q_{bg} [l/min]	Height of root face h_{rf} [mm]	Groove angle α [°]
10 mm			argon	SH5	argon	argon-20%$_2$	argon		
Steels 1-1 and 2-1									
- single V-groove	210	24							
without root face	..230	..28	3,0	3,0	15	15	5	0	60
- single V-groove	220	24							
with root face	..240	..28	3,0	3,0	15	15	5	3	60
								6	60
12 mm									
Steels 1-1 and 2-1									
- single V-groove	230	20							
without root face	..260	..24	3,0	3,0	15	15	5	0	60
- single V-groove	260	20							
with root face	..300	..24	3,0	3,0	15	15	5	3	60
								6	60
- single U-groove	260	16							
	..300	..20	3,0	3,0	15	15	5	root face 4 mm	
								root radius 5 mm	
16 mm									
Steels 1-1 and 2-1									
- single V-groove	230	17							
with root face	..250	..21	3,2	3,2	15	15	5	3	60
	260	17							
	..290	..19	4,0	4,0	15	15	5	6	60
20 mm									
Steel 2-1									
- single V-groove	260	18							
with root face	..290	..21	4,3	4,3	15	15	5	3	60
	270	16							
	..300	..19	4,3	4,3	15	15	5	6	60



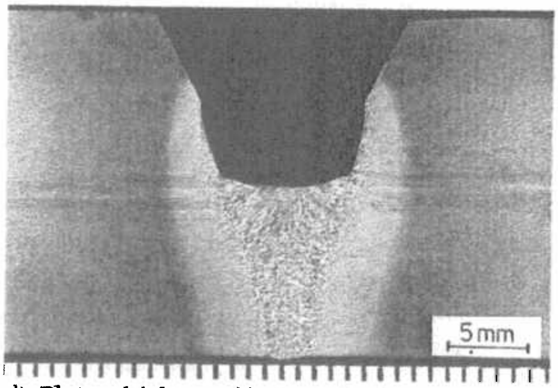
a) Plate thickness 10 mm. Root face 6 mm and groove angle 60^0. Plasma gas SH5 (3,0 l/min), shielding gas argon (15 l/min) and backing gas argon (5 l/min). Welding current 230 A and welding speed 26 cm/min.



b) Plate thickness 12 mm. Root face 6 mm and groove angle 60^0. Plasma gas SH5 (3,0 l/min), shielding gas argon (15 l/min) and backing gas argon (5 l/min). Welding current 280 A and welding speed 22 cm/min.



c) Plate thickness 16 mm. Root face 6 mm and groove angle 60^0. Plasma gas SH5 (4,0 l/min), shielding gas argon (15 l/min) and backing gas argon (5 l/min). Welding current 270 A and welding speed 20 cm/min.



d) Plate thickness 20 mm. Root face 6 mm and groove angle 60^0. Plasma gas SH5 (4,3 l/min), shielding gas argon (15 l/min) and backing gas argon (5 l/min). Welding current 295 A and welding speed 18 cm/min.

Fig. 17. Root welding of high strength, microalloyed steel (RAEX 384) with plate thicknesses 10, 12, 16 and 20 mm. Single V-groove with root face. Plasma gas argon-5% hydrogen, shielding and backing gas argon. One-hole nozzle, diameter 3,0 mm.

Table 7. The useful max root face and the min groove angle for root welding of structural steel. Flat position, single V-groove with root face (Y-groove).

Material thickness [mm]	Root face max [mm]	Groove angle min [^{0}]
10	4 6 8	40 50 60
12	4 6 8	40 50 -
16	4 6 8	50 60 -
20	4 6 8	60 60 -

The root welding of single U-grooves is similar to I-groove welding with the exception of plasma arc lengths. Figure 18 shows the cross-section of the root run in a single U-groove with a plate thickness of 12 mm. The welding parameters used are given in the figure caption.

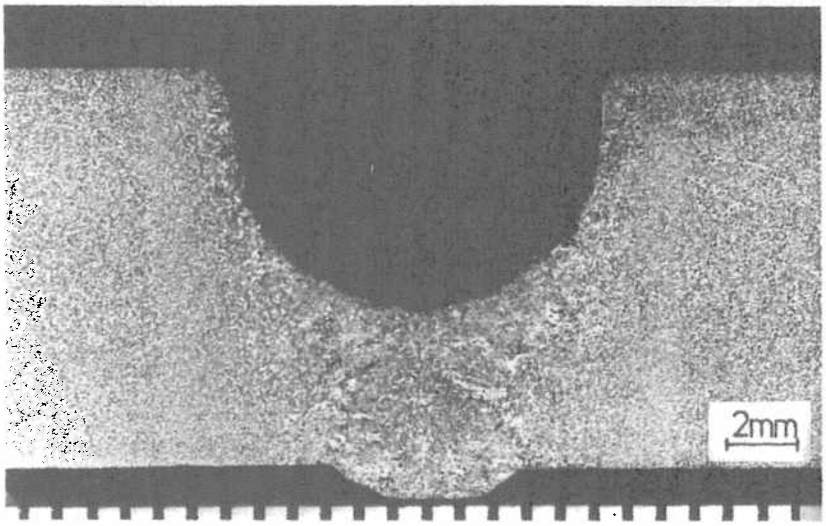


Fig. 18. Root welding of unalloyed structural steel (Fe 37B) with a single U-groove and plate thickness of 12 mm. Root face 4 mm and root radius 5 mm. Plasma gas SH5 (3,0 l/min), shielding gas argon (15 l/min) and backing gas argon (5 l/min). Welding current 300 A and welding speed 18 cm/min. One-hole nozzle, diameter 3,5mm.

6.3 Complementary experiments

The base welding parameters of these experiments were chosen according to the results of the butt welding experiments with I-groove and the root welding experiments (Sections 5.1 and 5.2). All welds were examinated by radiograhic testing, tensile and bending tests, hardness test and by macro- and microstructure examinations.

6.3.1 The effect of deoxidation of the base metal on plasma arc welding with different plasma and shielding gases

In this study the effect of deoxidation mode of unalloyed structural steels on plasma arc welding were established. The studied steels (Steels 1-1, 1-2, 1-3 and 1-4) were fully deoxidized, either by Si, Al or Si+Al. Besides Si+Al deoxidation Steel 1-4 was also Ca-Si -injected. Different plasma and shielding gases were used as welding gases. The backing gas was argon in all experiments. The behaviour of the weld pool was observed during the welding and the welds were examined with visual and radiographic testing after welding.

The chemical compositions and mechanical properties of the experimental steels and filler material are presented in Tables 1 to 4. The welding experiments were performed in the flat position on whole plates, thicknesses 3 and 6 mm, to avoiding the effects of groove and its deviations. The welding parameters were chosen to meet WA requirements.

The welding parameters used are presented in Table 8. The results of visual and radiographic examination of these experiments are shown in Table 9. The hardness distributions of weld joints with plate thickness 3 mm are shown in Fig. 19.

Table 8. The welding parameters in experiments used to study the effect of base material. Base materials: Steel 1-1 Fe 37B (Al-deoxidized), 1-2 Fe 37B (Si-deoxidized), 1-3 Fe 37B (Si+Al-deoxidized) and 1-4 Fe 37B (Si+Al-deoxidized and CaSi-injected). Filler material: Type A, OK Autrod 12.51, Ø 0.8 mm

I-GROOVE	Welding parameters					
Material and material thickness	Welding current I [A]	Welding speed v [cm/min]	Wire feed rate v_f [cm/min]	Plasma gas flow rate Q_{pg} [l/min]	Shielding gas flow rate Q_{sg} [l/min]	Backing gas flow rate Q_{bg} [l/min]
3 mm						
				argon	argon	argon
a) Steel 1-1	170	39	54	4,5	15	10
1-2	170	41	54	4,5	15	10
1-3	170	40	54	4,5	15	10
1-4	170	40	54	4,5	15	10
				SH5	argon	argon
b) Steel 1-1	170	49	54	4,5	15	10
1-2	170	52	54	4,5	15	10
1-3	170	49	54	4,5	15	10
1-4	170	50	54	4,5	15	10
				argon	SH5	argon
c) Steel 1-1	170	41	54	4,5	15	10
1-2	170	44	54	4,5	15	10
1-3	170	42	54	4,5	15	10
1-4	170	43	54	4,5	15	10

				SH5	SH5	argon
d) Steel 1-1	170	54	54	4,5	15	10
1-2	170	56	54	4,5	15	10
1-3	170	54	54	4,5	15	10
1-4	170	56	54	4,5	15	10
				SH5	argon-20% CO_2	argon
e) Steel 1-1	170	52	54	4,5	15	10
1-2	170	52	54	4,5	15	10
1-3	170	50	54	4,5	15	10
1-4	170	50	54	4,5	15	10
				argon	argon-20% CO_2	argon
f) Steel 1-1	170	46	54	4,5	15	10
1-2	170	46	54	4,5	15	10
1-3	170	46	54	4,5	15	10
1-4	170	46	54	4,5	15	10
<u>6 mm</u>						
				argon	argon	argon
g) Steel 1-3	240	26	60	5,5	20	10
				SH5	argon	argon
h) Steel 1-3	240	29	60	5,5	20	10
				SH5	SH5	argon
i) Steel 1-3	240	31	60	5,5	20	10
				argon	argon-20% CO_2	argon
j) Steel 1-3	240	28	60	5,5	20	10

Table 9. The behaviour of the weld pool, the appearance of the weld and internal weld defects of unalloyed, structural steels deoxidized in different modes when welding with different combinations of plasma and shielding gases.

	Behaviour of weld pool	Appearance of weld and internal weld defects
3mm		
a) argon/argon		- relatively high reinforcement, sharp joining with base material, narrow root reinforcement - (1-1, 1-3): local roughness on weld face, (1-2, 1-4): smooth weld face
b) SH5/argon	- (1-1): uniform solid slag film on the weld pool, at the solidification stage the slag makes the weld face irregular - (1-2): slag forming is very slight, weld pool is still - (1-3): like Steel (1-1) - (1-4): slag forming is stable, slag is found as drops on the weld pool, weld pool bubbles to extent	- wider and lower reinforcement compared with case a), continous joining with base material - (1-1, 1-3): local roughness on the weld face, (1-2): smooth weld face with a shall narrow groove in the middle of reinforcem. (1-4): very smooth weld face - (1-1): globular shape and very neat root reinforcement, (1-2): irregular root reinforcement, height and width vary, (1-3, 1-4): neat reinforcement and sharp joining with the base material
c) argon/SH5	- like case b)	
d) SH5/SH5	- like case b) except Steel (1-2), - (1-2): deeper line groove in reinforcement and more unregular root reinforcement	

e) SH5/argon-20% CO_2	- relative smooth reinforcement and continuous joining with base material, wider root reinforcement than in cases a)...d) - (1-2, 1-3): large-sized surface pores	- (1-1): slag on the weld pool melts and changes in form drops to be carried to the edge of reinforcement, slag does not give shape to weld face, weld pool bubbles strongly near the arc, stable further away
f) argon/argon-20% CO_2	- very irregular and rough reinforcement	
6mm		
g) argon/argon	- local roughness of weld face, narrow root reinforcement and sharp joining with base material	
h) SH5/argon	- like case g)	- some pores in the weld
i) SH5/SH5	- like case g)	- some pores in the weld
j) argon/argon-20% CO_2	- very rough weld face, narrow root reinforcement and sharp joining with the base material	

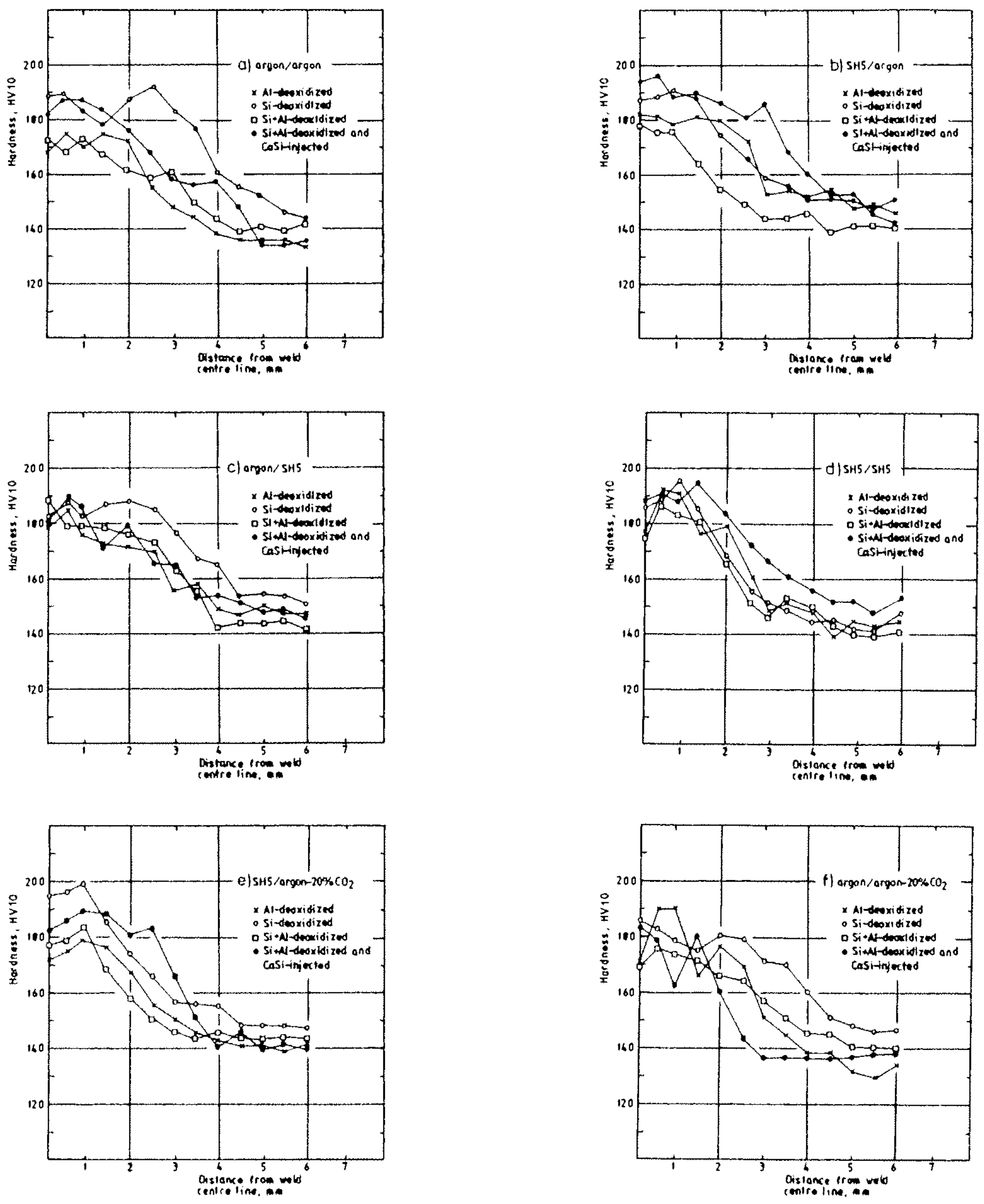


Figure 19. The hardness distributions of welded joints of unalloyed structural steels welded with different plasma gases: argon, argon-5% hydrogen and argon-10% hydrogen. Filler material: Type A, OK Autrod 12.51, ∅ 0.8 mm. Shielding gases: argon, argon-5% hydrogen (SH5) and argon-20% carbon dioxide. Backing gas: argon. The values of other welding parameters are presented in Table 8.

6.3.2 The effect of sulphur on plasma weldability of structural steels

Three unalloyed structural steels (Steels 1-3, 1-4 and 1-5) and one high strength, microalloyed steel (Steel 2-1) with different contents of sulphur were welded according to the welding parameters given in Table 10. The excessive penetration and the formation of undercut determinated the maximum welding speed. The experiments were performed in the flat position on a closed joint without filler material.

Visual and radiographic examinations were performed on all welds. The results are shown in Table 11. Figure 20 shows the relation between the welding current and welding speed for steels with different sulphur contents.

Table 10. The welding parameters used in the study of the effect of sulphur on plasma weldability. Steel 1-3 (0.012 wt-% S), 1-4 (0.008 wt-% S), 1-5 (0.042 wt-% S) and Steel 2-1 (0.009 and 0.015 wt-% S).

I-GROOVE	Welding parameters				
Material and material thickness	Welding current I [A]	Welding speed v [cm/min]	Plasma gas flow rate Q_{pg} [l/min]	Shielding gas flow rate Q_{sg} [l/min]	Backing gas flow rate Q_{bg} [l/min]
8 mm					
			SH5	argon	argon
Steel 1-3	240	14	3,5	15	10
	260	16	3,5	15	10
	280	20	3,5	15	10
	300	23	3,5	15	10
1-4	240	17	3,5	15	10
	260	19	3,5	15	10
	280	22	3,5	15	10
	300	24	3,5	15	10
1-5	240	23	3,5	15	10
	260	28	3,5	15	10
	280	31	3,5	15	10
	300	34	3,5	15	10
6 mm					
Steel 2-1	240	24	2,8	15	10
	260	28	2,8	15	10
	280	31	2,8	15	10
	300	34	2,8	15	10

Table 11. Weld pool behaviour, weld appearance and internal weld defects with different sulphur contents.

	Behaviour of weld pool, appearance of weld and internal weld defects
8 mm	
Steel 1-3 (0.012 wt-% S)	- solid slagfilm on the weld pool - local roughness in weld face - stable welding - no internal defects
1-4 (0.008 wt-% S)	- very slight slag on the weld pool - smooth weld face, concave weld - no internal defects
1-5 (0.042 wt-% S)	- slags on the weld pool - lower and wider reinforcement compared to Steels 1-3 and 1-4 - pleated and wavy reinforcement - clear noticeable infiltration line in the middle of reinforcement - excessive penetration easily occurs - unstable welding - no internal defects
6 mm	
Steel 2-1 (0.009 wt-% S)	- no visible slag - concave weld
(0.015 wt-% S)	- no visible slag - lower and wider reinforcement than with lower S content - somewhat excessive penetration

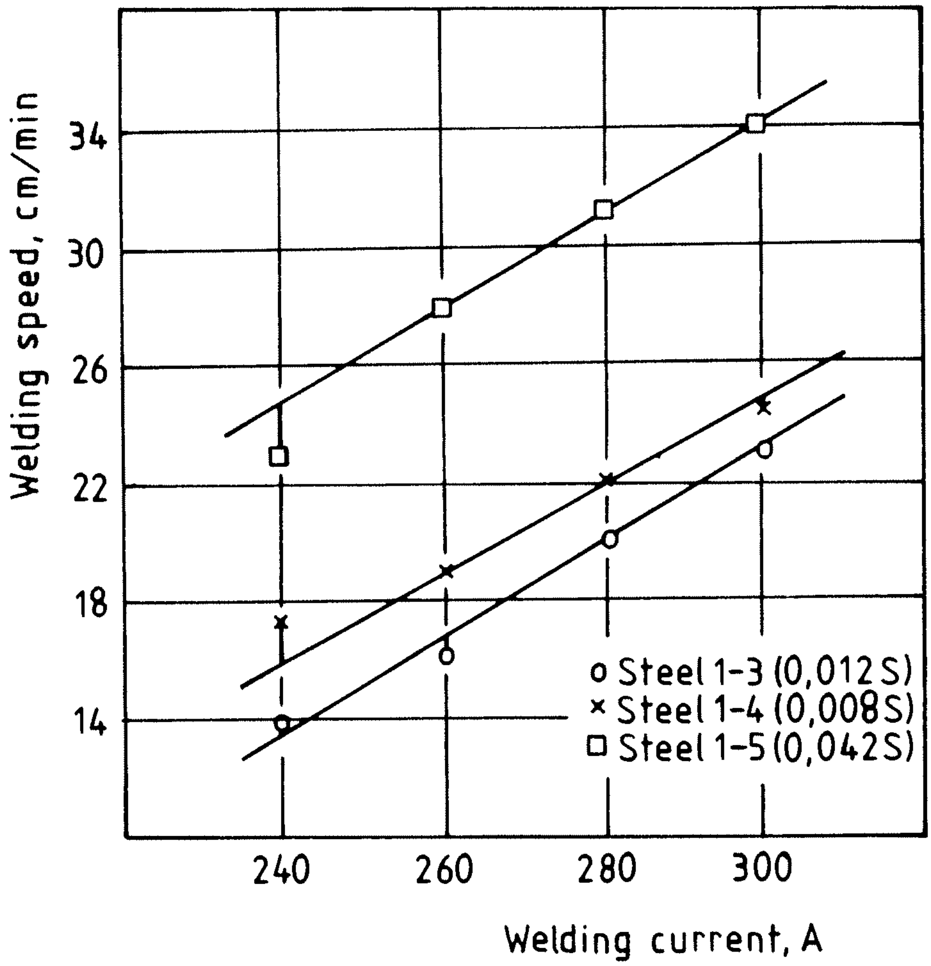


Fig. 20. The dependence of welding speed on welding current for structural steels with different sulphur contents.

6.3.3 The effect of plasma gas hydrogen content on mechanical properties of weld joint

The effect of plasma gas hydrogen content on welds in high strength microalloyed (Steels 2-1, 2-3 and 2-4) and strong, formable microalloyed steels (Steels 3-1 and 3-2) has been studied. The types of plasma gases were argon, argon-5% hydrogen (SH5) and argon-10% hydrogen (SH10). Two filler materials (Types A and C in Tables 3 and 4) were used. The experiments and welding parameters are shown in Table 12. Tables 13 and 14 show the results of tensile and bending tests. The results of the tensile tests are average values of five experiments in every cases. For the bending tests all results are presented. Figure 21 shows the hardness distributions and Table 15 the maximum hardness values of each weld joint.

The radiographic examination showed that all welds come up to the requirements of weld class WA. Single voids were noticed in some specimens.

Table 12. The welding parameters used in experiments to study the effect of plasma gas hydrogen content on weld quality. Shielding gas argon (15 l/min) and backing gas argon (5 l/min).

I - GROOVE	Plasma gas								
Material and material thickness	Ar			Ar - 5% H_2			Ar - 10% H_2		
	Q_{pg}	I	v	Q_{pg}	I	v	Q_{pg}	I	v
3 mm									
Steel 3-1	3,4	268	60	4,0	268	90	2,8	257	100
3-2	3,4	262	63	3,6	293	95	2,8	257	104
6 mm									
Steel 2-1	3,6	276	27	3,2	268	29	2,8	300	42
2-3	3,6	295	33	3,4	293	38	2,8	300	42
2-4	3,1	299	31	3,2	298	43	2,8	300	43
3-1	3,5	288	28	3,4	295	38	2,8	300	44
3-2	3,2	291	30	3,6	298	38	2,8	300	43

Table13. The results of tensile tests after welding with different plasma gases: Ar, Ar-5%H_2 and Ar-10%H_2. Filler materials: Types A and C. Shielding gas argon (15 l/min) and backing gas argon (5 l/min). The other welding parameters are presented in Table 12. The failure points of specimens are given: W weld, FL fusion line and BM base material.

I - GROOVE	PLASMA GAS											
Material and material thickness	Ar				Ar-5 % H_2				Ar-10 % H_2			
	R_m [MPa]	A_5 [%]	Z [%]	Failure point	R_m [MPa]	A_5 [%]	Z [%]	Failure point	R_m [MPa]	A_5 [%]	Z [%]	Failure point
3 mm Steel 3-2, filler mat. A	780	7,5	26	5 BM	789	7,5	25	5 BM	783	7,2	20	5 BM
3-2, filler mat. C	787	7,5	24	5 BM	780	8,4	20	5 BM	790	8,1	22	5 BM
6 mm Steel 2-3, filler mat. A	659	9,8	34	5 BM	650	9,2	33	5 BM	652	8,1	25	5 BM
Steel 3-2, filler mat. A	791	8,5	26	4 BM 1 FL	767	4,0	10	5 W	785	3,2	10	5 W
3-2, filler mat. C	794	8,6	32	5 BM	789	8,6	29	5 BM	792	7,2	28	5 BM

Table 14. The results of bending tests after welding with different plasma gases: Ar, Ar-5%H_2 and Ar-10%H_2. Filler materials: Types A and C. Shielding gas argon (15 l/min) and backing gas argon (5 l/min). The other welding parameters are presented in Table 12. The appearance of cracks (c), flaws (fl) or specimens failure (f) are presented: W weld, FL fusion line and BM base material. S means the surface of the weld and R the root of the weld under the tensile stress. All five experiments are presented.

I - GROOVE	PLASMA GAS					
Material and material thickness	Ar		Ar-5 % H_2		Ar- 10 % H_2	
	Bending angle [°]	Failure type and point	Bending angle [°]	Failure type and point	Bending angle [°]	Failure type and point
3 mm						
Steel 3-1, filler mat. A	1 180	R	1 180	R		
	2 165	c FL S	2 180	S		
	3 180	R	3 180	R		
	4 180	R	4 180	S		
	5 180	R	5 180	R		
3-2, filler mat. A	1 150	c FL S	1 155	c FL S	1 180	S
	2 180	R	2 180	R	2 155	fl W R
	3 160	c FL S	3 180	S	3 180	S
	4 180	S	4 180	S	4 180	S
	5 180	R	5 180	R	5 150	c W R
3-2, filler mat. C	1 155	c FL S	1 180	S		
	2 180	S	2 135	fl FL S		
	3 180	R	3 180	S		
	4 180	S	4 180	R		
	5 180	S	5 180	S		
6 mm						
Steel 2-1, filler mat. A	1 180	R	1 180	S		
	2 180	S	2 180	S		
	3 180	S	3 180	R		
	4 180	R	4 170	c FL S		
	5 180	S	5 180	R		
2-3, filler mat. A	1 180	S	1 180	S	1 160	c FL S
	2 180	S	2 180	S	2 180	S
	3 180	R	3 180	R	3 180	R
	4 170	c FL S	4 180	S	4 155	fl W S
	5 180	S	5 180	S	5 180	S
Steel 3-1, filler mat. A	1 125	f FL S				
	2 180	S				
	3 180	R				
	4 180					
	5 180					
3-2, filler mat. A	1 180	S	1 180	S	1 180	S
	2 180	R	2 180	R	2 160	c W R
	3 180	S	3 110	f W S	3 160	fl W S
	4 180	S	4 180	S	4 180	S
	5 180	S	5 180	S	5 180	S
3-2, filler mat. C	1 165	c FL S	1 180	S	1 180	S
	2 180	S	2 180	S	2 180	S
	3 180	R	3 180	R	3 180	R
	4 180	S	4 170	c FL S	4 150	f W S
	5 180	S	5 180	S	5 160	fl FL S

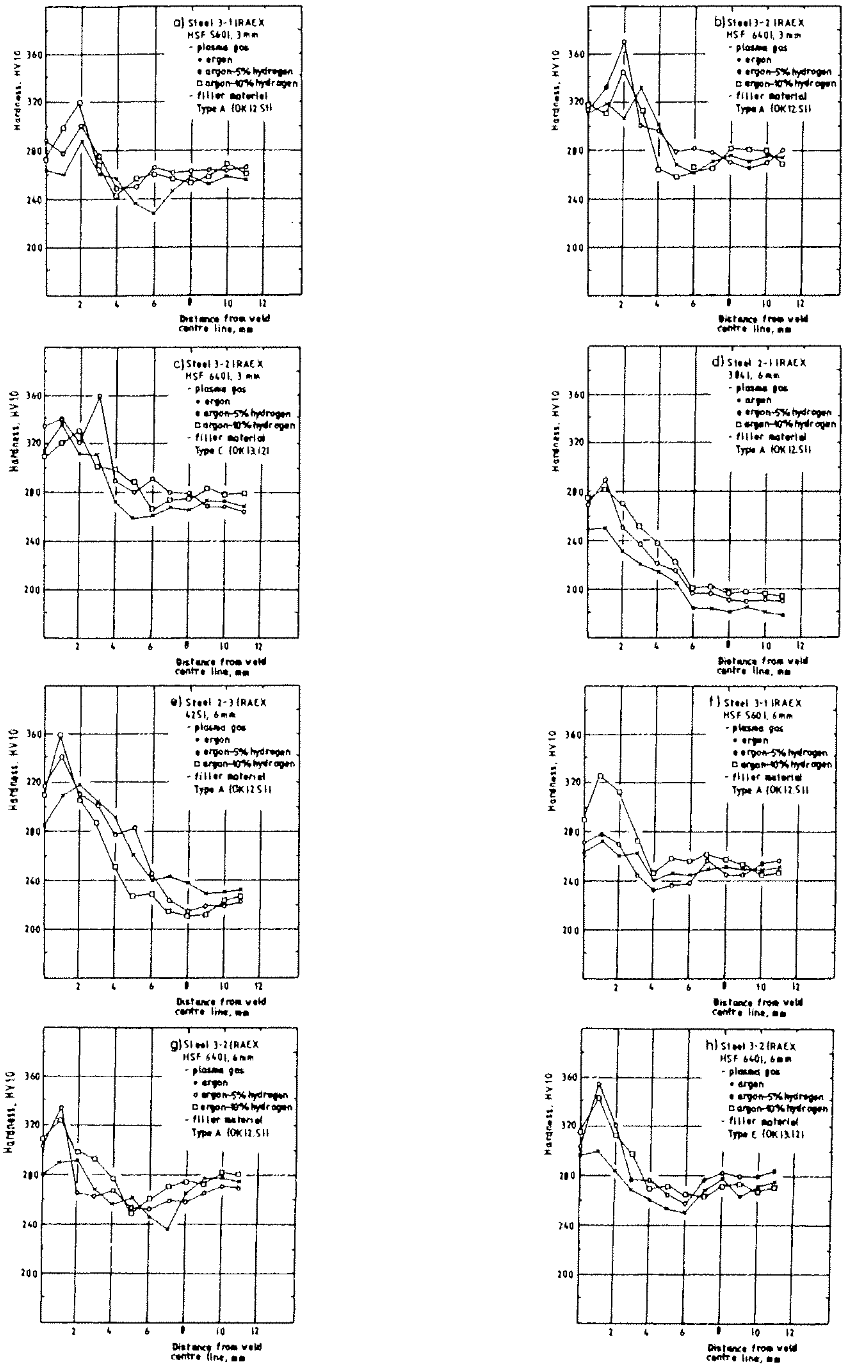


Figure 21. The hardness distributions of joints welded with different plasma gases: Ar, Ar-5%H_2 and Ar-10%H_2. Filler materials: Types A and C. Shielding gas argon (15 l/min) and backing gas argon (5 l/min). The other welding parameters are presented in Table 12.

Table 15. The maximum hardness values of joints welded high strength microalloyed and strong formable microalloyed steels with different filler materials and plasma gases.

Material and material thickness	3-1 (HSF 560) 3mm	3-2 (HSF 640) 3mm	3-2 (HSF 640) 3mm	2-1 (RAEX 384) 6mm	2-3 (RAEX 425) 6mm	3-1 (HSF 560) 6mm	3-2 (HSF 640) 6mm	3-2 (HSF 640) 6mm
Filler material	A	A	C	A	A	A	A	C
Plasma gas								
argon	285	332	334	250	318	272	292	300
argon-5%H_2	300	368	360	290	340	278	332	356
argon-10%H_2	320	345	330	282	358	324	324	344

6.3.4 The solubility of hydrogen in the weld metal with different plasma and shielding gases

The solubility of hydrogen from plasma and shielding gases in the weld metal were studied with high strength microalloyed (Steel 2-3) and with strong, formable microalloyed steels (Steel 3-2). Filler materials were not used in these experiments.

Initially the proportional amount of soluble hydrogen in the weld metal welded with different argon-hydrogen plasma gases were measured. The hydrogen content of the argon plasma gas varied from 2 to 10 %. Pure argon was used as a shielding and backing gas. The filler material was type A. Hydrogen contents in weld metal measured with the IIW mercury method are presented in Table 16. Figure 22 shows the corresponding results in the diagramatic form.

In the second stage the effects of the hydrogen content of the plasma and/or shielding gas were studied using different combinations of each:

plasma gas	argon	SH5	SH5	SH10
shielding gas	SH5	argon	SH5	argon

The soluble hydrogen contents were measured with the IIW mercury method and with the hot extraction method. The results of these experiments are presented in Table 17.

Table 16. The hydrogen content [ml/100g weld metal] of weld metal as a function of hydrogen content of argon plasma gas. Measured with the IIW mercury method.

I-GROOVE	STEEL		
Hydrogen content [%]	Steel 3-2 RAEX HSF 640 3 mm	Steel 2-3 RAEX 425 6 mm	Steel 3-2 RAEX HSF 640 6 mm
2	0,8	0,7	0,8
3	1,5	0,9	1,1
5	1,9	1,9	2,0
7,5	2,5	2,2	2,5
10	2,8	2,5	2,7

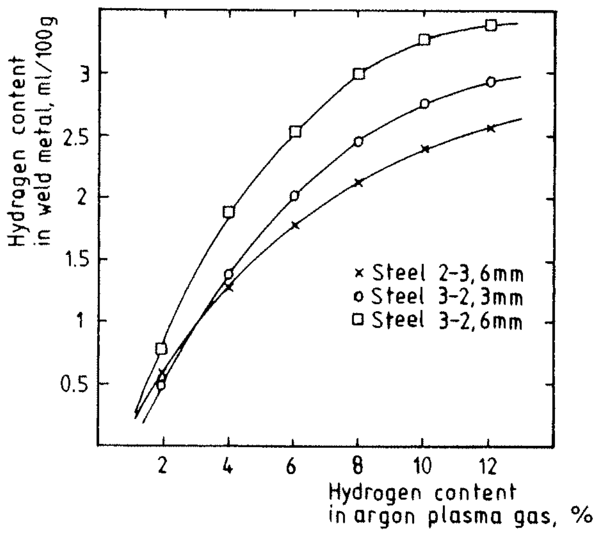


Figure 22. The hydrogen content [ml/100 g weld metal] of the weld metal as a function of the hydrogen content of the argon plasma gas. Measured with the IIW mercury method.

Table 17. The hydrogen content [ml/100 g weld metal] of the weld metal welded with different combinations of plasma and shielding gases. The hydrogen contents are measured with the IIW mercury and hot extraction methods. Steel 3-2 (RAEX HSF 640), plate thickness 6 mm.

I - GROOVE	Plasma gas / Shielding gas			
Measuring method	Ar/SH5	SH5/Ar	SH5/SH5	SH10/Ar
IIW mercury method	2,2	2,4	3,5	4,9
Hot extraction -method	5,0	5,4	7,1	8,9

6.3.5. The effect of backing gas on weld quality

Four steels (Steels 1-1, 1-2, 1-3 and 1-4) were welded with four different backing gases and without any backing gas. The experiments were performed as a keyhole welding in the flat position with a closed joint. The thickness of base material was 3 mm.

The flow of backing gas was 10 l/min in all experiments. Argon-5% hydrogen (SH5) was the plasma gas (flow 4,5 l/min) and pure argon the shielding gas (flow 15 l/min). The other welding parameters are given in Table 9, case b). The appearance of the root were examined visually in all cases. A summary of the visual examinations are presented in Table 18.

Table 18. The appearance of the root when welding unalloyed structural steels with different backing gases (flow 10 l/min) and without backing gas. Argon-5% hydrogen was used as the plasma gas (4,5 l/min) and argon as the shielding gas (15 l/min).

Backing gas	Appearance of root
a) argon (Ar)	- root neat and regular, partly clear metallic surface
b) nitrogen (N)	- root regular, grey-coloured surface
c) nitrogen - 10% hydrogen	- root regular, clear metallic surface on the whole width of backing bar
d) carbon dioxide (CO_2)	- root irregular, oxidized surface
e) without backing gas	- root irregular, often concave and oxidized surface - a closed backing bar gives a better shape to the root

6.3.6 The solubility of nitrogen from the backing gas on weld metal

The purpose of this study was to clear up the effect of plasma arc gas composition on the solubility of nitrogen from the backing gas on the weld metal. Argon and argon-5% hydrogen (SH5) were used as plasma gases and pure nitrogen (N_2) and nitrogen-12% hydrogen (Fo) as backing gases. Argon was the shielding gas in all experiments.

The experimental materials were Steels 2-3 and 3-2 with material thicknesses 3 and 6 mm. Filler material was not used.

The nitrogen contents in the weld metal were measured with the hot extraction-method and were compared with basic nitrogen levels of the base materials. The results are presented in Table 19.

Table. 19. The nitrogen content [wt-%] of weld metal welded with different combinations of plasma and backing gases. The basic nitrogen levels of base materials are presented in brackets. Plasma gases argon and argon-5% hydrogen (SH5), backing gases pure nitrogen (N_2) and nitrogen-12% hydrogen (Fo) and shielding gas argon. The nitrogen contents are measured with the hot extraction-method.

I - GROOVE	Plasma gas / backing gas			
Material and material thickness	argon/N_2	argon/Fo	SH5/N_2	SH5/Fo
3 mm Steel 3-2	0,022(0,011)	0,016(0,011)	0,011(0,011)	0,010(0,011)
6mm Steel 2-3	0,013(0,008)	0,012(0,008)	0,008(0,008)	0,009(0,008)
Steel 3-2	0,016(0,010)	0,014(0,010)	0,012(0,010)	0,011(0,010)

6.3.7 The effect of the surface quality of the base material on weld quality

To clear up the effect of the surface quality of the base material on weld quality two steels (Steels 1-2 and 1-4) were welded with different qualities of surface. Steels 1-2 and 1-4 were chosen on the basis of earlier results because of their neat and smooth welds.

The plate surfaces studied were:

- sand blasted (quartz sand)
- shot blasted (steel shot)
- ground (grinding stone)
- non-treated (hot rolling scale).

The experiments were performed in the flat position with I-grooves with machined groove faces. Plate thickness was 3 mm. The welding parameters are presented in Table 20. Results of visual and radiographic examinations are shown in Table 21.

Table 20. The welding parameters for experiments to study the effect of surface quality of the base material on weld quality. Base materials: Steel 1-2 Fe 37B (Si-deoxidized) and 1-4 Fe 37B (Si+Al-deoxidized and CaSi-injected). Filler material: Type A, OK Autrod 12.51, Ø 0.8 mm.

I-GROOVE	Welding parameters					
Material and material thickness	Welding current I [A]	Welding speed v [cm/min]	Wire feed rate v_f [cm/min]	Plasma gas flow rate Q_{pg} [l/min]	Shielding gas flow rate Q_{sg} [l/min]	Backing gas flow rate Q_{bg} [l/min]
3 mm						
				SH5	argon	argon
a) Steel 1-2	185	59	60	4,5	16	10
b) Steel 1-4	165	49	53	4,5	16	10

Table 21. The influence of surface quality on weld quality.

	Behaviour of weld pool, appearance of weld and internal weld defects
3 mm	
a) Steel 1-2	
- both sides sand blasted	- slag on the weld pool, slag make the weld face irregular - no internal weld defects
- both sides ground	- no slag on the weld pool - smooth weld face, shallow line groove in the middle of the reinforcement - no internal weld defects
b) Steel 1-4	
- rolling scale on the side of the root, the side of the weld face shot blasted	- behaviour of the weld pool like the ground plates - irregular joining of root with base material - no internal weld defects
- rolling scale on the side of the weld face, the root side shot blasted	- more slag than with ground plates, no effect on quality of weld face - no internal weld defects

6.3.8 The effect of nozzle on weld penetration and welding speed

The effects of the nozzle and working distance on the penetration and welding speed for I-groove and root welding were studied as described below.

The I-groove welding experiments were performed in the flat position without filler material. Steel 1-5 in thicknesses of 5, 6, 7 and 8 mm, was used as the base material. Root welding experiments were also performed in the flat position using plate thicknesses of 12, 16 and 20 mm.

The nozzles studied were straight cylindrical, 60^0 restrictive, 60^0 expanding and cutting nozzle as shown in Fig. 23.

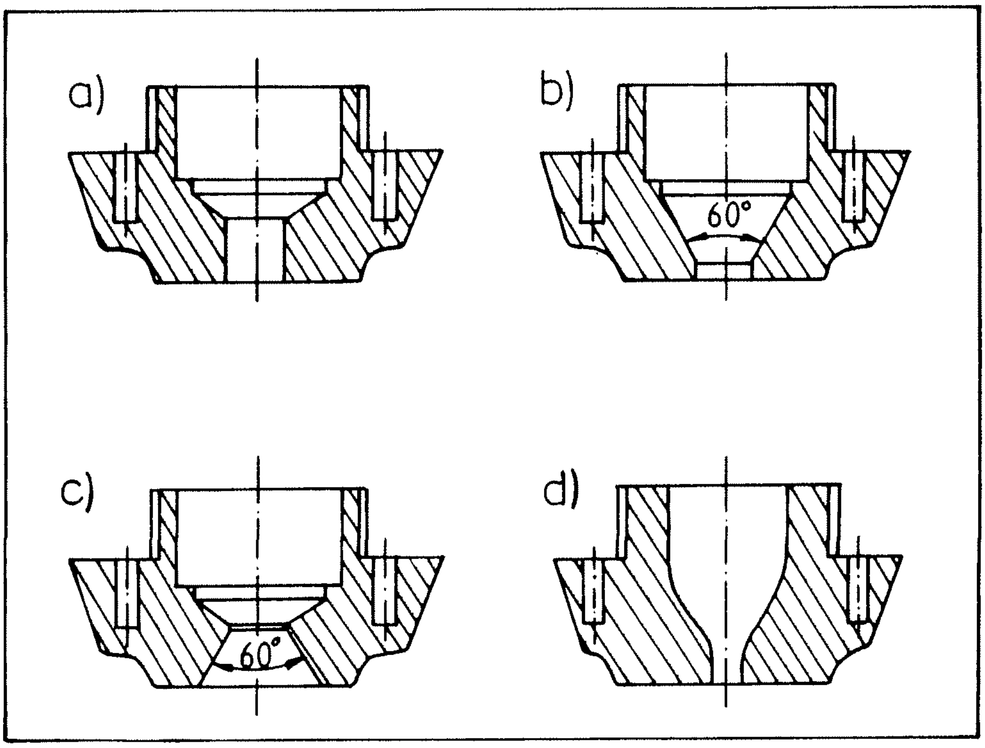


Figure 23. The nozzle types performed in nozzle experiments. a) straight cylindrical, b) 60^0 restrictive, c) 60^0 expanding and d) cutting nozzle.

The I-groove welding experiments were composed of five parts with the aim of studying the forms of penetration (Exp. 1) and required welding current (Exp. 2) by straight cylindrical, restrictive and expanding nozzles. The effect of working distance (Exp. 3), the correlation between welding current and working distance (Exp. 4) and the effect of diameter of the breakdown hole of the nozzle on welding speed (Exp. 5) were studied by straight cylindrical nozzle types. The experiments with welding parameters are presented in Table 22.

The results of these experiments are shown in Figures 24 to 27. Fig. 24 (penetration) is based on Exp. 1. The penetration is clearly lower with an expanding nozzle than with other types of nozzles. Exp. 2 shows that the required welding current with an expanding nozzle is higher than with the others, Table 22. Fig. 25 shows penetration as a function of working distance with a straight cylindrical nozzle. The correlation between working distance and welding current are seen in Fig. 26. The diameter of the breakdown hole affects welding speed particularly at small hole diameters, Fig. 27. The effect is the same for all plate thicknesses.

Table 22. The welding parameters for I-groove experiments used to study the effects of nozzle types on penetration and welding speed.

I-GROOVE	Welding parameters						
Material and material thickness	Welding current I [A]	Welding speed v [m/min]	Plasma gas flow rate Q_{pg} [l/min]	Shielding gas flow rate Q_{sg} [l/min]	Backing gas flow rate Q_{bg} [l/min]	Working distance l [mm]	Nozzle diameter d_n [mm]
Steel 1-5							
6 mm							
Exp. 1:							
(form of penetration)			SH5	argon	argon		
- straight cylindrical,	215	23	2,5	15	15	6	3,5
restrictive and ex-	215	23	2,5	15	15	6	3,5
panding nozzles	215	23	2,5	15	15	6	3,5
Exp. 2:							
(welding current required)			SH5	argon	argon		
- straight cylindrical	300	31	2,5	15	15	6	4,0
- restrictive	300	31	2,5	15	15	6	4,0
- expanding	330	31	2,5	15	15	6	4,0
Exp. 3:							
(variable working distance)			argon	argon	argon		
- straight cylindrical	300	32	2,5	15	15	3	4,6
	300	32	2,5	15	15	6	4,6
	300	32	2,5	15	15	9	4,6
	300	32	2,5	15	15	12	4,6

Exp. 4:
(correlation between welding current and
working distance)

			SF6	argon	argon		
- straight cylindrical	300	32	2,5	15	15	3	4,6
	350	32	2,5	15	15	6	4,6
	380	32	2,5	15	15	9	4,6
	410	32	2,5	15	15	12	4,6

5,6,7 and 8 mm

Exp. 5:
(diameter of breakdown hole and
welding speed)

			SF6	argon	argon		
- straight cylindrical	190 ...405	20 ...42	2,6 ...2,8	15	15	5 ...5,5	3,0

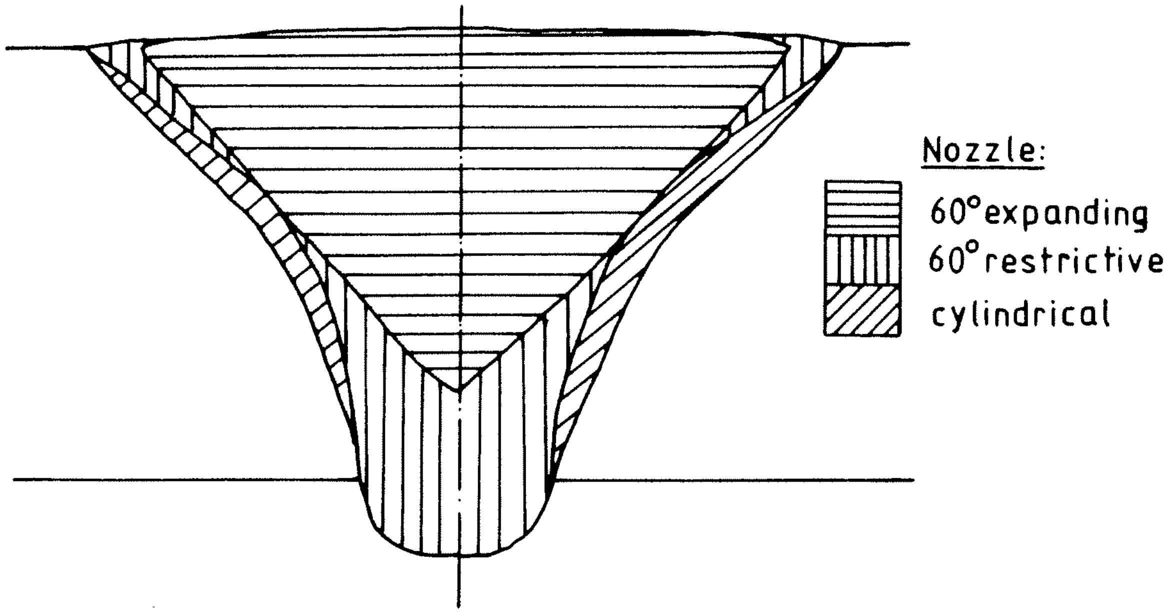


Fig. 24. The types of penetration for straight cylindrical, restrictive and expanding nozzles.

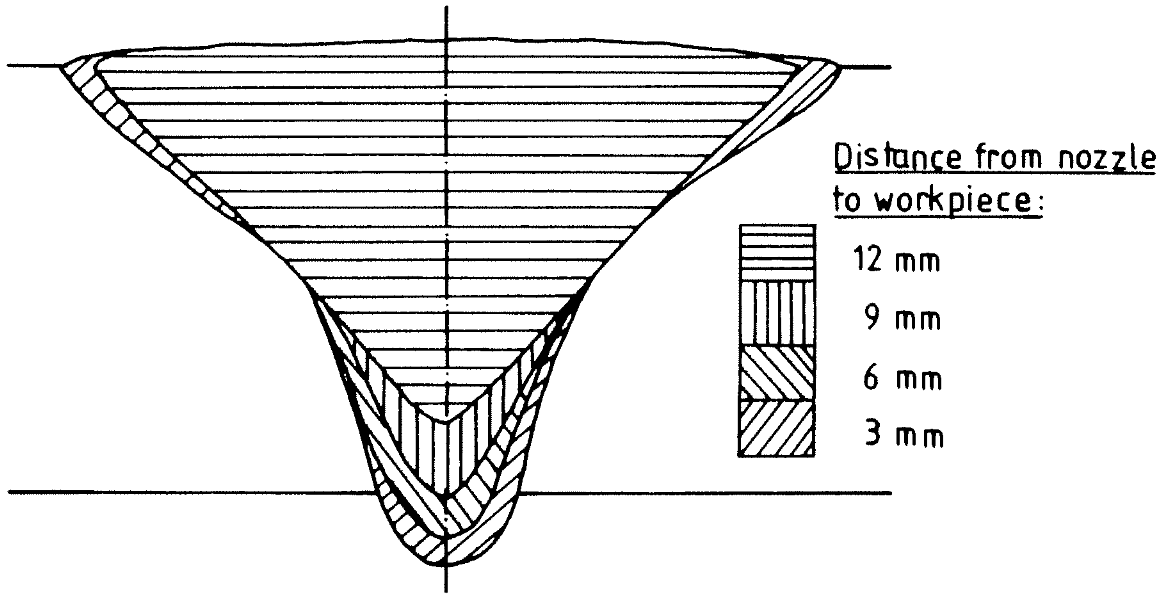


Fig. 25. The types of penetration for different distances between the nozzle and the workpiece for a straight cylindrical nozzle.

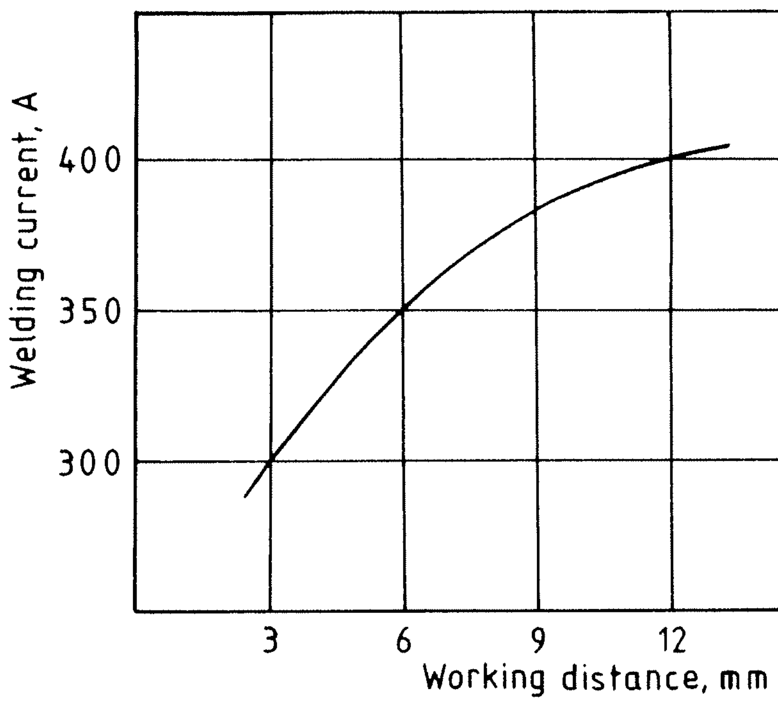


Fig. 26. The relationship between working distance and welding current for a straight cylindrical nozzle.

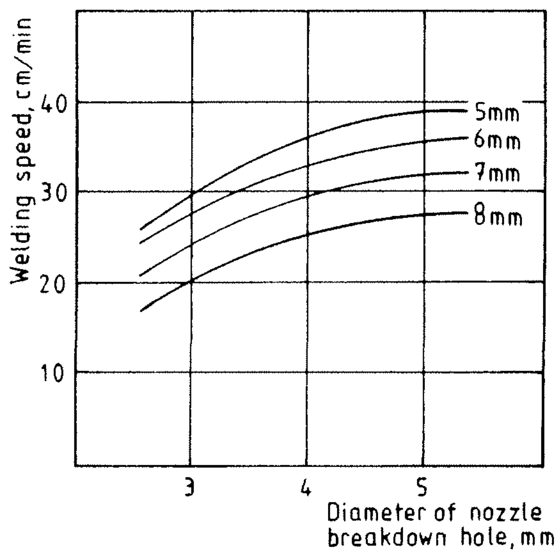


Fig. 27. The effect of the diameter of the break-down hole on welding speed for different plate thicknesses. Straight cylindrical nozzle.

In root welding the distance from the nozzle to the root is considerable higher than for I-groove welding. E.g. the distance from the nozzle to root face is 16 to 18 mm for 20 mm plate when the corresponding distance For I-groove welding is 2 to 3 mm. To ensure full penetration the welding energy must be greater than for corresponding I-groove welding.

In addition to straight cylindrical, restrictive and expanding nozzles, a cutting nozzle was also studied in the root welding experiments. The cutting nozzle causes an efficient flow of plasma gas that is not sensitive to the working distance. The effect of nozzle design in root welding was established using experiments shown in Table 23.

Table 23. The welding parameters used in root welding experiments to study the effect of nozzle design.

Y-GROOVE			Welding parameters						
Material and material thickness	Welding current I [A]	Welding speed v [cm/min]	Plasma gas flow rate Q_{pg} [l/min]	Shielding gas flow rate Q_{sg} [l/min]	Backing gas flow rate Q_{bg} [l/min]	Working distance l [mm]	Nozzle diameter ϕ [mm]	Root face h_{rf} [mm]	Groove angle α [^{0}]
Steel 2-2									
Exp.1:									
(welding current required)									
12 mm			SH5	argon	argon				
- straight cylindrical	260	21	4,2	15	5	8	3,0	6	60
- restrictive	260	21	4,2	15	5	8	3,0	6	60
- expanding	>350	21	4,2	15	5	8	3,0	6	60
- cutting	220	21	2,1	15	5	8	3,0	6	60
20mm									
- straight cylindrical	285	18	4,3	15	5	18	3,0	4	60
- restrictive	285	18	4,3	15	5	18	3,0	4	60
- expanding	welding is unsuccessful								
- cutting	240	18	2,2	15	5	18	3,0	4	60
Exp.2:									
(diameter of breakdown hole and welding speed)									
12 mm			SH5	argon	argon				
- straight cylindrical	240	18	4,2	15	5	8	3,0	6	60
	...310	..25	4,2	15	5	8	...4,5	6	60
- cutting	180	18	2,1	15	5	8	3,0	6	60
	...260	..25	2,1	15	5	8	...4,5	6	60
20 mm									
- straight cylindrical	260	14	4,2	15	5	18	3,0	4	60
	...340	..22	4,2	15	5	18	...4,5	4	60
- cutting	220	14	2,1	15	5	18	3,0	4	60
	...270	..22	2,1	15	5	18	...4,5	4	60

In root welding the penetration obtained with the various nozzle types is similar to that obtained in I-groove welding. The penetration caused by the cutting nozzle is the narrowest but at same time the risk of excessive penetration is the greatest. In I-groove welding the cutting nozzle causes undercut and a rough weld face. In root welding the appearance of the weld face is not so important.

The expanding nozzle is not suitable for root welding due to wide column of plasma arc. Then the keyholing is not possible by useful values of welding current. The effects of diameter of breakdown hole of straight cylindrical and cutting nozzles on welding speed are seen in Fig. 28.

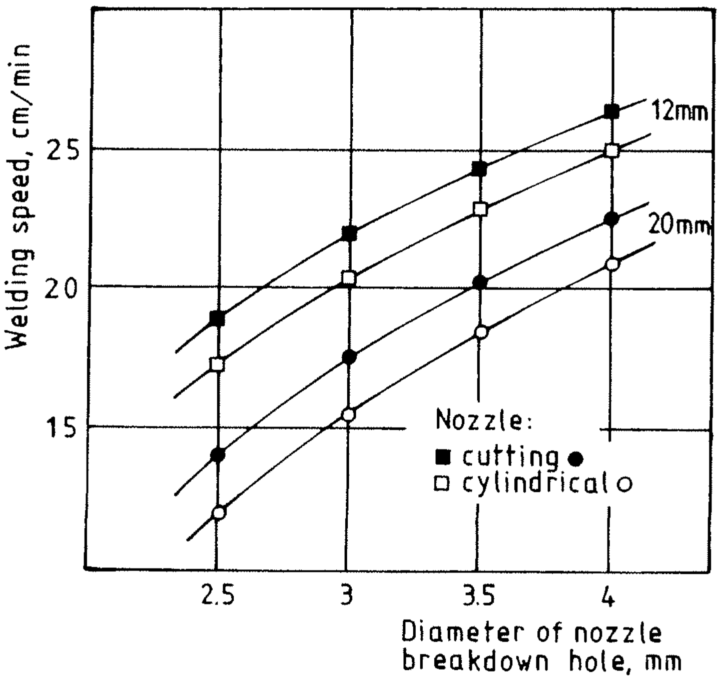


Fig. 28. The effect of the diameter of the breakdown hole on welding speed in the root welding of 12 and 20 mm plates. Straight cylindrical and cutting nozzles.

6.3.9 Weld distortion in plasma keyhole welding

The distortions introduced when welding flat butt welds of a strong formable microalloyed steel (Steel 3-2, RAEX HSF 640) have been measured for the geometry shown in Fig. 29. The welding parameters are given in Table 24. The results of welding using MIG, TIG, submerged arc (SAW) and plasma methods are given in Table 25.

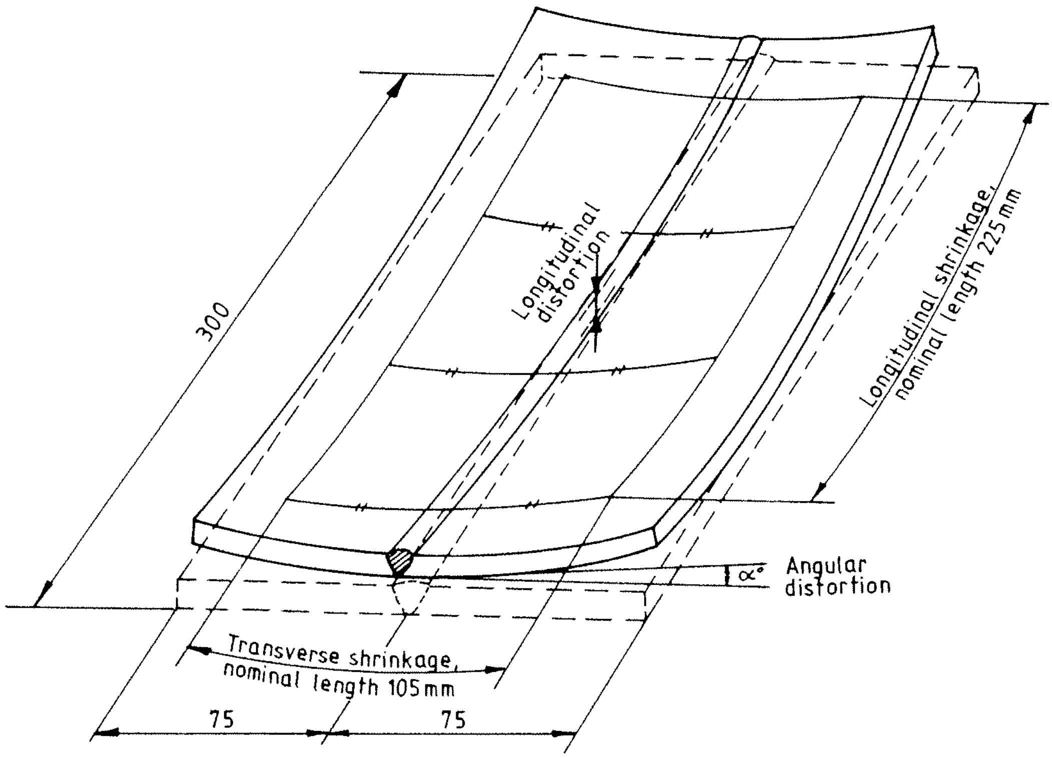


Figure 29. Weld distortion test pieces. The geometry of the test pieces and the measuring points are presented. Material thickness 4 mm.

Table 24. The welding parameters used for distortion tests on strong formable microalloyed steel (Steel 3-2, RAEX HSF 640).

	MIG	TIG	SAW	Plasma
* current A	201	252	420	206
* voltage V	24.0	14.0	30.0	16.5
* speed cm/min	36.5	24.5	67.0	45.0
* energy kJ/cm	7.9	8.6	11.2	4.5
* shielding gas	SK20	argon	-	argon
* backing gas	-	-	-	argon
* plasma gas	-	-	-	SH5
* filler material	OK Autrod 12.64	OK Tigrod 13.09	OK Autrod 12.22	OK Autrod 12.64
* powder	-	-	-	OK Flux 10.70
* groove form	Y	Y	I	I

Table 25. Distortions in butt joints measured as shown in Fig. 29 using plasma and conventional methods. * nominal length 225 mm, ** nominal length 105 mm. Base material microalloyed RAEX HSF 640 steel and material thickness 4 mm.

	MIG	TIG	SAW	Plasma
longitudinal shrinkage, mm *	0.28	0.33	0.60	0.24
transverse shrinkage, mm **	0.16	0.68	0.46	0.06
longitudinal distortion, mm	2.9	3.7	6.7	1.4
angular distortion, ^{0}	2.2	4.0	3.2	1.0

6.3.10 Other complementary experiments

In addition to the experiments described above experiments were also carried out to investigate the following:

- groove preparation,
- acceptable groove tolerances,
- the need for and the effects of filler material and
- the effect of welding energy on microstructures.

The results of these experiments are presented in the discussion section.

7. DISCUSSION

In the welding work the quality, productivity and economy improvements are crucial for survival. New welding methods and new applications of conventional methods create the necessary conditions for making high quality products economically. With this in mind plasma keyhole welding has been studied and developed for welding structural steels.

In industrial fabrication plasma keyhole welding is used successfully for welding high alloyed steels and titanium and its alloys. The usual opinion is that the plasma keyhole welding of structural steels is impossible or anyhow very unreliable. The physical chracteristics of structural steels (low viscocity and low surface tension of the molten metal) together with the high energy density of the plasma arc (a heat arc and a keyhole mode in welding) cause that control of keyhole stability and molten weld metal is difficult. Drews and Böhme (1975), Böhme (1977), Larue and Thomsen (1980), Messager and Cuny (1982), Engfeldt and Fager (1984), Nielsen (1984), Cuny (1986), Moisio (1986) and Bakarjiev and Varbenova (1987), have shown by single experiments that even structural steel can be welded in flat position without weld defects using the plasma keyhole technique. In those studies the conditions and possibilities of the plasma keyhole welding have not been widespreadly characterized or systemised and the qualities of the welds have been very variable. The single and interactive effects of welding parameters on weld quality have not been precisely elucidated. It has also been said that the plasma keyhole welding of structural steels in horizontal-vertical and vertical positions is quite impossible.

The present study together with single studies mentioned above shows that plasma keyhole welding is a useful method for both unalloyed and microalloyed structural steels giving welds with good quality with relatively good mechanical properties without weld defects. This study shows the technological conditions to weld repeatedly and with a high quality structural steels with different compositions and material thicknesses and in various welding positions. The study also evaluates the effects of welding parameters on weld quality.

7.1 The conditions for welding

The weld quality of keyhole welding depends on the keyhole stability which itself depends on the combinations of the principles of welding and variable welding parameters. When the keyhole is achieved, it must be maintained and it does not close and the melt must be held together. Sosnin and Shemonaev (1981) have shown that in welding with a penetrating arc an important role is played by the hydrodynamic processes which take place in the molten weld metal and are directly connected with the forces affecting in the arc and thermal circumstances in the welding zone. The investigations by Sosnin (1988) show that the stability of keyhole welding process is determinated by the coefficient of welded metal surface tension and the hydrodynamic and thermal circumtances which are characterised by the thermal efficiency of the process and optimum combinations of the welding parameters.

According to Quigley (1984), as seen in Eq. (1) to (5), the high beam pressure (p_b), recoil pressure (p_r) and vapour pressure (p_v) increase the depth of the keyhole, or in other words high power densities with associated high pool temperatures and vapour pressures lead to the greatest weld penetrations. Gravitational pressure (p_g) at any point in the liquid surrounding the keyhole is directly proportional to the density and height of the metal above it. Surface tension pressure (p_γ) tends to minimise the surface area of a liquid and close the keyhole if the material thickness is greater than the keyhole diameter. If the material thickness is thinner than the keyhole diameter, surface tension tends to pull the molten metal back to the parent material, overcoming the force tending to close the keyhole and so producing a cut.

By Drews and Böhme (1975) in plasma keyhole welding the keyhole is produced mainly by the pressure of the impinging gas and by the high concentration of heat input. In welding, behind the plasma jet, the molten metal flows together as a result of the surface tension and the gravitational pressure in the keyhole, solidifies and forms the weld. Quigley (1984) shows that the effect of vaporisation is not dominant, however the vapour pressure has a significant effect on the plasma keyhole process as compared with conventional methods.

This study shows that there are regions of the technological conditions of plasma keyhole welding in which welds of high quality are formed not only in materials normally welded by this method (high alloy steels and titanium) but also in structural steels. The principles that must be taken into consideration when welding with plasma keyhole method structural steels are:

- material thickness
- groove form
- groove preparation
- surface quality
- groove tolerances
- welding position
- nozzle type

These principles together with the knowledge of the effects of the variable welding parameters create the necessary conditions for successful welding. Plasma keyhole welding must be mechanized because of difficulties in manually maintaining a consistent welding speed, torch position, gas protection, filler material addition etc.

Material thickness and groove form

Butt welding experiments of this study show that plasma keyhole welding can be successfully used for structural steels to produce without backing I-groove welds in material thicknesses of 3 to 6 mm or to 10 mm depending on composition of the base material. Reliable I-groove welding is possible for material thickness of 3 to 6 mm in the case of unalloyed structural steels and of 3 to 10 mm in the case of high strength microalloyed steels. When material thickness is over the range of I-groove, a V-, Y- or U-groove is necessary. In thick plate welding all usual forms of groove are possible but single V-groove, single V-groove with a root face (Y-groove) and single U-groove are most useful due to the possibility of one-side welding.

The groove form is determinated primarily by material thickness and the need for complete penetration. The other factors are joint gap, nozzle type (Figs 24 and 28), working distance (Figs 25 and 26) and to some extend also welding position. The most useful groove is the single V-groove with a root face (Y-groove). As seen in Fig. 17 and in Table 7, depending on material thickness the root face should be from 4 to 8 mm and root angle from 40^0 to 60^0. In this case welds are reminiscent of I-groove welds. Excessive melting of the root edge and excessive penetration are problems in the welding of a single V-groove without root face. U-groove welding is like I-groove welding, Fig. 18, but the cost of single U-groove preparations often prevent its use. The natural application of plasma keyhole welding for thick plates is for the root pass only because more effective methods (e.g. MIG/MAG and submerged arc welding) are available for welding the filling layers.

Groove preparation and surface quality

The groove faces can be machined or flame-cut. Machining is naturally suitable with regard to the tolerances of the groove and the cleanness of the groove faces but high quality flame-cutting can also be sufficient in some cases. As seen in Table 21 the surface quality of the base material do not affect the internal quality of the weld but to some extent the quality of weld face. When the surfaces of the base materials are ground the weld face is clearest and smoothest.

Groove tolerances

The tolerances of groove preparation and joint gap are smaller for plasma keyhole welding than for TIG welding for example. According to Messager and Cuny (1982) the maximum acceptable gap between plate edges increases from 0,5 to 2 mm, when the thickness increases from 3 to 12 mm. In this range, the maximum height difference between the plates is from 0,8 to 2 mm. Bakardjiev and Varbenova (1987) have arrived at the following result: the gap in the I-groove welding changes from 0 to 1 mm, when the thickness increases from 2 to 5 mm. In root welding the gap of a V-groove increases from 0 to 1 mm, when the thickness changes from 6 to 15 mm. At the same time, the maximum difference in the level of the plates can increase from 0 to 1 mm.

This study shows that the greatest joint gap allowed both in butt welding with I-groove and in root welding is about 1,5 mm, when welding with filler material. If the joint gap is greater the risk of excessive penetration is present. If the joint gap is smaller than about 0,3 mm the use of filler material is unnecessary. It is important that the groove faces are parallel and of equal size on the whole welding length.

Plasma keyhole welding can be performed with or without filler material. The primary purpose of the filler material is to relieve the groove tolerances, and so to improve the joining between base materials. The filler material has also in some cases a metallurgical role. The feed of filler material can performed either with the leftward wire welding or with the rightward wire welding.

As said, the use of filler material relieves the groove tolerances, but increases the welding energy, stresses and distortions. From the point of view of the economy of the whole welding work the low level of distortion in plasma keyhole welding is very important. As seen in Table 25 the angular distortions between plates caused by plasma keyhole welding without filler material are about 1/2 of those in MIG welding, about 1/3 of those in SAW welding and 1/4 of those in TIG welding. The same tendency also exists in the longitudinal and transverse shrinkages and in the longitudinal distortions.

Welding position

Welding is possible in flat, horizontal-vertical and vertical positions (Figs 8 to 16). In flat and horizontal-vertical positions it is possible to achieve the highest weld quality, but in vertical position it is impossible because of incompletely filled groove (Figs 10, 13 and 16).

The penetration in the horizontal-vertical and vertical positions is 2 to 3 mm smaller than in the flat position welded with the same welding parameters. That is caused by the differences of the forces affecting the keyhole. However in horizontal-vertical and vertical positions the welding energy can be higher, as seen in Figs 8 to 16, without excessive penetration such that the same penetration as in flat welding can be reached. In horizontal-vertical position the solid base material under the molten weld metal and in vertical position the position of the torch (5 to 10^0 deviation down from the horizontal plane) support the molten weld metal.

Nozzle type

Nozzle dimensions, shape and constriction affect the nature of plasma jet and thereby also the welding process. With mechanical constriction of the arc, the keyhole is only steady for currents less than 250 A. Above this the outer layers of cold gas that normally isolate the plasma from the nozzle are destroyed and there are erratic double arcs. Using pneumatic constriction avoids this problem and allows the use of plasma arcs of up to 500 A without any instability or nozzle erosion. Such currents which are impossible to obtain with mechanical constriction, are necessary for welding structural steels because of their high thermal conductivity, [Messager and Cuny (1982)].

Larue and Thomsen (1980) recommend that the mechanical constriction of the plasma gives a very confined arc (precious for position welding), but limited in intensity to about 200...250 A. The pneumatic constriction of the plasma allows an increase of the arc power and an increase of the thicknesses that can be welded.

The present study shows that both straight cylindrical and restrictive nozzles are useful for butt joint welding with I-groove. As shown in Fig. 28 and in Table 23 in root welding in addition to straight cylindrical and restrictive nozzles it is also possible to use cutting nozzle. It provides the narrowest penetration but at the same time the risk of excessive penetration is greatest. In butt joint welding with I-groove the cutting nozzle causes a undercut and the weld face is rough.

The investigations by Sosnin (1988) show that an increase of the concentration of heat input in plasma welding is possible especially with an increasing I/d_n ratio, where d_n is nozzle diameter and I is welding current. However, to prevent the formation of a dual arc, it is necessary to restrict the current. Reliable welding is ensured at $d_n = 1 + 0{,}01 \times I$. Thus, according to Sosnin (1988), the increase of plasma welding rate, associated with increasing current, increases the minimum permissible nozzle diameter d_n.

Sosnin and Shemonaev (1981) have demonstrated that the extent of restriction of the maximum value of d_n is determinated by the increase of the pressure spot diameter D_p to the dimensions of the pool crater $D_{cr} = 0{,}9B$ (Fig. 6.), where B is the weld width. At $D_p \rightarrow D_{cr}$ the liquid metal flow rate on the crater sidewalls rapidly increases and the extend of undercutting of the welded joint becomes greater. In addition to this the diameter of the crater outlet orifice d_0 and the probability of burnthrough increase. Taking the above ratios into account the maximum possible nozzle diameter is $d_{n\ max} = 0{,}64...0{,}69B$. If a reduction of welding speed is allowed or it is necessary to reduce the extent of undercutting, it is convenient to reduce d_n. According to Sosnin and Shemonaev (1981) the minimum possible nozzle diameter $d_{n\ min} = 0{,}32...0{,}35B$. Thus, the optimum range of d_n is $0{,}4...0{,}6B$.

Figs 8 to 16 of this study show that the optimum nozzle diameter in welding structural steels is $d_n = 0{,}4B$. If the increase in extent of undercutting is permissible, d_n can be inreased to 0,6B, and at the same time the welding speed can be doubled. Figs 27 and 28 show that the effect of the diameter of the nozzle breakdown hole on welding speed is noteable for small diameters both in butt welding with I-groove and in root welding. Fig. 28 show also that the use of cutting nozzle increases the welding speed 10 to 20 % both in material thicknesses of 12 and 20 mm.

The nozzle diameter affect the diameter of keyhole crater outlet. Figs 8 to 18 show that, because of the characteristics of the weld pool of structural steels, the diameter of keyhole crater outlet must be $d_0 < 0,2...0,3$ x weld width. That minimizes the risk of excessive penetration and weld metal run-through.

7.2 The effect of base material

7.2.1 Unalloyed structural steels

The possible applications of plasma keyhole welding for unalloyed structural steels are:
- butt joint with I-grooves in the material thickness range 3 to 6 mm, and
- sealing runs in single V-groove with or without root face.

The essential factors affecting the weldability of unalloyed structural steels are:
- the type of deoxidation of the steel, and
- the sulphur content of the base material.

Studies by Moisio (1986) show that the chemistry of welding gases and the method of deoxidation of base metal affect the behaviour of the weld pool. In deoxidized steels aluminium occurs mainly as a high melting oxides. It forms a solid slag film on top of the solidifying weld. The surface tension between the slag film and the melt makes bulges to form on the weld bead. Besides this, by Moisio, in calsium-silicon treated silicon-aluminium deoxidized steels, aluminium exists as a low melting aluminates and slag on top of the melt forms droplets on the solidifying weld. The surface is smooth. The choice of plasma gas has a detrimental effect on the weld quality.

Regardless of the type of deoxidation it is possible to produce acceptable welds as shown in Figs 8 to 10 and 19 and in Table 9. However, the type of deoxidation affects the behaviour of the weld pool and the weld quality, particularly the quality of the weld face. The risk of weld pool run-through is more greater when welding Si-deoxidized steels than welding Al-deoxidized steels. The welds of Al-deoxidized steels have local roughness because of early solidification of the Al_2O_3 rich slag films that shape the weld pool at the solidification stage. The weld face is neatest with Si+Al-deoxidized, CaSi-injected steels. Then aluminium is bound to Ca-aluminates that solidify at low temperatures so that the slag film is still liquid when the pool solidifies resulting in a smooth weld.

The mechanical properties of plasma keyhole welds in unalloyed structural steel do not cause any practical limitations as seen in Figs 8 to 10. The strength values of welds are 5 to 10 % higher than those of the base material. The deformability of the welds is excellent and impact toughness values in the weld are equal to or a little higher than those of the base material. The mixing of hydrogen (total content max 10 %) to the plasma or shielding gas does not cause any brittleness for unalloyed structural steels. Failures always happen in the HAZ about 10 to 5 mm from the fusion line. The bendability of plasma welds is excellent: it is possible to bend the flawless welds through 180^0 without cracking. Fig. 19 shows that the hardness values of the weld and the HAZ are 30 to 40 HV10 units higher than in base material regardless of the type of deoxidation.

Sulphur is a surface active element having an effect on the behaviour of the weld pool. As seen in Table 11 a higher sulphur content lowers and widens the reinforcement. It is also seen a clear noticeable infiltration line in the middle of reinforcement. Table 10 and Fig. 20 show that the welding speed is 30 to 60 % higher welding a steel with high sulphur content (0,042 wt-% S) compared to steels with low sulphur contents (0,008 - 0,012 wt-% S).

7.2.2 High strength microalloyed and strong formable microalloyed steels

The essential factors affecting the weldability of unalloyed structural steels are:
- the type of deoxidation of the steel, and
- the sulphur content of the base material.

The essential factors of high strength microalloyed and strong formable microalloyed steels affecting their weldability are:
- the chemical composition of the base material, especially carbon content,
- the metallurgical compatibility of base material, filler material and welding gases, and
- the welding energy (i.e. heat input per unit length).

It is typical of weld joints in high strength microalloyed and strong formable microalloyed steels that the changes of microstructure affect the whole area of the weld joint. Thus, as seen in Fig. 21, the hardness values of the weld metal and the HAZ, are higher than those of the base material. The reasons for this are the hardenability of those steels and the high energy density of plasma keyhole welding, which cause a straight heat distribution (i.e. both heating and cooling are very fast in a narrow area through the whole thickness of the joint).

As seen in Figs 11 to 16, on certain conditions plasma welding also produces acceptable weld joints in the high strength microalloyed and strong formable microalloyed steels. If the weld joint is defect free, the strength values of the weld are higher than those of the base material, and fracture occurs in the base material, Tables 13 and 14.

With increased alloying and strength of the base material the toughness of the welds decrease, and it is restricting the deformability. The impact toughness of plasma welds is very low without filler material or with highly alloying filler material (Types B and C). Figs 11 to 16 show that the toughness values are in these cases about 40 to 50 % lower than those of the base materials. The low-alloying filler material (Type A) gives toughness values 10 to 20 % lower than the base material.

With the strongest materials (Steels 2-4, 3-1 and 3-2) the bending angles may only be 40 to 60^0 with the first cracks appearing in the weld metal. In spite of the high hardness values of the weld metal, as seen in Fig. 21, the impact toughness values of the plasma weld joint of high strength microalloyed and strong formable microalloyed steels are comparable to the toughness reached with conventional arc welding methods, specially at room temperature. The strength, toughness and bendability of welds are not primarily dependent on welding gas types.

The decrease of ductility and the risk of weld metal cracking must be taken into consideration when welding very high strength, highly alloyed steels, especially when carbon and impurity levels (e.g. sulphur) are high. The accumulation of impurities to the weld centre line together with a strong directional solidification structure increase the risk of weld metal cracking. The solidification and segregation mechanisms of the weld pool weaken the impact toughness, because rapid solidification together with high carbon content favour the solidification of primary austenite as a result of which impurities accumulate to the grain boundaries.

Plasma welding of high strength microalloyed and strong formable microalloyed steels puts demands on the composition of the base material: low carbon content (about 0.05 to 0.10 wt-% C), low amount of impurities (especially sulphur, phosphorus and nitrogen) and low amounts of carbide-forming elements (e.g. chromium and vanadinium).

The greatest material thickness (10 mm) in butt welding with I-grooves is reached with very low sulphur and high silicon steel (Steel 2-4). Low sulphur content increases the surface tension of weld pool.

In plasma multi-run welding the mechanical properties of the weld metal and the whole weld joint are better than in single run welding. The sealing run in a V-groove cools rapidly and the temperature of phase transformation is low giving a small grain size. Also, the filling runs normalize or temper the sealing run. In multi-run welding unalloyed or lowalloyed, low strength filler material can be used, when the toughness values improve and the welding stresses decrease.

The welding energy is critical in the welding of high strength microalloyed and strong formable microalloyed steels. The magnitude of the welding energy is connected to material thickness through the welding parameters. According to the results of the butt welding experiments with I-grooves in order to obtain high quality welds the limits of welding energy in butt joint welding with I-grooves are:

s = 3 mm: I = 230...270 A ; Q = 4...7 kJ/cm
v = 60...80 cm/min

s = 6 mm: I = 230...270 A ; Q = 11...14 kJ/cm
v = 30...40 cm/min

In root welding it is impossible to give corresponding unambiguous values because in addition to the sealing run one or more filling runs are also welded.

7.3 The effect of welding parameters

The most important welding parameters affecting the weld quality of plasma keyhole welding are welding current, welding speed and welding gases, especially plasma gas flow. The quality of the weld joint depend primarily on the combinations of these parameters. The parameter windows ("quality boxes") in Figs 8 to 16 show the acceptable welding parameter combinations in butt welding with I-groove for which specific weld class (class WA in flat and horizontal-vertical positions and WC in vertical position) are obtained and combinations leading to typical weld defects.

To maintain the stability of plasma keyhole, the control of welding parameters must be very exact. Instabilities can easily result in excessive or insufficient penetration or undercutting of the weld joint.

7.3.1 The effect of welding current

The welding current affects weld quality through the arc pressure and the arc temperature. Studies by Bethlehem

(1987) and ME Technical Report (1986) show that increased welding current widens the weld on both the surface and root sides. An inadequate current level causes lack of penetration and slight undercutting in the toe area of the weld. Excessive current levels cause electrode damage either immediately in the starting stage of welding or later.

The effect of welding current on weld quality is nearly always connected to welding speed and plasma gas type and flow rate. Welding current alone has no direct effect if welding occurs inside the acceptable range of variation of current. Figs 8 to 16 show that for the highest weld class WA (WC in vertical position) the permitted range of variation of current is $\pm$ 25 A when the welding speed is constant. An increase of welding current widens the weld joint, the reinforcement and the root. Inadequate current level leads to lack of penetration and too high current level causes excessive penetration.

The appearance of the weld and the mechanical properties of the weld joint are best when a low plasma gas flow rate and high welding current are used. At the same time the welding speed will be high, which is also most economical of course.

7.3.2 The effect of welding speed

For economical reasons it is reasonable to weld at the highest possible welding speed. As seen in Figs 8 to 16 the formation of undercut determines the maximum allowed welding speed. If the increase in extent of undercutting is permissible, the welding speed can be increased. Figs 27 and 28 show that the effect of the diameter of the nozzle breakdown hole on welding speed is noteable for small diameters both in butt welding with I-groove and in root welding.

It is possible to weld acceptable welds with a wide range of variation of welding speed, if the welding current is suitable. With constant welding current the permitted range of variation of welding speed is ± 3,5 cm/min for weld class WA (WC in vertical position). Inadequate welding speed leads to the excessive penetration.

7.3.3 The effect of welding gases

The selection and the combinations of welding gases (including plasma, shielding and backing gases) affect essentially weld quality. The choice and combinations of these gases affect particularly bead width, melted zone shape and welding speed.

The effect of welding gases on the welding process are interconnected. This study shows that the following combination of welding gases gives welds with the highest quality: an argon-hydrogen plasma gas, an argon shielding gas and an argon backing gas.

7.3.3.1 The effect of plasma gas

Plasma gas has direct effects through the plasma jet on the results of welding. The composition of plasma gas and the mode of its flow have a strong effect on the behaviour of the weld pool, on the appearance of the weld, on the welding speed and on the weld defects. It is possible to use argon and argon-hydrogen mixtures as plasma gases.

Butt welding with I-groove

Pure argon is a preferred and reliable plasma gas, but it does not produce optimum results for all cases. Argon is totally inert gas and it has a low coefficient of thermal conductivity. It causes a convex and rough reinforcement. The addition of small amounts of hydrogen (about 5 %) to the argon is recommended by Böhme (1977), Nielsen (1984), Cuny (1986) and Moisio (1986). Argon-hydrogen mixtures provide a higher power density with a hotter arc, assisting in both penetration and weld-puddle fluidity. Too low a plasma gas flow rate causes electrode damage and lack of penetration. Porosity in welds and undercutting are a result of too high a plasma gas flow rate.

According to Lavigne et al. (1988), when welding with argon-hydrogen plasma gas some molecular hydrogen dissociates and ionises in the hottest areas of the arc. On contact with the molten weld metal recombination occurs, generating high pool temperatures and resulting in widening of the bead and increase in welding speed, since arc voltage is higher than in pure argon. When welding with argon-hydrogen plasma gas the surface is flatter and smoother than welding with argon plasma gas. The phenomenon becomes stronger if the percentage of sulphur in the base material increases.

Cuny (1988) has noticed and this study shows in Table 9 that when welding with argon plasma gas local yellowish slag bowls (MnO, MnSiO, MnS) form on the surface of weld pool. The phenomenon does not occur during welding with argon-hydrogen plasma gas. When welding with argon-hydrogen plasma gas hydrogen reacts with the oxides and sulfides reducing the percentage of these pure impurities.

Drews and Böhme (1975) recommend that argon plasma gas produce more easily undercut than argon-hydrogen plasma gas. This is emphasized at greater material thicknesses (6 mm), when the movement of weld pool is otherwise critical. Undercut is produced at slower welding speeds with argon plasma gas than with argon-hydrogen mixture. The difference is greater with thinner (3 mm) than thicker material (6 mm).

For material thicknesses of 3 and 4 mm, Larue and Thomsen (1980) found that it is impossible to obtain butt welds with both regular penetration and a smooth and uniform appearance when using argon plasma and shielding gas. The best results were obtained by using argon-5 % hydrogen for the plasma gas and argon-20 % carbon dioxide for the shielding gas. For thicknesses of 6 mm argon is suitable both as plasma and shielding gases.

Nielsen (1984) recommends that with pure argon as plasma and shielding gas both Si and Al de-oxidized structural steels can be welded without weld defects. By Nielsen, with 3,5 % hydrogen in the plasma gas there is little difference to pure argon, but with 7 % hydrogen in plasma gas the weld pool is unstable and it is very difficult to achieve a stable keyhole without burn through. With 3,5 % hydrogen in the shielding gas the weld pool is a little more unstable than with pure argon, and with 7 % hydrogen in the shielding gas the weld pool is very unstable and there is local porosity. With 20 % carbon dioxide in the shielding gas the weld pool is a little unstable but there is no porosity. With hydrogen in the plasma gas and carbon dioxide in the shielding gas the weld pool is very unstable, and it is difficult to get a stable keyhole without burn through, there are many pores and a high tendency for undercutting and sagging.

Studies by Cuny (1986) show that with argon-5 % hydrogen plasma gas and argon-20 % carbon dioxide shielding gas pore formation is prevented and there is a smoother surface and less tendency to undercutting than with pure argon gas.

This study shows that the use of 5 to 7 % hydrogen in argon plasma or shielding gas is possible, since the soluble hydrogen content stays at the level of 5 to 6 ml/100 g weld metal (Fig. 22 and Tables 16 and 17). It doesn't cause any brittleness not even with high strength microalloyed or strong formable microalloyed steels. An argon-hydrogen plasma gas causes a narrowest weld.

As shown in Table 8 the maximum welding speed is 30 to 40 % faster using argon-5% hydrogen plasma gas than pure argon with a material thickness of 3 mm. The corresponding value with material thickness of 6 mm is 20 to 30 %. Welding speed is raised another 6 to 8 % by using argon-10% hydrogen plasma gas instead of argon-5% hydrogen with a material thickness of 3 mm. The corresponding value with a material thickness of 6 mm is 10 to 12 %. For a given plasma gas higher values of welding current and welding speed without undercutting can be used with high strength microalloyed and strong formable microalloyed steels than with unalloyed, structural steels.

The behaviour of the weld pool and the weld quality of quenched and tempered microalloyed steel (Steel 2-4) is in principal similar to that of normalized high strength microalloyed steels (Steels 2-1, 2-2 and 2-3). However some differences should be noted. Steel 2-4 has a higher surface tension and viscocity than Steels 2-1 and 2-2 because of low percentage of sulphur. When welding with argon plasma gas the weld becomes very convex and high and undercutting easily occurs at high welding speeds. When welding with argon-hydrogen plasma gas the weld becomes flat and smooth. It is possible to weld up to a material thickness of 10 mm with I-grooves without excessive penetration. With the other microalloyed steels (Steels 2-1, 2-2 and 2-3) butt welding with I-groove is possible up to a material thickness of 8 mm. The maximum welding speed is 10 to 12 % faster with Steel 2-4 than with the other high strength, microalloyed steels examined.

Root welding

In root welding the interactive effect of welding gases is more important than in butt welding with I-groove because of the narrow and nearly closed groove space. Therefore the effect of plasma gas must be examined together with shielding and backing gases.

The results of the root welding experiments (Table 6) show that when welding with argon plasma and shielding gases the weld pool rises up to the sides of the groove and solidifies one-sided. The joining between the base materials is sharp. The use of argon-20% carbon dioxide shielding gas together with argon plasma gas increases the volume of weld. The reinforcement becomes wider. The reason for this influence is the raised temperature of the weld pool caused by dissociation of carbon dioxide. The oxygen freed by the carbon dioxide dissociation reduces the surface tension of weld pool. Besides these effects carbon dioxide in the argon shielding gas causes a slight boiling of the weld pool, slight roughness of weld surface and thin sooty slag layer to the surface of the reinforcement.

When welding with argon-carbon dioxide shielding gas slag formation is very strong. The slags are glassy, dark greenish oxide bowls. The high amount of slag shows the high oxygen potential in the weld pool. The oxygen is a result of dissociation of carbon dioxide in the shielding gas in the plasma arc atmosphere. Besides this the oxygen can also come from base and filler materials.

The effect of the addition of hydrogen to argon plasma gas in root welding is similar like with butt welding with I-groove. Hydrogen addition to argon plasma gas make it possible to use greater welding speed than with pure argon.

The addition of 5% hydrogen increases the welding speed by 20 %.

The use of argon-20% carbon dioxide shielding gas together with argon-5% hydrogen plasma gas leads to strong boiling of weld pool as a result of overheating, to the disturbance and splashing of the weld pool and to the formation of open voids on the surface of the reinforcement.

The effects of plasma gas on the root welding of quenched and tempered steel (Steel 2-4) are similar to those observed with the other high strength microalloyed steels (Steels 2-1, 2-2 and 2-3).

7.3.3.2 The effect of shielding gas

The shielding gas, in addition to protecting the molten metal, penetrates into the plasma stream, and depending on its physical properties, affects arc and weld properties.

The effect of shielding gas on the weld quality of plasma welding is not so important as that of the plasma gas, but it can not be entirely ignored. The effects are particularly noticeable in root welding. The possible shielding gases are argon, argon-hydrogen, argon-carbon dioxide and argon-oxygen gas mixtures.

Argon does not react with the weld pool and it does not dissolve into the base material. The shielding effect is good even with a low flow rate (5 to 10 l/min). According to Larue and Thomsen (1980) and Cuny (1986) carbon dioxide is most suitable shielding gas. This study together with Nielsen (1984) show that best result are obtained by using argon shielding gas. This study shows that argon is the most reliable shielding gas for all kinds of structural steels.

Argon-hydrogen mixtures can also be used and the effects of hydrogen in the shielding gas are similar to those in the plasma gas. However the shielding gas is not in contact with the weld pool like the plasma gas and so the effects are not so pronounced. It is reasonable to avoid the simultaneous use of argon-hydrogen plasma gas and argon-hydrogen shielding gas. According to Table 17, when welding high strength and strong formable microalloyed steels the total hydrogen content can not be more than 5 to 7 %. With unalloyed structural steels the maximum value is about 10 %.

When welding with argon-carbon dioxide or argon-oxygen shielding gases the fluidity of the weld pool increases, the weld toe becomes smooth and continuous and the sensitivity to undercut decreases. The weld surface becomes relatively rough and therefore the argon-carbon dioxide and argon-oxygen shielding gases are not suitable for welding the final run.

By Hays and Schultz (1983) when welding high strength and strong formable microalloyed steels the percentage of carbon dioxide in the argon shielding gas should not exceed 20 % because of increasing carbon content in weld metal, and so of the risk of decreasing toughness values. With unalloyed structural steels the amount of carbon-dioxide can be greater. The same reference presents that the percentage of oxygen in the argon shielding gas must be restricted to 2 to 3 %. Higher percentages of oxygen oxidize the alloying elements and increase porosity. The stronger and more alloyed the steel is the lower the percentage of oxygen must be.

According to Table 9 of this study the simultaneous use of argon-carbon dioxide shielding gas and argon-hydrogen plasma gas is not acceptable for all kinds of structural steel.

It leads to strong boiling of the weld pool, to the disturbance of the plasma arc and to pore formation. The phenomenon is at its greatest with Al- and Al+Si-deoxidized steels. The only possible shielding gas in this case is argon.

Welding speed is 20 to 30 % faster when welding with argon-20 % carbon dioxide shielding gas than pure argon shielding gas with a material thickness of 3 mm. With a material thickness of 6 mm the corresponding value is 15 to 20 %.

7.3.3.3 The effect of backing gas

Backing gas, the shielding gas of the weld root area, is necessary in most cases [Drews and Böhme (1975), Engfeldt and Fager (1984) and Nielsen (1984)]. This is particularly important to ensure uniform solidification of highly fluid materials like structural steels. Argon is usually used as backing gas. By Drews and Böhme (1975) a satisfactory weld root can only be achieved if the root area of the molten weld metal is protected by an inert gas and the sagging of the low viscosity molten weld metal is prevented by the use of an appropriate backing.

The need for backing gas must considered from case to case. This study shows that it is often a question about the appearance of the root. The lack of backing gas can cause porosity in the weld and the root can be irregular. The root is also often concave and has an oxidized surface. The use or omission of backing gas does not affect the mechanical properties of the weld joint, except if the geometrical irregularity of the root is considerable.

Table 18 shows the possible backing gases. The most suitable backing gas for structural steels is argon. Also nitrogen and a nitrogen-10 % hydrogen mixture are possible to use as backing gases. Because of its lightness the nitrogen-10 % hydrogen gas has a good shielding effect on the root side and at the same time hydrogen has a reduced effect. The use of carbon dioxide backing gas causes irregular root with oxidized surface.

The risk of excessive penetration is smaller with an argon backing gas atmosphere than nitrogen or nitrogen/hydrogen atmospheres. This is particularly notable with unalloyed structural steels the weld pool of which is more sensitive to movement than that of e.g. high strength microalloyed steels.

7.4 Summary of discussion

Some research workers, mentioned before, have shown by single studies that unalloyed structural steels can be welded in a flat position without weld defects using the plasma keyhole technique. However, in those studies the plasma welding conditions have not been systemised and the weld quality has been very variable.

The present study is the first widespreadly examination about the possibilities and the usefulness of applying plasma keyhole welding to structural steels with different compositions and material thicknesses, and in various welding positions. This study produces a new knowledge and completes and specifies the earlier one about the plasma keyhole welding of structural steels. The study shows that there are technological conditions to weld structural steels reproducibly and with a high quality. These conditions together with the knowledge of the effects of the variable welding parameters on weld quality create the necessary conditions for successful plasma keyhole welding.

On the basis of the results of this study the following new conclusions can be drawn:

- Plasma keyhole welding is a useful technique besides for unalloyed structural steels also for different microalloyed steels.
- Welding is possible also in horizontal-vertical and vertical positions.
- It is possible to achieve defect free high quality welds in the flat and horizontal-vertical positions and limitedly also in vertical position.
- Welding current, welding speed and plasma gas flow are the most important welding parameters. The acceptable range of welding parameters is narrow.
- Lack of penetration (caused by inadequate welding current in relation to welding speed), excessive penetration (caused by too high welding current in relation to welding speed) and undercut (too high welding speed) are the most common weld defects.
- An argon-hydrogen mixture as the plasma gas together with argon as a shielding gas and a backing gas gives the best quality. The use of argon-hydrogen plasma gas is posssible also for welding of high strength microalloyed and strong formable microalloyed steels. Argon-hydrogen plasma gas increases the acceptable welding speed 20 to 40 % compared to pure argon plasma gas.
- The compositions of the welding gases and base materials primarily affect the quality of the weld face and secondarily the mechanical properties of the weld joint.
- The cutting nozzle is useful for one side root welding with V-, Y- and U-grooves.

8. CONCLUSIONS

The present study examines the possibility and the usefulness of applying plasma keyhole welding to structural steels with different compositions and material thicknesses, and in various welding positions. The study shows the technological conditions to weld structural steels reproducibly and with high quality. The study also identifies the effects of welding parameters on weld quality and presents the welding parameter combinations providing the best quality welds.

Welding experiments were carried out on the single pass butt welding with I-groove and the root welding of V-, Y- and U-grooves. Complementary experiments were also carried out. All welded joints were tested both nondestructively and destructively. The welds were classified into four classes according to surface weld defects, geometrical errors and internal weld defects. The mechanical properties of the weld joints were measured.

On the basis of the results of this study and the knowledge of the references used in this study the following conclusions can be drawn:

- Plasma keyhole welding is a useful technique for unalloyed, high strength microalloyed and strong formable microalloyed structural steels.
- The method can be used for butt welding with I-groove and root welding with V-, Y- and U-grooves. Butt welding with I-groove is possible for material thicknesses of 3 to 6 mm in the case of unalloyed structural steels and of 3 to 10 mm in the case of high strength microalloyed steels. When the material thickness exceeds the range of I-groove, a V-, Y- or U-groove is possible.

- The groove faces can be machined or, in some cases, flame-cut with a high quality.
- The greatest allowed joint gap is 1,5 mm when welding with filler material. Without filler material the joint gap can be 0,3 mm. The groove faces must be parallel and the joint gap equal the whole welding length.
- Welding is possible in the flat, horizontal-vertical and vertical positions. It is possible to achieve defect free high quality welds with good strength and toughness properties in the flat and horizontal-vertical positions and limitedly also in vertical position.
- Straight cylindrical and restrictive nozzles are useful for butt welding with I-groove. For the success of the welding the diameter of the nozzle must be about $d_n = 1 + 0,01$ x welding current and keyhole crater outlet about $d_0 =$ 0,2...0,3 x weld width. In root welding with V-, Y- and U-grooves the cutting nozzle is recommended.
- The essential factors affecting the weldability of unalloyed structural steels are (1) the type of deoxidation of the steel, and (2) the sulphur content of the base material.
- The essential factors of high strength microalloyed and strong formable microalloyed steels affecting their weldability are (1) the chemical composition of the base material, especially carbon content, (2) the metallurgical compatibility of base material, filler material and welding gases, and (3) the welding energy (i.e. heat input per unit length).
- When the composition and strength of base material increases, impact toughness can be the limiting factor with regard to deformability.
- Welding current, welding speed and welding gases, especially plasma gas flow, are the most important welding parameters.
- The range of variation of welding parameters, especially for the highest weld class, is narrow.

- Lack of penetration (caused by inadequate welding current in relation to welding speed), excessive penetration (caused by too high welding current in relation to welding speed) and undercut (too high welding speed) are the most common weld defects.
- An argon-hydrogen mixture as the plasma gas together with argon as a shielding gas and a backing gas gives the best results as regards quality.
- The use of argon-hydrogen plasma gas increases the welding speed 20 to 40 % and it also enables the welding of high strength microalloyed and strong formable microalloyed steels.
- The compositions of the welding gases and base materials primarily affect the quality of the weld face and secondarily the mechanical properties of the weld joint.
- Welding must be mechanized because of difficulties in manually maintaining a consistent welding speed, torch position, gas protection, filler material addition etc.

It has been shown that mechanized plasma keyhole welding is a very useful method for both unalloyed structural, high strength microalloyed and strong formable microalloyed steels. It may successfully compete with common MIG/MAG and SAW welding as well as with electron and laser beam welding, especially in large industrial works like welding of large plates, tanks and pressure vessels and large diameter pipes. Then it is a question of quality, productivity and economy. Plasma keyhole welding can be a step towards high quality and more effective welding methods, also in the case of structural steels.

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