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TUNGSTEN ACTIVE GAS (TAG) WELDING OF AUSTENITIC STAINLESS STEEL SHEET WITH Ar + H₂ GAS MIXTURE

ZAVARIVANJE LIMA OD AUSTENITNOG NERĐAJUĆEG ČELIKA VOLFRAMOVOM ELEKTRODOM (TAG) U MEŠAVINI AKTIVNOG GASA Ar + H₂

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Abstract

TIG welding is used when a good weld appearance and a highest quality of the weld are required. Nevertheless, the process has also some major disadvantages like relatively shallow penetration capability and low productivity. To increase the penetration and/or productivity, instead of traditional pure Ar, gas mixtures containing gases with high thermal conduction can be used. For austenitic stainless steels, as they are not prone to hydrogen cracking, also H₂ is suitable. As H₂ is active gas, the process is called Tungsten Active Gas (TAG). In this research, austenitic stainless steel sheet was welded with a competitive welding speed of 40 cm min⁻¹, with pure argon and with Ar+7.5 %H₂ mixture. With pure Ar, a welding current of 220 A was far too small to reach full penetration in 3 mm sheet. With the 7.5 %H₂ active gas mixture, only 130 A was sufficient with unchanged welding speed.

Rezime

TIG zavarivanje se koristi kada je potreban dobar izgled zavara i najviši kvalitet zavarenog spoja. Ipak, postupak ima i neke velike nedostatke poput relativno malog provara i niske produktivnosti. Da bi se povećala dubina provara i/ili produktivnost, umesto tradicionalnog čistog argona, mogu se koristiti smeše gasova koje sadrže gasove sa visokom toplotnom provodljivošću. Za austenitne nerđajuće čelike, pošto nisu skloni pojavi vodoničnih prslina, pogodan je i H₂. Pošto je H₂ aktivni gas, postupak se naziva volfram aktivni gas (TAG). U ovom istraživanju, lim od austenitnog nerđajućeg čelika je zavaren brzinom zavarivanja od 40 cm min⁻¹, sa čistim argonom i sa smešom Ar+7,5 %H₂. Sa čistim Ar, struja zavarivanja od 220 A bila je premala da bi se postigao pun provar na limu od 3 mm. Sa aktivnom smešom gasa Ar sa 7,5 %H₂, samo 130 A bilo je dovoljno uz nepromenjenu brzinu zavarivanja.

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1. Introduction

Application of Tungsten Inert Gas welding (TIG) started during 2nd world war. It is one of the cleanest and most important processes for welding stainless steel and non-iron alloys [1]. It is used when a good weld appearance and a high quality of the weld are required [2, 3]. Nevertheless, the process has also some major disadvantages like relatively shallow penetration capability (particularly in single pass welding operations), the high sensibility of the weld bead shape to variations of the chemical composition of the base metal, and its low productivity [4].

One possibility to overcome the disadvantages of TIG is the Activated Tungsten Inert Gas process (ATIG), which uses active fluxes. This variant of the process was developed in the 1960s for the welding of titanium in the Paton Institute of Electric Welding [5, 6]. Compared to conventional TIG, the advantages are eliminating the need of edge preparation, increasing the penetration depth, and reducing the number of weld pass. Consequently, the process resulted in narrow welds, small size of HAZ, low heat input, and decrease in residual welding distortions, and the productivity of ATIG process can be increased up to three times compared to the conventional TIG process [3, 7-11]. The use of fluxes can improve penetration up to 300 % [4], or, at unchanged penetration depth, about 25 % lower currents are sufficient [2]. Nevertheless, ATIG also has some disadvantages [2]: First, preparation and application of flux are additional steps in the production, which increase costs and time consumption. Second, optimum results are achievable only with a sufficiently narrow gap (preferably 0) between the work pieces. Third, the process is sensitive to amount of applied flux and application of an evenly thick flux layer is hard to achieve by untrained workers. Fourth, heat reflects from the flux which increases the temperature of the electrode. And finally, fluxes are applied in form of suspension in fast evaporating organic solvents like acetone or alcohols, which are flammable greenhouse gases.

The other possibility to enjoy the advantages of ATIG but to avoid problems associated with this process is application of appropriate gas mixtures instead of traditional pure argon (Ar). Suitable are gases with significantly higher thermal conductivity than Ar and polyatomic gases. A gas with a high thermal conductivity conducts heat outward from the core; this results in a wider, hotter arc core. This gives a more even distribution of heat to the work surface and produces a wider fusion area,

and more conduction of the thermal energy into the workpiece [12, 13]. The other possibility is application of polyatomic gases, which dissociate and recombine. When heated to high temperatures within the arc plasma, these gases break down, or dissociate, into their component atoms. They are then at least partially ionized, producing free electrons and current flow. As the dissociated gas comes into contact with the relatively cool work surface, the atoms recombine and release heat at that point. This heat of recombination causes multiatomic gases to behave as if they have a higher thermal conductivity, similar to that of helium. Thus, at the same arc temperature, the heat generated at the work surface can be considerably greater with gases such as carbon dioxide and hydrogen [12].

As mentioned above, one of applicable additions to Ar is helium (He). It is applicable in welding of practically all metallic materials but is quite costly and has much higher ionization energy than Ar (Ar: 15.7 eV, He: 24.5 eV [13]), which impedes the arc start and decreases the arc stability, and consequently, increases the arc voltage.

In case of austenitic stainless steels, the other suitable gas is hydrogen (H_2). H_2 is applicable because austenitic stainless steels are, due to high solubility of hydrogen in face centered cubic structure, immune to hydrogen cracking – except possibly very heavily cold-worked materials containing significant fractions of strain induced martensite. This allows the addition of hydrogen to the shielding gas in quantities from 2–15% providing more heat in the arc and better penetration [14]. As H_2 is an active gas, the process is in this case called TAG (Tungsten Active Gas). Hydrogen's ionization energy is comparable to Ar [15], thermal conductivity is very high even compared to He, and, in addition it is a polyatomic gas. In the temperature range approx. 7000-14000 K the difference in conductivity is increasing, and in the range 12500-15000 K the hydrogen's conductivity is between $6 \text{ W m}^{-1} \text{ K}^{-1}$ and $7.3 \text{ W m}^{-1} \text{ K}^{-1}$, which is ca. twice the conductivity of He. In the same temperature range, conductivity of Ar does not exceed $3.5 \text{ W m}^{-1} \text{ K}^{-1}$ [15]. In addition, H_2 costs only a small fraction of what helium costs. Although H_2 is also a greenhouse gas and even Ar + H_2 mixtures with low H_2 contents are flammable [16], this should not be a major problem in practice, as during welding, hydrogen burns in contact with oxygen contained in the surrounding air.



Therefore, for our research, an Ar + H₂ gas mixture was selected for comparison to traditional TIG welding with pure Ar. The aim of the research was to demonstrate that with use of an Ar + H₂ gas mixture it is possible to reduce (compared to conventional TIG) the welding current (and thus heat input) and weld metal cross-section while maintaining full penetration. For experimental welding, a welding speed competitive with other processes, i.e. MIG/MAG, was selected.

2. Experimental

The research was conducted with commercially available materials. Stainless steel sheet X5CrNi18-10 (1.4301, AISI 304) according to DIN EN 10088-2 [17], 3 mm thick, was selected as the base metal. 3 mm thick sheets were butt welded with no gap. Most welds were welded without filler material, and some with filler wire. As the filler material, a $\phi = 1$ mm wire TIG 19/9 NC Si from Elektrode Jesenice (W 19 9 LSi according to EN ISO 14343-A [18]) was used. Chemical compositions and mechanical properties are summarized in Table 1.

Table 1: Chemical compositions and mechanical properties of materials

Tabela 1: Hemijski sastav i mehanička svojstva materijala

	Base Metal X5CrNi18-10 [17]	Filler Wire TIG 19/9 NC Si [18]
C / wt. %	0.07	0.025
Si / wt. %	1.0	0.8
Mn / wt. %	2.0	2.0
P / wt. %	Max. 0.045	Max. 0.045
S / wt. %	Max. 0.03	Max 0.03
Ni / wt. %	8-10	9
Cr / wt. %	17.5-19.5	19
Fe / wt. %	Balance	Balance
R_{p02} / MPa	215	400
R_m / MPa	505-735	280
E / GPa	193-200	193
A_5 / %	40-60	40-50
HBW	124-204	170-200

One sample was welded with the traditional TIG process using pure Ar 4.6, other samples were welded with active mixture Ar + vol. 7.5 % H₂ with

different welding currents, some without filler wire, others with filler wire. The welding plan is summarized in Table 2.

Table 2: The welding plan

Tabela 2: Plan zavarivanja

Constant parameters	
Welding speed	40 m min ⁻¹
Gas TIG	Ar 4.6 (I1 according to EN ISO 14175 [19])
Gas TAG	Ar + vol. 7.5 % H ₂ (R1 according to EN ISO 14175 [19])
Gas flow	13 L/min
Voltage	12 V
Filler wire (if used)	Elektrode Jesenice TIG 19/9 NC Si, $\phi = 1$ mm (W 19 9 LSi according to EN ISO 14343A:2017 [18])



Variable parameters				
Specimen No.	Process	Current / A	Wire speed / cm min ⁻¹	Heat input / kJ cm ⁻¹
1	TIG	220	-	2.376
2	TAG	220	-	2.376
3	TAG	210	-	2.268
4	TAG	180	-	1.944
5	TAG	160	-	1.728
6	TAG	130	-	1.404
7	TAG	100	-	1.08
8	TAG	80	-	0.864
9	TAG	210	80	2.268
10	TAG	210	120	2.268
11	TAG	180	120	1.944

Welding was done by a robot using a Daihen-Varstroj Vartig 221 AC-DC machine. Samples were first subjected to visual inspection, and δ -ferrite content was nondestructively measured with the apparatus Institute Dr. Förster, Ferritgehaltsmesser 1.054. After that, standard short specimens were laser-cut (3 kW Jinan Bodor laser cutting machine) for tensile tests according to EN ISO 6892-1 [20]. A testing machine Zwick Vibrophore 100 was used. In addition, cross-sections were prepared for examination with an optical microscope Leica Wild

M10) and subsequent Vickers hardness measurements (Zwick 3202) according to EN ISO 6507 [21] and ISO 9015-1 [22]. Nevertheless, due to very small dimensions of heat affected zones, the hardness was only measured in the weld metal. On the micrographs, weld metal area was measured with the Digimizer software.

3. Results And discussion

The welds are presented in Figures 1 through 11. A macro photograph of the weld face always on the left, a micrograph of the cross-section always on the right.

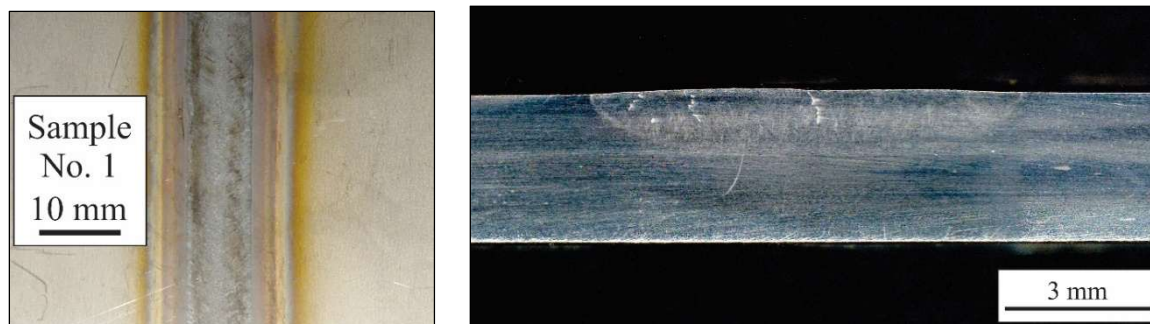


Figure 1: Specimen N° 1 - TIG, 220 A, no filler material
Slika 1: Uzorak br. 1 - TIG, 220 A, bez dodatnog materijala

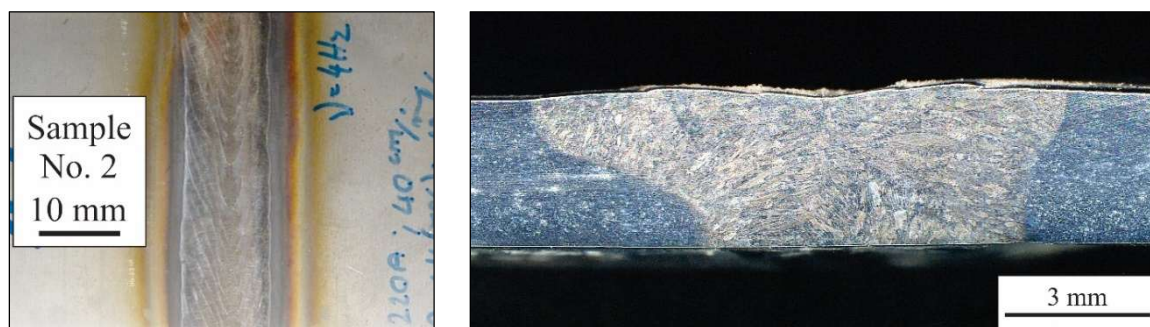


Figure 2: Specimen N° 2 - TAG, 220 A, no filler material
Slika 2: Uzorak br. 2 - TAG, 220 A, bez dodatnog materijala

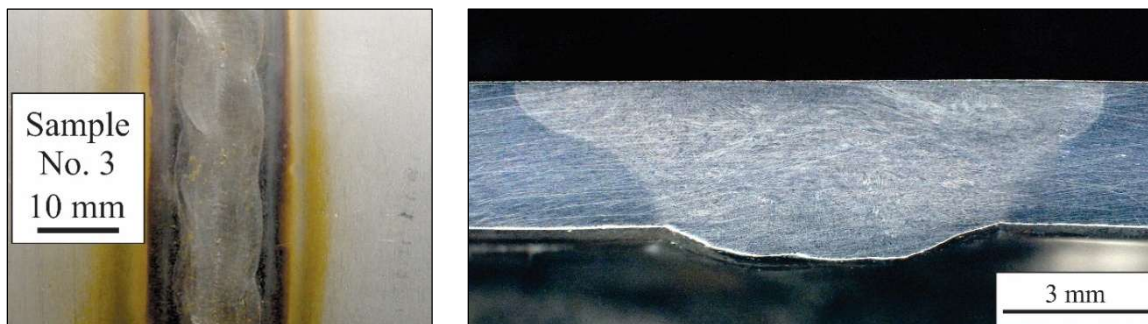


Figure 3: Specimen N° 3 - TAG, 210 A, no filler material
Slika 3: Uzorak br. 3 - TAG, 210 A, bez dodatnog materijala

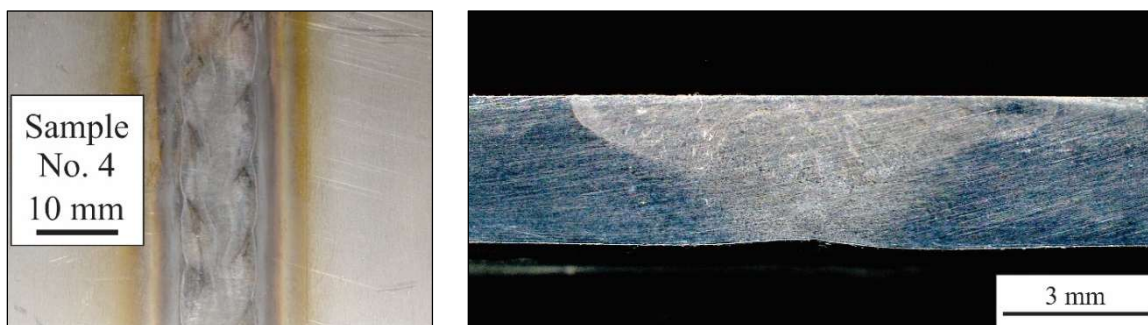


Figure 4: Specimen N° 4 - TAG, 180 A, no filler material
Slika 4: Uzorak br. 4 - TAG, 180 A, bez dodatnog materijala

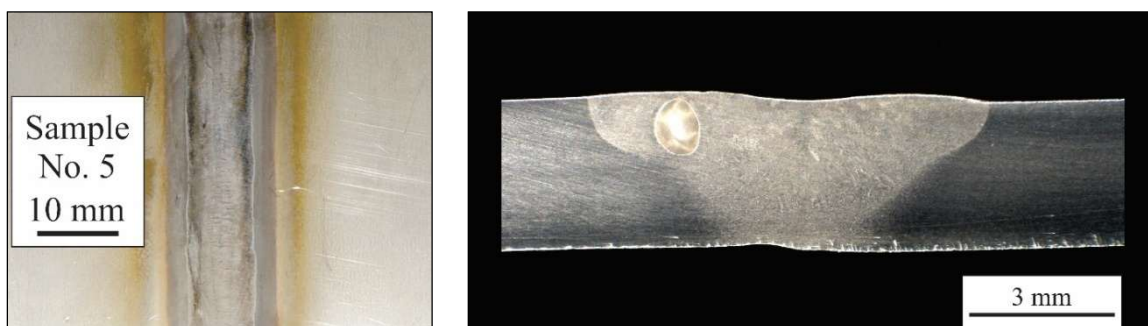


Figure 5: Specimen N° 5 - TAG, 160 A, no filler material
Slika 5: Uzorak br. 5 - TAG, 160 A, bez dodatnog materijala

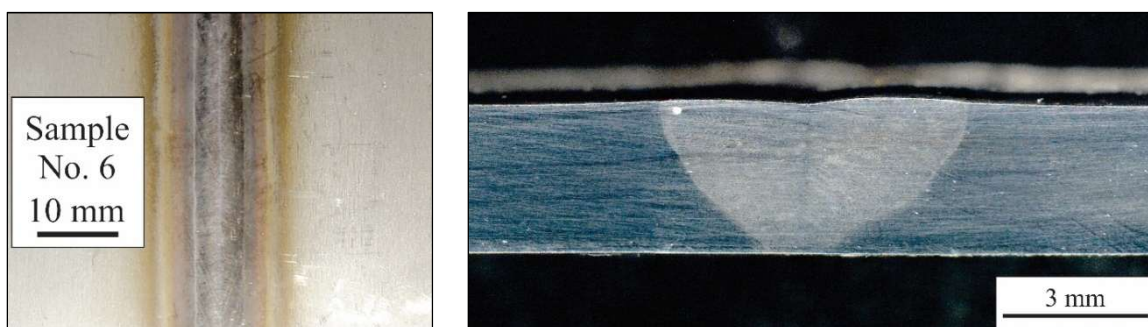


Figure 6: Specimen No 6 - TAG, 130 A, no filler material
Slika 6: Uzorak br. 6 - TAG, 130 A, bez dodatnog materijala

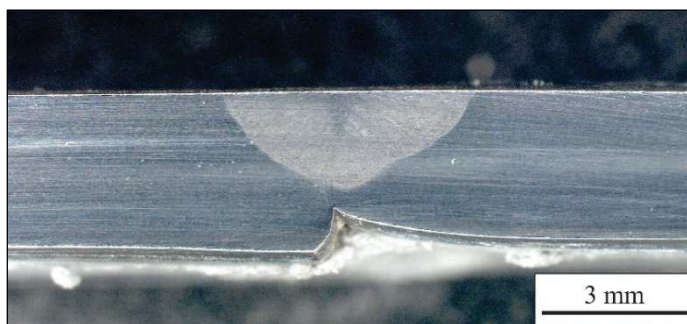
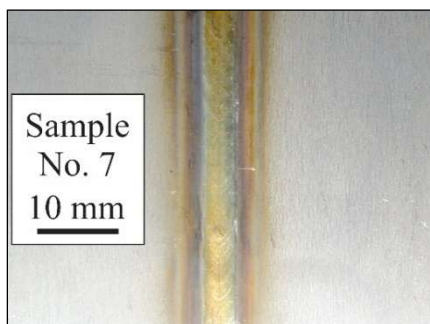


Figure 7: Specimen N° 7 - TAG, 100 A, no filler material

Slika 7: Uzorak br. 7 - TAG, 100 A, bez dodatnog materijala

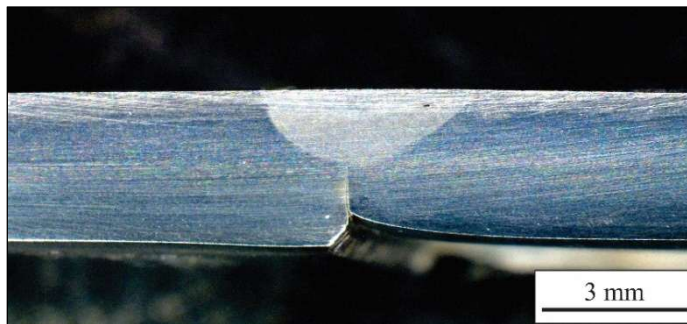
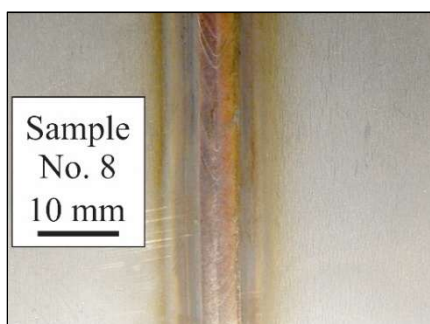


Figure 8: Specimen N° 8 - TAG, 80 A, no filler material

Slika 8: Uzorak br. 8 - TAG, 80 A, bez dodatnog materijala

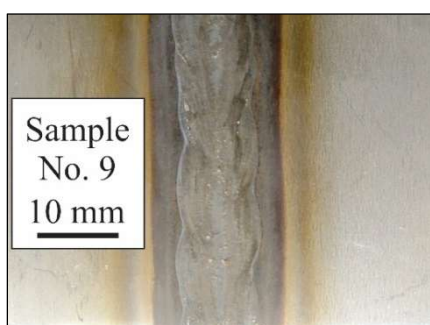


Figure 9: Specimen N° 9 - TAG, 210 A, filler wire 80 cm/min.

Slika 9: Uzorak br. 9 - TAG, 210 A, dodatni materijal žica 80 cm/min.

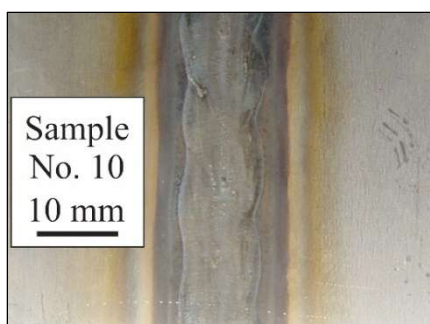


Figure 10: Specimen N° 10 - TAG, 210 A, filler wire 120 cm/min

Slika 10: Uzorak br. 10 - TAG, 210 A, dodatni materijal žica 120 cm/min.

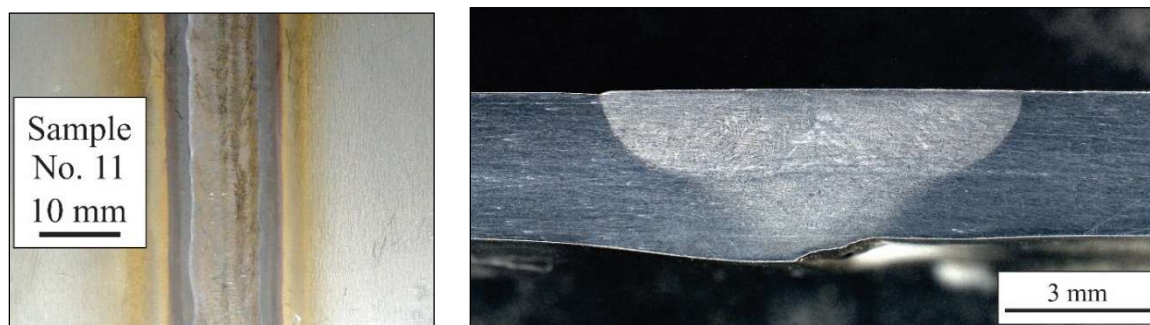


Figure 11: Specimen N° 11 - TAG, 180 A, filler wire 120 cm/min

Slika 11: Uzorak br. 11 - TAG, 180 A dodatni materijal žica 120 cm/min

It is obvious that at the selected welding speed even a welding current $I = 220$ A was insufficient to achieve full penetration with conventional TIG process with pure Ar. The fusion area was wide, but very shallow, Figure 1. When welding with same parameters but with H_2 containing active gas mixture, full penetration was achieved. Nevertheless, the width of fusion area was excessive, Figure 2.

In Figures 3 to 8 it can be observed that with decreasing welding current the width and cross-section of fusion area gradually decrease, until at $I = 100$ A full penetration is not achieved any more, despite using H_2 containing active gas mixture.

Figures 9 to 11 show welds made with active gas mixture and with filler wire. One can see that with the welding current $I = 210$ A the fusion area was excessively wide on the face side as well as in the root. Consequently, it can be concluded that the current was too high regardless of the filler wire speed. Figure 11 leads to the conclusion that at the same filler wire speed of 120 cm/min with a lower current of 180 A better result was obtained, but it also implies that perhaps even a lower current would be sufficient.

Results of fusion area geometry measurements are summarized in Table 3. Table 3 contains also the results of the tensile tests, hardness measurements and δ -ferrite measurements.

Table 3: Summary of the testing results: weld geometry, tensile properties, hardness and δ -ferrite content

Tabela 3: Rezime rezultata ispitivanja: geometrija zavara, zatezna svojstva, tvrdoća i sadržaj δ -ferita

Specimen No.	Process	Current / A	Heat input / kJ cm^{-1}	Wire speed / cm min^{-1}	Penetration / mm	Weld face width / mm	Reinforcement height / mm	Weld metal cross-section / mm^2	Rm / MPa	A_5 / %	Fracture in*	HV 5 (weld metal)	\square ferrite / %
1	TIG	220	2,38	-	1,2	8,4	0,14	9,8	534	10	WM	300	6
2	TAG	220	2,38	-	Full	10,6	0,3	26,7	656	46	BM	291	5.5
3	TAG	210	2,27	-	Full	12,4	0	32,4	637	36	WM	355	6
4	TAG	180	1,94	-	Full	9,9	0	18,5	675	49	BM	339	6
5	TAG	160	1,73	-	Full	7,9	0,22	15,5	659	40	WM	187	6.5
6	TAG	130	1,40	-	Full	6,4	0,2	14,6	636	44	WM	301	5
7	TAG	100	1,08	-	2	4,8	0	6,0	487	3	WM	335	3.5
8	TAG	80	0,86	-	1,6	4,4	0	4,7	409	1	WM	306	3.5
9	TAG	210	2,27	80	Full	9,8	0,75	27,5	650	47	BM	297	6
10	TAG	210	2,27	120	Full	11,2	0	31,5	650	46	WM	349	7.5
11	TAG	180	1,94	120	Full	9,0	0	20,2	652	45	BM	242	9.5

*BM = Base Metal; WM = Weld Metall



Except for the specimens 7 and 8, where only partial penetration was achieved, mechanical properties corresponded to the data available in the literature [e.g. 23 or 24] for the X5CrNi18-10 stainless steel annealed strip. The δ -ferrite content in the weld metal was also in the range usually regarded as sufficient to prevent hot cracking. As mentioned, the tensile strengths of samples 7 and 8 were significantly lower. The reason was only

partially penetration and consequently much smaller load-bearing cross-section. Also, the determined δ -ferrite content in these two samples was apparently lower. Nevertheless, the lower measured δ -ferrite values most likely result from the fact that due to small weld metal cross-sections the volume of material interacting with the probe also contained a significant fraction of the base metal.

4. Conclusions

Welding with conventional TIG process with pure Ar was compared with TIG welding with active gas mixture Ar + 7.5 % H₂ (TAG welding). A 3 mm thick austenitic stainless sheet was welded with a welding speed of 40 cm min⁻¹, which is competitive to other processes, i.e. MIG/MAG. The obtained results lead to following conclusions:

- 1) Hydrogen is a highly effective addition to pure argon, which greatly increases the penetration depth or allows to significantly reduce the welding current at unchanged welding speed. Thin sheets can be welded with full penetration, without edge preparation, with welding speeds comparable to MIG process.
- 2) Hydrogen is cheap and easily available, but only suitable for austenitic stainless steels.
- 3) With Ar+7.5 % H₂ containing shielding gas, much deeper penetration was reached than with pure Ar, and full penetration could be obtained with unchanged welding speed of 40 cm min⁻¹ but with more than 60 % smaller welding current.
- 4) With pure Ar (traditional TIG process), without a filler wire, a welding current of 220 A was not enough to obtain full penetration. The fusion area was 8.4 mm wide but only about 1.2 mm deep.
- 5) With addition of 7.5 % H₂ and 220 A, full penetration was obtained, whereat the fusion area was excessively large: the weld face width increased to almost 11 mm, the width of the root was over 6 mm, and the cross-section area was about 30 mm².
- 6) The smallest welding current which assured full penetration with H₂ containing gas and without filler was 130 A. The face width was 6.4 mm, and fusion area cross-section only 14.6 mm².
- 7) With filler material and H₂ containing gas, a welding current of 180 A was significantly higher than needed to obtain full penetration.

4. Zaključci

Zavarivanje konvencionalnim TIG postupkom sa čistim Argonom upoređeno je sa TIG zavarivanjem sa aktivnom smešom gasa Ar + 7,5 % H₂ (TAG zavarivanje). Austenitni lim od nerđajućeg čelika debljine 3 mm zavaren je brzinom zavarivanja od 40 cm min⁻¹, što je konkurentno drugim postupcima, tj. MIG/MAG. Dobijeni rezultati dovode do sledećih zaključaka:

- 1) Vodonik je veoma efikasan dodatak čistom argonu, koji značajno povećava dubinu provara ili omogućava značajno smanjenje struje zavarivanja pri nepromenjenoj brzini zavarivanja. Tanki limovi se mogu zavarivati sa punim provarom, bez pripreme ivica, brzinama zavarivanja uporedivim sa MIG postupkom.
- 2) Vodonik je jeftin i lako dostupan, ali je pogodan samo za austenitne nerđajuće čelike.
- 3) Sa zaštitnim gasom koji sadrži Ar + 7,5 % H₂, postignut je mnogo dublji provar nego sa čistim Argonom, a pun provar se mogao dobiti sa nepromenjenom brzinom zavarivanja od 40 cm min⁻¹, ali sa više od 60% manjom strujom zavarivanja.
- 4) Sa čistim argonom (tradicionalni TIG postupak), bez dodatne žice, struja zavarivanja od 220 A nije bila dovoljna za postizanje potpunog provara. Površina zavara je bila široka 8,4 mm, ali duboka samo oko 1,2 mm.
- 5) Sa dodatkom 7,5% H₂ i 220 A, dobijen je potpuni provar, pri čemu je površina zavara bila preterano velika: širina površine zavara povećala se na skoro 11 mm, širina korena je bila preko 6 mm, a površina poprečnog preseka oko 30 mm².
- 6) Najmanja struja zavarivanja koja je osigurala potpuni provar sa gasom koji sadrži H₂ i bez dodatnog materijala bila je 130 A. Širina površine je bila 6,4 mm, a poprečni presek površine zavara samo 14,6 mm².



- 8) Mechanical properties of all welds with full penetration were in the range of the base metal, and sufficient fractions of δ -ferrite to prevent hot cracking were measured.
- 7) Sa dodatnim materijalom i gasom koji sadrži H_2 , struja zavarivanja od 180 A bila je znatno veća nego što je potrebno za postizanje potpunog provara.
- 8) Mehanička svojstva svih zavara sa potpunim provarom bila su u opsegu osnovnog metala, a izmereni su i dovoljni udeli δ -ferita da bi se sprečile tople prsline.

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