



ZAVARIVANJE I



ZAVARENE KONSTRUKCIJE WELDING & WELDED STRUCTURES

God. 70 Vol. 70	Br. 4 No. 4	193-240 193-240	Beograd Belgrade	Srbija Serbia	2025. 2025.
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ČASOPIS DRUŠTVA ZA UNAPREĐIVANJE ZAVARIVANJA U
SRBIJI I TEHNOLOŠKO-METALURŠKOG FAKULTETA
UNIVERZITETA U BEOGRADU

SERBIAN WELDING SOCIETY AND FACULTY OF TECHNOLOGY
AND METALLURGY OF THE UNIVERSITY OF BELGRADE
QUARTERLY REVIEW

PERIODIČNOST IZLAŽENJA – ČETIRI PUTA GODIŠNJE
PUBLISHED IN FOUR ISSUES ANNUALLY

IZDAVAČI / PUBLISHERS

**DUZS - Društvo za unapređivanje
zavarivanja u Srbiji**

Grčića Milenka 67, Beograd, Srbija

TMF - Tehnološko-metalurški fakultet

Univerziteta u Beogradu

Karnegijeva 4, Beograd, Srbija

Za izdavača / For Publisher

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11000 Beograd

Tel / Fax + 381 (11) 2420-652
(10-16h)

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www.wwsjournal.org.rs



CIP - Каталогизacija u publikaciji
Narodna biblioteka Srbije, Beograd
621.791

ZAVARIVANJE i zavarene konstrukcije : časopis Društva za unapređivanje zavarivanja u Srbiji i Tehnološko-metalurškog fakulteta Univerziteta u Beogradu = Welding & welded structures : Serbian welding society and Faculty of Technology and metallurgy of the University of Belgrade quarterly review / glavni i odgovorni urednik Zoran Odanović. - Vol. 41, no. 1 (1996) - Beograd : DUZS - Društvo za unapređivanje zavarivanja u Srbiji : TMF - Tehnološko-metalurški fakultet Univerziteta u Beogradu, 1996- (Beograd : RIC grafičkog inženjerstva Tehnološkometalurškog fakulteta Univerziteta u Beogradu). - 29 cm

Tromesečno. - Je nastavak: Zavarivač = ISSN 0513-8523. - Drugo izdanje na drugom medijumu: Zavarivanje i zavarene konstrukcije (Online) = ISSN 3042-3163 ISSN 0354-7965 = Zavarivanje i zavarene konstrukcije COBISS.SR-ID 105396743

CENE I NARUŽBINA ZA 2025.

Cena pojedinačnog broja 1.150,00 dinara
Godišnja pretplata 3.520,00 dinara
Tekući račun: 325-950060002588-46

PRICE AND ORDER

Annual subscription: EUR 100

Account No. RS35325960160000041546
OTPVRS22 (VOJVODANSKA BANKA AD)
IBAN RS35325960160000041546

ŠTAMPA / PRINT

RIC grafičkog inženjerstva
Tehnološko-metalurški fakultet Beograd
Karnegijeva 4, Beograd
Tiraž / Circulation: 150

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IN MEMORIAM

ŽIVKO ŠTRBAČKI, dipl. inž. IWE, IWI-C**1956-2025**

Dana 07. maja 2025. godine preminuo je naš dragi prijatelj i dugogodišnji saradnik.

Živko Štrbački je rođen 05.09.1956. godine u Bečeju. Diplomirao je na Metalurškom fakultetu Univerziteta u Podgorici 1982. godine.

Želja za znanjem i obrazovanjem ga je gurala u pravcu onoga što mu je bila profesionalna orijentacija.

Želeo je i uspevao da bude obrazovan u delatnostima kojima se bavio, a što je najvažnije uspeo je da bude vrh kao Međunarodni inženjer ili Inspektor zavarivanja, ali i vrhunski u delu metoda ispitivanja bez razaranja.

Radnu karijeru je započeo u Institutu za crnu metalurgiju Željezare Nikšić, gde je počeo istraživanja u oblasti razvoja i primena mikrostrukturnih ispitivanja.

1987. je proveo godinu dana preko DAAD projekta sa Nemačkom na Univerzitetu u Ahenu, na specijalizaciji u oblasti skening elektronske mikroskopije i mikroanalize. To mu je trasiralo dalji profesionalni put, da sa svojom suprugom Svetlanom postanu svakako u samom vrhu kompetentnih metalurga, odnosno vrhunski eksperti u oblasti ispitivanja metalnih materijala sa stanovišta metalografije.

Okolnosti devedesetih godina prošlog veka su doprinele njegovoj odluci da prekine naučno-istraživačku karijeru u korist industrijske prakse. U periodu od 1992. do 1995. radi u firmi Petrolcomet – Beograd, gde je savladio koroziona ispitivanja, a od 1996.-1997. radi na poziciji Tehničkog rukovodioca Kontrolinženjeringa. Naravno prekretnica je bila 1997. godina, kada je zahvaljujući hrabrosti, upornosti i želji da podele svoje znanje, sa suprugom Svetlanom formirao KonMat. Od samog osnivanja KonMat je postala cenjena firma koja je našla svoje mesto u samom vrhu u oblasti ispitivanja materijala i zavarenih spojeva metodama bez razaranja.

Osnivači i suvlasnici preduzeća su Svetlana i Živko Štrbački, koji su nakon višegodišnjeg iskustva u istraživanju, ispitivanju i kontroli materijala, odlučili da stečena znanja primene u inženjerskoj praksi. Od onda počinje priča o Svetlani i Živku ili o paru Živko i Svetlana koji se praktično "niodkuda" nametnuli kao kompetentni poznavaoци metalnih materijala.

Od laboratorije koja je na početku ispitivala samo metalografske replike, srpljivim radom i stalnim ulaganjem u kadrove i opremu, a svesni potreba tržišta, KonMat je prerastao u laboratoriju koja potpuno samostalno pruža usluge iz svih važnijih metoda ispitivanja bez razaranja (IBR) uključujući i radiografiju i gamagrafiju.

Samo formiranje KonMat-a treba pratiti u konstalaciji previranja krajem devedesetih godina prošlog veka, kada su aktivnosti u području zavarivanja bile sporadične, firme se gasile ili napuštale tržište. Svetlana i Živko su pokazali izuzetnu hrabrost, odlučnost i vizionarstvo i osnovali sopstvenu firmu Kon Mat koja je zahvaljujući, pre svega, upornosti osnivača, časnim stavom, posvćenosti poslu uspela kroz svoj dugogodišnji rad da se nametne kao značajan faktor na tržištu, a veličinom ličnosti i karaktera osnivača postigne da bude poštovana od čitave zavarivačke zajednice kao kompetentna i profesionalna.

Živkovo opredeljenje da pomogne zavarivačku zajednicu, pa čak i konkurenciju, je realnost koja ga je pratila. Zbog toga, sa sigurnošću se može reći da svako ko je poznavao ili imao privilegiju da saraduje ili se druži sa njim ima samo reči hvale i poštovanja. Ne manje značajan je i spisak istraživačko-razvojnih i tehničkih radova koje je Živko, uglavnom sa Svetlanom objavio. Ne smemo zaboraviti da Živko i njegov KonMat od osnivanja postaju deo zavarivačke zajednice i kroz podršku DUZS-u i časopisu ZIZK i ostalim aktivnostima DUZS-a.

Odlazak Živka Štrbačkog predstavlja nenadoknativ gubitak za zavarivačku zajednicu i ostaće upamćen kao častan, kompetentan poslovni čovek i saradnik, ostaće njegova veličina u posvećenosti poslu, izuzetnom radu i sposobnosti da animira saradnike da ga prate i postignu uspeh. Iza njega ostaće praznina, ali ostaće pamćenje na izvanrednog saradnika, prijatelja i čoveka, kome je pored profesije iznad svega bila porodica. Ostaće neizbrisiv trag i sećanje koje će večno živeti sa nama i u nama.

Dr Vencislav Grabulov, dipl.ing.



Emina Husković¹, Mersida Manjgo¹, Ljubica Milović², Edvard Bjelajac³, Gorazd Lojen⁴, Tomaž Vuherer^{4,a}

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

Original scientific paper / Originalni naučni rad

Paper received / Rad primljen:

September 2024.

Paper accepted / Rad prihvaćen:

April 2025.

Author's address / Adresa autora:

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Keywords: TAG welding, active shielding gas, welding parameters, weld geometry, mechanical properties

Ključne reči: TAG zavarivanje, aktivni zaštitni gas, parametri zavarivanja, geometrija zavara, mehanička svojstva

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 nepromenjenju brzinu zavarivanja.

The paper was published in its original form in the Proceedings of the 33rd Conference with international participation "Welding 2024" held in Vrnjačka Banja, Serbia from October 2 to 5, 2024.



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.

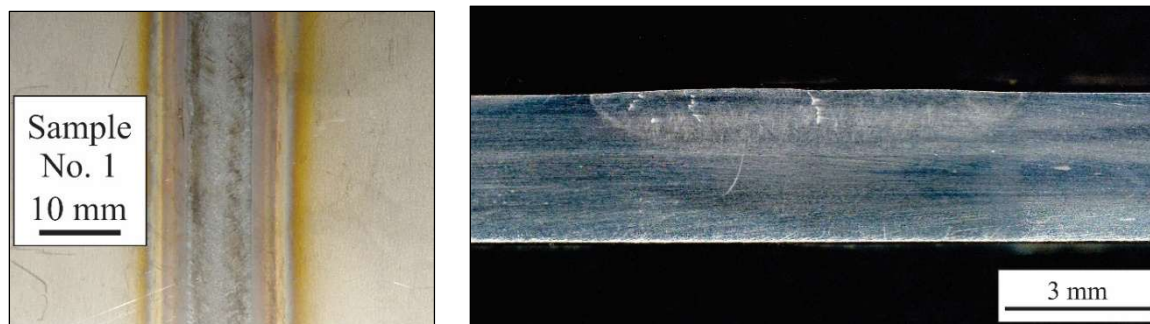


Figure 1: Specimen N° 1 - TIG, 220 A, no filler material

Slika 1: Uzorak br. 1 - TIG, 220 A, bez dodatnog materijala

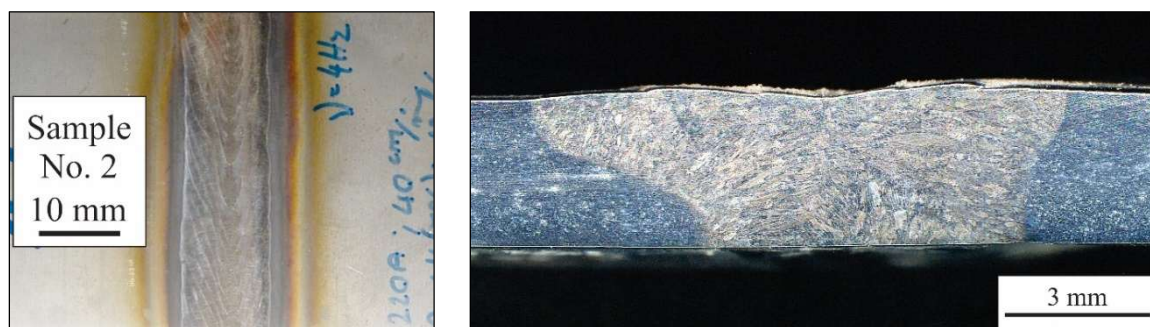


Figure 2: Specimen N° 2 - TAG, 220 A, no filler material

Slika 2: Uzorak br. 2 - TAG, 220 A, bez dodatnog materijala

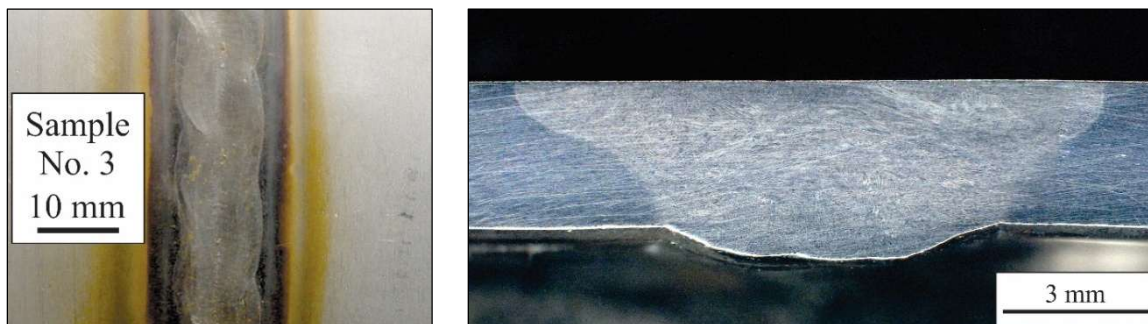


Figure 3: Specimen N° 3 - TAG, 210 A, no filler material
Slika 3: Uzorak br. 3 - TAG, 210 A, bez dodatnog materijala

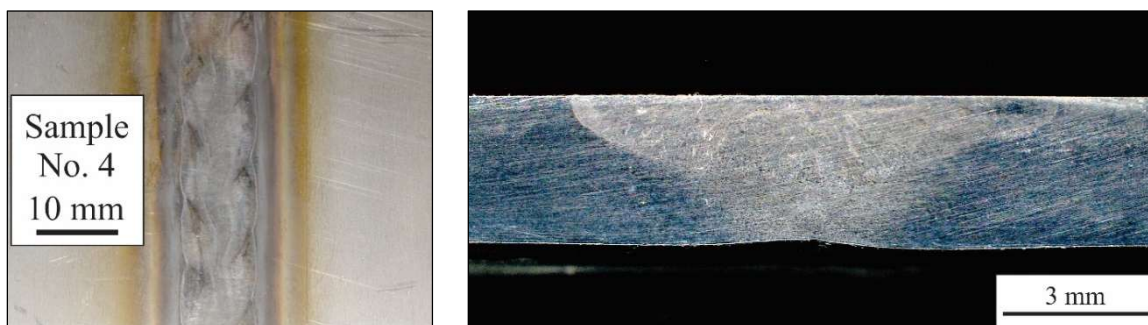


Figure 4: Specimen N° 4 - TAG, 180 A, no filler material
Slika 4: Uzorak br. 4 - TAG, 180 A, bez dodatnog materijala

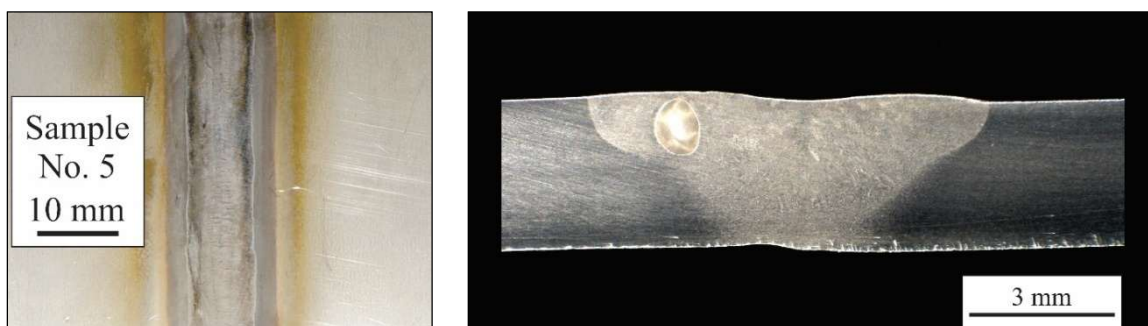


Figure 5: Specimen N° 5 - TAG, 160 A, no filler material
Slika 5: Uzorak br. 5 - TAG, 160 A, bez dodatnog materijala

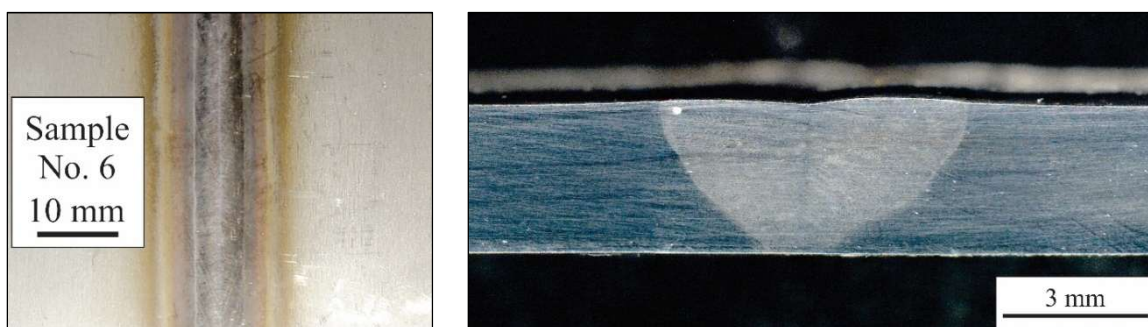


Figure 6: Specimen No 6 - TAG, 130 A, no filler material
Slika 6: Uzorak br. 6 - TAG, 130 A, bez dodatnog materijala

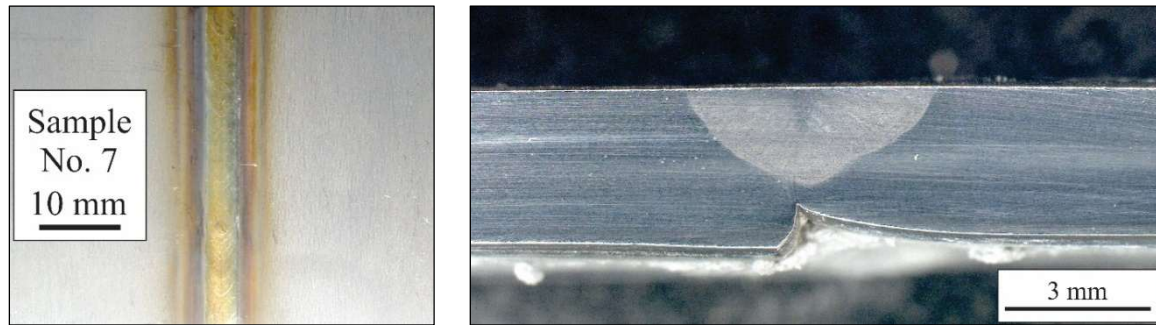


Figure 7: Specimen N° 7 - TAG, 100 A, no filler material

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

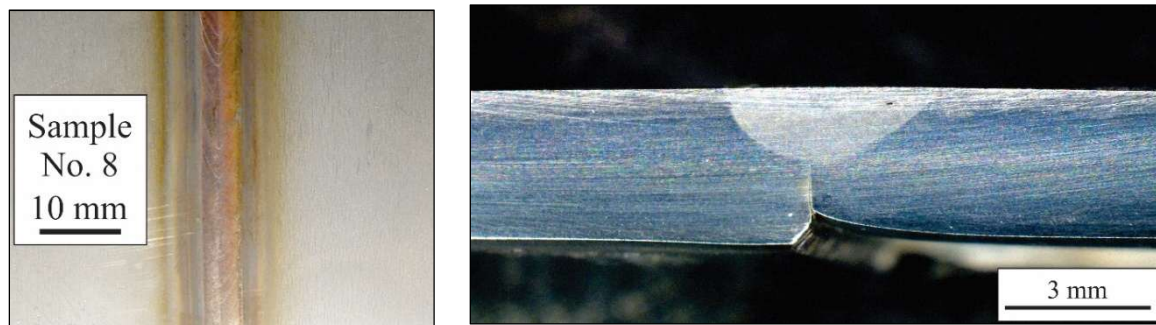


Figure 8: Specimen N° 8 - TAG, 80 A, no filler material

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

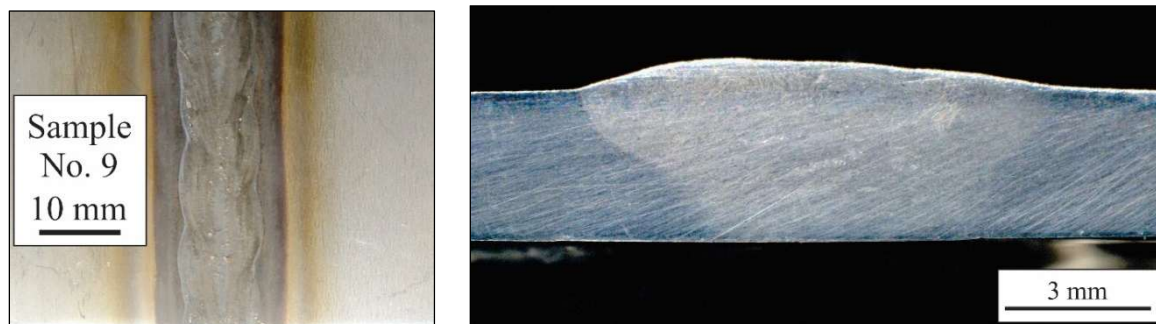


Figure 9: Specimen N° 9 - TAG, 210 A, filler wire 80 cm/min.

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

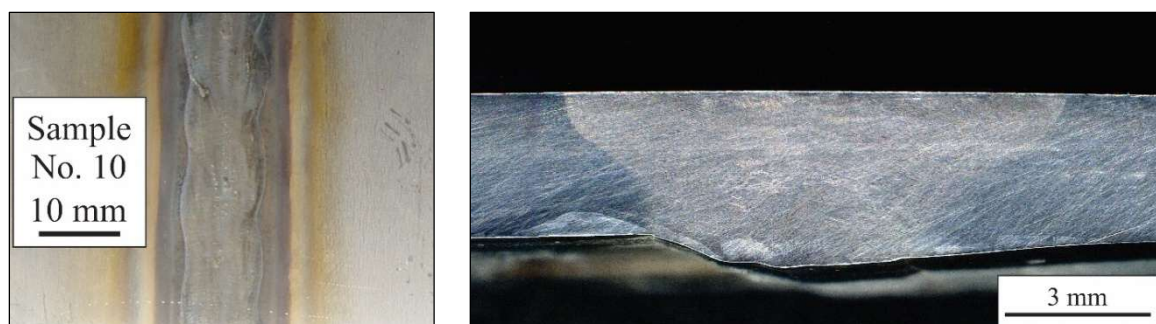


Figure 10: Specimen N° 10 - TAG, 210 A, filler wire 120 cm/min

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

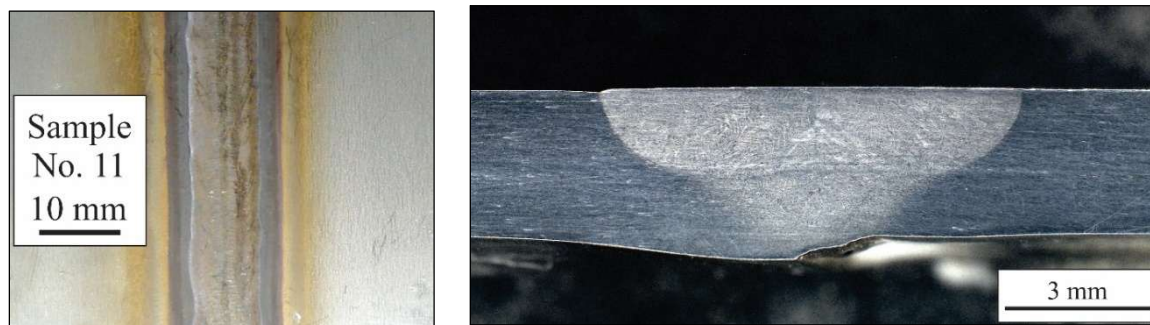


Figure 11: Specimen N° 11 - TAG, 180 A, filler wire 120 cm/min

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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Maja B. Poser ^{1,a}, Filip Zdraveski ^{1,b}

EFFECT OF CASTING AND HEAT TREATMENT ON CHANGE IN MICROSTRUCTURE AND MECHANICAL PROPERTIES IN AUSTENITIC HADFIELD STEEL

UTICAJ LIVENJA I TERMIČKE OBRADJE NA PROMENU MIKROSTRUKTURE I MEHANIČKIH OSOBINA AUSTENITNOG HADFILDVOG ČELIKA

Original scientific paper / Originalni naučni rad

Paper received / Rad primljen:

November 2025.

Paper accepted / Rad prihvaćen:

December 2025.

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Keywords: Heat treatment, solution treatment, microstructure characterization, carbides, tensile properties, Charpy V-notch test

Ključne reči: Termička obrada, tretman rastvaranjem, karakterizacija mikrostrukture, karbidi, zatezna svojstva, Šarpijev test sa V-zarezom

Abstract

Cast Hadfield steel is a material with high resistance to abrasion, provided, however, that it is used under the conditions of high dynamic loads. Typically, Hadfield steel starts with a hardness value of 200HB after solution heat treatment and can reach values of over 600HB after work hardening. The above characteristics make it an ideal material for manufacturing casting components used in mining, crushing, drilling, steelmaking, naval, automotive and excavation applications. Manganese steel castings require a rapid water quench following the high temperature soak. A slack quench can reduce the toughness of the material dramatically. The mechanical properties of manganese steels are greatly enhanced by a fine grain size. Strength and ductility can be as much as 30% greater for fine-grained material. The refinement of the austenitic grain structure in Hadfield's Manganese Steel improves the weldability of the material, especially in cases where repair welding is required, in addition to enhancing the mechanical characteristics of the final products. This paper deals with the effect of heat treatment on casting process on the final properties of the Hadfield steel.

Rezime

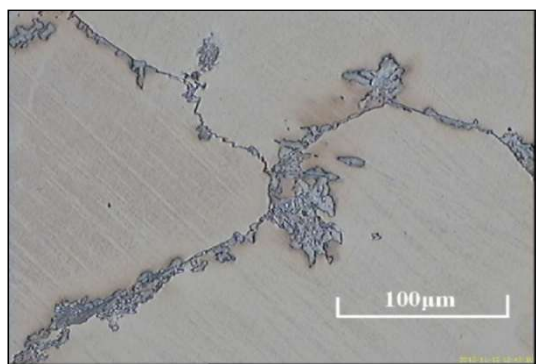
Liveni Hadfield-ovi čelik je materijal sa visokom otpornošću na abraziju, međutim samo kad se koristi u uslovima visokih dinamičkih opterećenja. Tipično, Hadfield čelik počinje sa vrednošću tvrdoće od 200HB nakon termičke obrade rastvorno kaljenje i može dostići vrednosti preko 600HB nakon očvršćavanja. Gore navedene karakteristike čine ga idealnim materijalom za proizvodnju livenih komponenti koje se koriste u rudarstvu, drobljenju, bušenju, proizvodnji čelika, pomorstvu, automobilskoj industriji i iskopavanju. Odlivci od manganskog čelika zahtevaju brzo kaljenje u vodi nakon zagrevanje na visokoj temperaturi. Usporeno kaljenje može dramatično smanjiti žilavost materijala. Mehanička svojstva manganskih čelika su značajno poboljšana finom veličinom zrna. Čvrstoća i duktilnost mogu biti i do 30% veće kod finostrukturnog materijala. Usitnjavanje austenitnog zrna u mikrostrukтури Hadfieldovog manganskog čelika osim mehaničkih karakteristika finalnih proizvoda, poboljšava i zavarljivost tog materijala u slučajevima potrebe reparaturnog zavarivanja. Ovaj rad se bavi uticajem termičke obrade i procesa livenja na konačna svojstva Hadfield čelika.



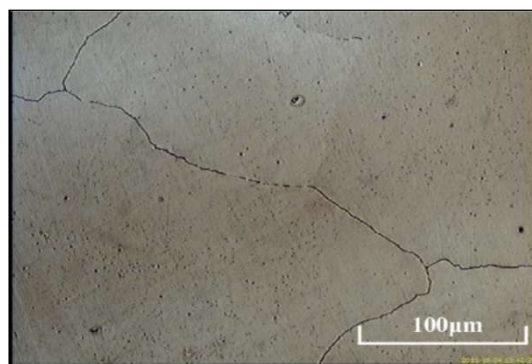
1. Introduction

Austenitic manganese steel was invented in 1882 by Sir Robert Hadfield from whom it took its commercial name (Hadfield Steel). It is a ferrous alloy, usually, containing 1.0-1.4 wt% carbon and 10-14 wt% manganese [1]. Similarly to nickel, sufficient additions of manganese can extend the γ -loop in the iron carbon equilibrium diagram and the austenitic structure can be sustained at room temperatures [2]. Hadfield steel alloys are known for their high toughness, high ductility and exceptional work hardening ability and wear resistance.

In the as-cast condition (fig.1) [3], the steel contains carbides and embrittling transformation product [4]. Carbides form in castings that are cooled slowly in the moulds regardless of mould cooling rates. These carbides can also form when the as-cast contains more than 1.0 %C or the addition of alloying element such as Cr, V, Ti, etc. They form in heavy section castings during heat treatment if quenching is ineffective in producing rapid cooling throughout the entire section thickness [4]. Casting structure of these steels is including of carbides as $(Fe,Mn)_3C$ that through appropriate heat treatment, it could be achieve full austenitic structure from these steels [5-7].



a)



b)

Figure 1: As Cast vs full austenitic Hadfield steel, a) As Cast Hadfield steel austenitic matrix with carbide precipitates, b) Cast Hadfield steel after solution treatment in water austenitic matrix free from the carbide precipitates

Slika 1: Liveni u odnosu na potpuno austenitni Hadfildov čelik, a) Liveni Hadfildov čelik, austenitna matrica sa karbidnim precipitatima, b) Liveni Hadfildov čelik nakon tretmana u vodi, austenitna matrica bez karbidnih taloga

Solution heat treatment (fig.2) [8] of Hadfield steel increases the strength of the material by dissolving the soft carbide phases that precipitate on the grain boundaries during solidification but also results in the coarsening of the microstructure [9].

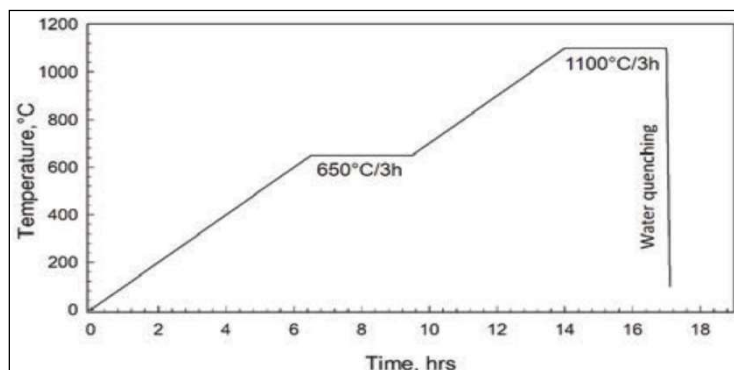


Figure 2: Example of heat treatment process of the Hadfield steel

Slika 2: Primer procesa termičke obrade Hadfildovog čelika



Microstructural refinement through inoculation (fig.3) with foreign particles or elements is a trending method, especially for light metal alloys and cast iron. Inoculants are added to the molten metal to promote the formation of fine and randomly oriented equiaxed grains during solidification.



a)



b)

Figure 3: Influence of pouring temperature on the grain refinement: a) Low pouring temperature, b) High pouring temperature

Slika 3: Uticaj temperature livenja na usitnjavanje zrna: a) niska temperatura livenja, b) visoka temperatura livenja

The fluidity of manganese steel is quite high, approaching that of cast iron, which makes it possible to fill intricate shapes and pour at low superheats. Most reliable method to obtain a fine grain structure is to pour the metal with low superheat just above its liquidus point [11].

Fig.3 [12] show the fracture surfaces of bars that were broken as cast to reveal the grain size. Both bars are from the same (12% Mn) heat with a) being poured at 1377°C and b) being at 1486°C.

In practice, pouring temperatures below 1427°C are typical for the 12% Mn grades and can be much lower as carbon and alloy levels are increased. Temperatures near 1371°C are desirable for pouring the higher manganese and carbon grades.

Currently, the industrial demand is to develop improved austenitic steel alloys for manufacturing components with longer operational life and reduced failure rates. In that way, the non-operational time of larger machinery during

maintenance and part replacement would also be reduced and thus decrease operational costs, increase workforce productivity and improve sustainability.

Considering that operational life and failure rates of a casting component are directly connected with the material's mechanical properties which in turn are influenced by the microstructural features of the material such as the grain size, it is of high importance to investigate the reasons that cause them in relation to the casting process and heat treatment.

2. Case study no.1 castings with same chemical composition different grain refinement

The subject of comparison in this study are two castings, specifically excavation teeth (fig.4) for rotor excavator SRS 2000. Both are made of same chemical composition GX120MnCr13-2 (tab.1), but have different microstructure, more precisely different grain refinement.



a)

b)

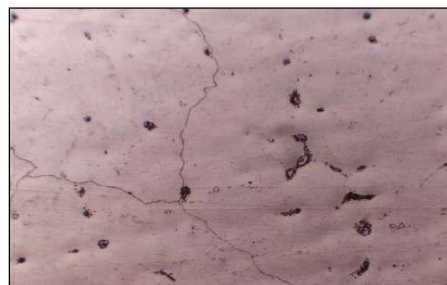
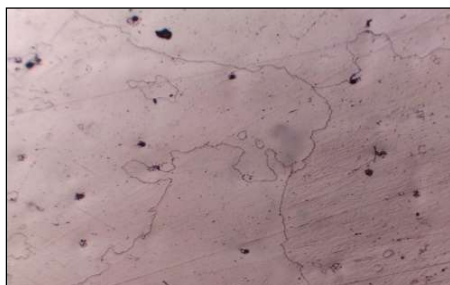
Figure 4: Excavation teeth used for analysis of the effect of microstructure on mechanical properties: a) microstructure with dominant columnar grains, b) microstructure with dominant equiaxed grains

Slika 4: Zupci za iskop korišćeni za analizu uticaja mikrostrukture na mehanička svojstva: a) mikrostruktura sa dominantnim stubastim zrnima, b) mikrostruktura sa dominantnim jednakoosnim zrnima

Table 1: Chemical composition of cast steel GX120MnCr13-2 according to EN 10349

Tabela 1: Hemijski sastav livenog čelika GX120MnCr13-2 prema EN 10349

Cast steel (Hadfield)	chemical composition in wt, %							
	C	Si	Mn	Cr	Fe	Cu	S	P
						Not more than		
GX120MnCr13-2	1.05-1.35	0.3-0.9	11-14	1.5-2.5	rest	/	0.045	0.060



a)

b)

Figure 5: Microstructure - grain boundaries of both specimens: a) no presence of carbides along grain boundaries b) no presence of carbides along grain boundaries

Slika 5: Mikrostruktura - granice zrna oba uzorka: a) nema prisustva karbida duž granica zrna b) nema prisustva karbida duž granica zrna



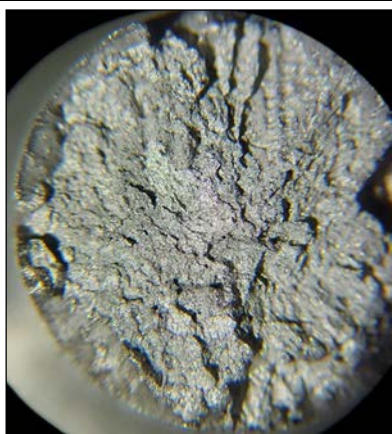
Fig.4 and fig.5 show that both samples of excavation teeth, produced by two different manufacturers, differ from each other in the applied grain size control mechanism.

Thus, the influence of this microstructural feature on the mechanical properties of the final product can be clearly differentiated. For this purpose, tensile and Charpy V-notch tests were performed on both samples. The comparison results are given in tab.2.

Table 2: Results from tensile and Charpy V-notch test

Tabela 2: Rezultati testa zatezanja i Šarpijevog testa sa V-zarezom

Speciment	R _{p0.2} [MPa]	R _m [MPa]	A [%]	KV [J]
a)	446	742	31.5	36.0
b)	501	907	34.0	42.0
Expected values for tensile test for Hadfield steel:				
coarse microstructure and section of 50mm R _{p0.2} =445MPa, R _m =634MPa, A=37%, Z=36%.		refined microstructure and section of 50mm R _{p0.2} =445MPa, R _m =820MPa A=45.5% Z=37.4%.		
Expected values for Charpy V-notch test for Hadfield steel (DIN): KV=16J at 22°C				



a)



b)

Figure 6: Macrostructure of the break surface of two specimens: a) coarse fracture surface, b) refined fracture surface

Slika 6: Makrostruktura površine preloma dva uzorka: a) površina grubog preloma, b) površina rafinisanog preloma

This case shows that chemical composition is not a sufficient criterion (given in EN 10349-2012 *Steel castings -Austenitic manganese steel castings*) to evaluate the quality of the casting as a whole.

In summary, for Hadfield steel, grain refinement generally decreases hardenability due to an increase in grain boundary area, which impedes martensite transformation and reduces the maximum depth of hardening achievable—all while improving other mechanical properties such as strength and toughness.

Therefore, the microstructure should be a balance between the desired hardness obtained by impact hardening, as well as resistance to fracture under strong dynamic impacts.

A balanced microstructure will contribute to a longer lifespan of parts, as in the case of roto excavator teeth, in terms of wear, but also in terms of dynamic fracture.



3. Case study no.2 premature fracture failure of bucket tooth

The most common reasons for fracture failure of Hadfield steel excavator teeth are related to a combination of material defects, operational stresses, and environmental factors, with both metallurgical and external conditions playing important roles.

Metallurgical and materials defects-Fracture origins often include casting defects such as hot foundry cracks, large non-metallic inclusions, and porosities, which act as crack initiation sites during operation. Hadfield steel's tendency for carbide precipitation during post-cooling and improper heat treatment can cause brittle zones, micro-cracks, and a reduction in toughness.

Operational and environmental factors-High impact and abrasive wear during excavation in

tough mineral environments are key contributors, progressively weakening the teeth and causing cracks and fractures. Improper use, such as prying or using the teeth for unintended mechanical tasks, can overload or shock the steel, leading to premature failure. Exposure to chemicals that increase vulnerability to structure failure.

Other causes-Design flaws, such as unsuitable tooth geometry or uneven load distribution, further concentrate stress and encourage fracture under operational loads.

In case study no.2, a failure analysis is performed on a sample of series of broken excavator bucket teeth for rotor excavator [fig.7]. The exact chemical composition of the castings is GX120Mn12 according to EN 10349-2012.



Figure 7: Example fracture surface of broken bucket tooth

Slika 7: Primer površine preloma polomljenog zuba kašike

During operation, the microstructure of Hadfield steel changes because of work hardening. The mechanisms by which hardening occurs include twinning, stacking fault formation and dynamic

strain. Fig. 8 shows for a work-hardened microstructure of manganese steel; clearly visible slip lines are the result of the work hardening to the grains.



Figure 8: Work hardened manganese steel microstructure of the broken tooth

Slika 8: Mikrostruktura ojačanog manganskog čelika polomljenog zuba



Due to the effect of work hardening, to isolate the effect of the load, an analysis was performed on a non hardened sample from the same manufacturing series. By abstracting the load, only the influence of possible metallurgical and material defects was analyzed. The fracture surface (fig.7) is also taken into account in the analysis of the broken tooth.

By analyzing the broken surface of the tooth (fig.7), it is possible to determine damage that originates from the presence of segregation and impurities. These defects in the material occurred during the casting of the tooth.

The most common defects that occur in this steel, in addition to segregations, are macro and micro pores. In fig. 8, macro pores (gray-blue fields) or cavities in the fracture surface are visible.

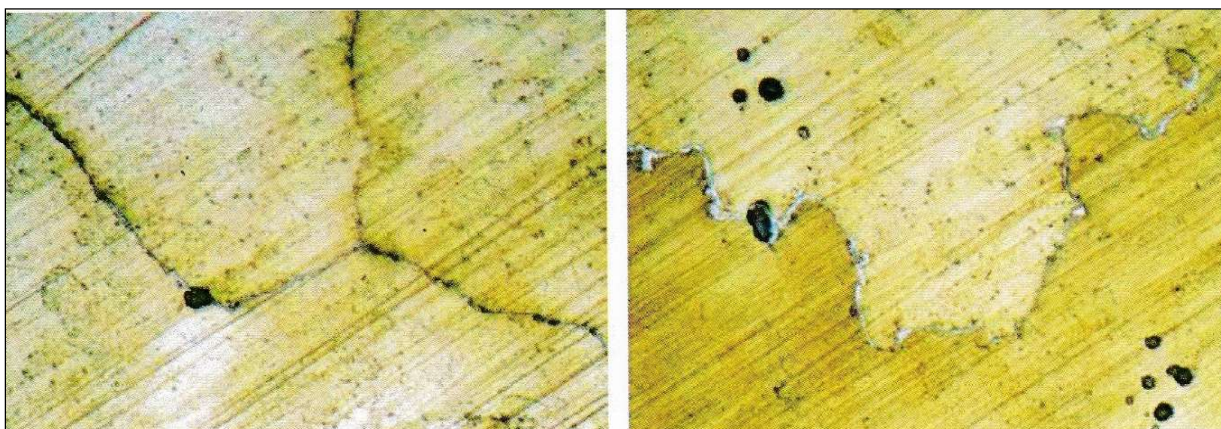


Figure 9: Metallographic image of austenite grain boundaries-presence of undissolved carbides

Slika 9: Metalografski prikaz granica zrna austenita - prisustvo nerastvorenih karbida

Metallographic samples were prepared from non hardened teeth from the same series as the the broken tooth (fig.7). The austenite grain boundaries are revealed with a 5% nital etchant for 15 seconds.

Table 3: Chemical composition of cast steel GX120Mn12 according to EN 10349

Tabela 3: Hemijski sastav livenog čelika GX120Mn12 prema EN 10349

Cast steel (Hadfield)	chemical composition in wt, %							
	C	Si	Mn	Cr max.	Fe	Cu	S	P
						Not more than		
GX120Mn12	1.10-1.30	0.3-0.5	12-13	1.50	rest	/	0.04	0.10

By analyzing the obtained microstructure, it can be concluded that it is austenitic, with the presence of carbides along the grain boundaries (fig.9). The presence of carbides is observed whenever the carbon content is above 1% (tab. 3). In the presence of Cr, the separation of carbides is more intense. Two types of carbides are observed in the microstructure: in the form of nodules and elongated. The elongated ones are dominant.

As can be seen from this case, there are two types of metallurgical defects occurring in two different processes: during casting of the part and during solution heat treatment. Both processes, metallurgical by origin, failed to produce suitable microstructure so as to prevent structural defects (voids, cracks, inclusions) and the formation of brittle phases (carbides). This led to the tooth premature fracture failure and better weldability.



4. Conclusions

Manganese steel is used extensively in the mining industry and in other applications that require extreme toughness. The mechanisms for improving its properties are generally known. However, regardless of the improvements made to achieve better properties, if the part fails early in service, the gain is unlikely to be useful.

Therefore, it is necessary to pay attention to the following points before putting the castings into operation, in order to guarantee a long service life:

1. Checking the chemical composition is not a sufficient criterion to ensure that the castings have the required mechanical properties; in principle, it is one of several criteria that should be controlled during production (case no.1),
2. Microstructure control is a second mandatory criterion that the casting must satisfy in terms of grain shape and size, as well as the presence of other phases (case no.1),
3. The microstructure is the final record of the parameters of the casting process (presence of inoculants, pouring temperature, etc.); if they are not properly selected and implemented, the casting has weaker mechanical properties even though the chemical composition is met as a condition (case no.1 and 2),
4. The as-cast microstructure of Hadfield steel with an chromium content is composed of an austenitic matrix and alloyed cementite present mainly in the form of lamella,
5. The solution annealing increased the ductility of the as-cast alloys by the dissolution of the brittle carbides in the austenite matrix,
6. If the heat treatment is not optimized in terms of dissolution temperature, dissolution time, and cooling rate, it can lead to casting failure in service due to reduced dynamic load capacity (case no.2),
7. Care needs to be taken to avoid excessive air entrainment due to turbulence when pouring at low superheats, to avoid pores (case no.2).
8. The presented procedures, in addition to improving the mechanical characteristics of the finished products, also have an impact on improving the weldability in case of the need for reparative welding, considering that the welding of Hadfield manganese steel is a challenge due to its unique properties.

4. Zaključak

Manganski čelik se intenzivno koristi u rudarskoj industriji i u drugim primenama koje zahtevaju ekstremnu žilavost. Mehanizmi za poboljšanje njegovih svojstava su opšte poznati. Međutim, bez obzira na poboljšanja napravljena radi postizanja boljih svojstava, ako deo otkáže rano u upotrebi, dobitak verovatno neće biti koristan.

Stoga je potrebno obratiti pažnju na sledeće tačke pre puštanja odlivaka u rad, kako bi se garantovao dug vek trajanja:

1. Provera hemijskog sastava nije dovoljan kriterijum da se osigura da odlivci imaju potrebna mehanička svojstva; u principu, to je jedan od nekoliko kriterijuma koje treba kontrolisati tokom proizvodnje (slučaj br. 1),
2. Kontrola mikrostrukture je drugi obavezni kriterijum koji odlivak mora da zadovolji u pogledu oblika i veličine zrna, kao i prisustva drugih faza (slučaj br. 1),
3. Mikrostruktura je konačni zapis parametara procesa livenja (prisustvo inokulanta, temperatura livenja itd.); Ako nisu pravilno odabrani i primenjeni, odlivak ima slabija mehanička svojstva iako je hemijski sastav ispunjen kao uslov (slučaj br. 1 i 2),
4. Mikrostruktura Hadfieldovog čelika sa sadržajem hroma u livenom stanju sastoji se od austenitne matrice i legiranog cementita prisutnog uglavnom u obliku lamela,
5. Žarenje je povećalo duktilnost legura u livenom stanju rastvaranjem krutih karbida u austenitnoj matrici,
6. Ako termička obrada nije optimizovana u pogledu temperature rastvaranja, vremena rastvaranja i brzine hlađenja, to može dovesti do kvara odlivaka u upotrebi zbog smanjenog dinamičkog nosivosti (slučaj br. 2),
7. Potrebno je voditi računa da se izbegne prekomerno unošenje vazduha zbog turbulencije prilikom livenja na niskim pregrevanjima, kako bi se izbegle pore (slučaj br. 2).
8. Prikazane procedure osim poboljšanja mehaničkih karakteristika gotovih proizvoda imaju uticaj i na poboljšanje zavarljivosti u slučaju potrebe za reparativnim zavarivanjem, obzirom da zavarivanje Hadfieldovog manganskog čelika predstavlja izazov zbog njegovih jedinstvenih svojstava.



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ZAVARIVANJE TITANIJUMA I KVALIFIKACIJA TEHNOLOGIJE ZAVARIVANJA

TITANIUM WELDING AND QUALIFICATION OF WELDING TECHNOLOGY

Stručni rad / Professional paper

Rad primljen / Paper received:

Septembar 2024.

Rad prihvaćen / Paper accepted:

Maj 2025.

Adresa autora / Author's address:

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Ključne reči: materijali, titanijum, kvalifikacija, zavarivanje

Keywords: materials, titanium, qualification, welding

Rezime

U radu je prikazan postupak izrade kvalifikacije tehnologije zavarivanja titanijuma, kao i metalurška, tehnološka, fizička i mehanička svojstva dobijenih zavarenih spojeva titanijuma. U radu su prikazani i problemi i izazovi sa kojima se susreću i koji se mogu javiti prilikom zavarivanja titanijuma i načini obezbeđenja kvaliteta zavarenog spoja, kao i rezultata ispitivanja relevantnih uzoraka u skladu sa standardom SRPS EN ISO 15614-5 [10]. Rezultati ispitivanja reprezentativnih uzoraka pokazuju da je odabrana adekvatna tehnologija zavarivanja i da kao takva omogućava uspešno zavarivanje titana u praksi.

Abstract

The paper provides an overview of the qualification of titanium welding technology, as well as the metallurgical, technological, physical, and mechanical properties of titanium welded joints. Problems that may occur during the welding and methods of ensuring the quality of the welded joint, along with the results of the testing of relevant samples in accordance with SRPS EN ISO 15614-5 [10], are given in this paper. The test results of representative samples indicate that welding technology is adequately specified. In that manner, it could be expected that welding in practice could be done properly.

Rad je u originalnom obliku objavljen u Zborniku radova sa 33. Savetovanja sa međunarodnim učešćem „Zavarivanje 2024“ održanog u Vrnjačkoj Banji, Srbija od 2. do 5. oktobra 2024. godine.



1. Uvod

Titanijum i legure titanijuma nisu često zastupljene u komercijalnoj industriji i upotrebi, i ne nailaze se u svakodnevnoj upotrebi. Međutim, kako titanijum ima visoke vrednosti čvrstoće, koje su na nivou čvrstoće poboljšanih čelika i svoje specifične gustine koja ga čini dvostruko lakšim, primenu nalazi u vazduhoplovstvu, raznim vrstama letilica, vojnoj tehnici i industriji, aeronautici i lakim konstrukcijama [1-9].

Reputaciju teško zavarljivog materijala, titanijuma, najverovatnije leži u njegovim fizičkim i hemijskim svojstvima, višoj tački topljenja od drugih metala i legura, kao i zahtevanim merama opreza da se izbegne kontaminacija tokom zavarivanja i slojevima zaštite za sprečavanje oksidacije [1-9]. Zbog toga titanijum se smatra veoma teško zavarljivim dok nepoznavanje tehnologije zavarivanja i striktnih zahteva koje treba ispoštovati može dovesti do pojave niza grešaka usled čega se često karakteriše kao misteriozan metal za zavarivanje. Pored niza mera koje je potrebno ispoštovati pri zavarivanju titanijuma, i visoka cena ovog metala doprinosi razvoju stava da je primena titanijuma limitirana na industrije i proizvode sa zahtevima visokog kvaliteta na tržištu. Iskustvo u zavarivanju titanijuma ukazuje da su tehnike zavarivanja titanijuma i njegovih legura veoma slične onima koje se koriste za zavarivanje legura nikla i nerđajućih čelika što značajno poboljšava stav o njegovoj zavarljivosti.

Zbog svojih mehaničkih, fizičkih i hemijskih svojstva titanijum je veoma privlačan, a u prethodnom periodu, prema statističkim podacima, prodaja i upotreba titanijuma su značajno porasle. Prema najvećem svetskom snabdevaču titanijuma "Verkhaya Salda Metallurgical Production Association", očekuje se da će ukupna potražnja na tržištu porasti za 34% u periodu od 2025. do 2035. godine [1,2].

Kako postoji rastuća tendencija primene titanijuma i njegovih legura u proizvodnji i upotrebi, tako se javlja i potreba za osvajanjem tehnologija zavarivanja od strane proizvođača opreme i proizvoda od titanijuma. U cilju obezbeđenja kvaliteta proizvoda i zavarenih spojeva izrađenih od titanijuma, sve veći broj proizvođača teži osvajanju tehnologija zavarivanja i izradi kvalifikacija tehnologija zavarivanja (u daljem tekstu "WPQR").

Kriterijumi za kvalifikovanje tehnologije zavarivanja titanijuma i njegovih legura navedeni su u standardu SRPS EN ISO 15614-5 [10]. Sprovedenjem ispitivanja naznačenih u referentnom standardu [10] može se dokazati umešnost i zavarivački kapaciteti uporedo sa osvedočenjem ispravnosti izabrane tehnologije zavarivanja.

2. Metalurške, tehnološke i mehaničke karakteristike titanijuma

Najvažnija svojstva titanijuma su: temperatura topljenja $T_{top}=1668^{\circ}\text{C}$, gustina $4,5\text{ g/cm}^3$ (na 20°C), zatezna čvrstoća veća od 315 N/mm^2 , izduženje $A=50\%$, dobra koroziona otpornost prema morskoj vodi i azotnoj kiselini (bez obzira na koncentraciju kiseline), kao i sumpornoj kiselini male koncentracije i svim organskim kiselinama [1-3].

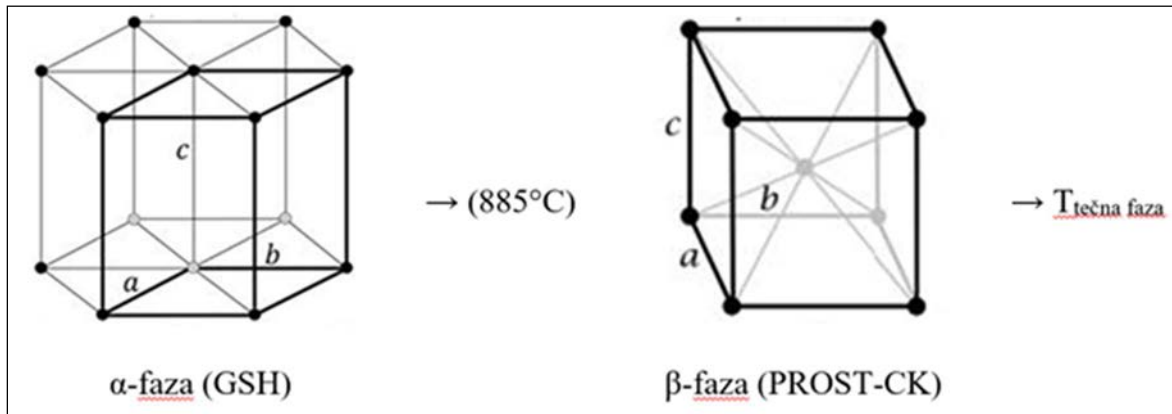
Kao takav, titanijum (Ti) može imati široku upotrebu, ali je ona ograničena njegovom znatno većom cenom na tržištu. Ova cena se znatno povećava ukoliko je neophodno i dobijanje konačnog proizvoda zavarivanjem, odnosno njegovom zahtevnošću pri zavarivanju zarad dobijanja kvalitetnog zavarenog spoja.

Titanijum je polimorfni materijal i kao takav, čist titanijum na sobnoj temperaturi ima gustosloženu heksagonalnu rešetku, i sa povećanjem temperature, na 885°C struktura prelazi u prostornu centriranu kristalnu rešetku (Slika 1) [9].

Legirajući elementi se dele na:

- neutralne, odnosno elementi koji ne utiču na temperaturu transformacije (cirkonijum),
- α -stabilizatori, odnosno elementi koji podižu temperaturu transformacije i koju stabilizuju α -fazu (npr. aluminijum),
- β -stabilizatori, odnosno elementi koji snižavaju temperaturu transformacije i koju stabilizuju β -fazu koja je u pojedinim slučajevima postojana ispod sobne temperature (vanadijum, molibden, hrom, mangan, niobijum) [9].

Podela legirajućih elemenata se osim na osnovu faze koju stabilizuju vrši i na osnovu mesta koje zauzimaju u rešetki titana, kako je prikazano u Tabeli 1.



Slika 1: Polimorfnost titanijuma [9]

Figure 1: Polymorphism of titanium [9]

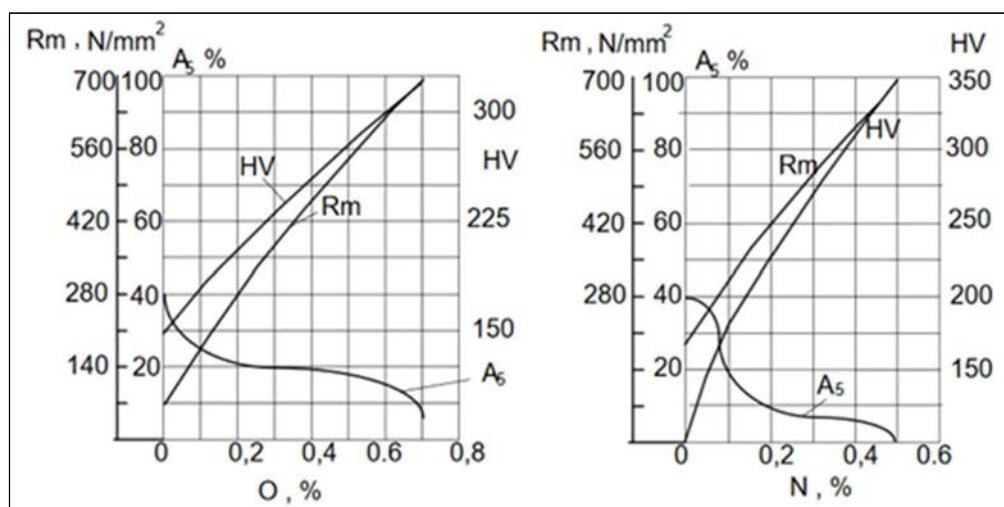
Tabela 1: Legirajući elementi u titanijumu

Table 1: Alloying elements in titanium

α-stabilizatori		β-stabilizatori	
Intersticijski	supstitucijski	Intersticijski	supstitucijski
O, N, C	Al, Pb	H	Ag, Au, Nb, Cr, Co, Cu, Fe, Mn, Mo, Ni, W, V, Pd, Pt, Ta

Najveći problem pri zavarivanju Ti je pojava degradacije mehaničkih svojstva usled pojave nečistoća, najčešće usled reakcija sa gasovima (O_2 , N_2 i H_2), kao i zbog strukturnih transformacija u zoni uticaja toplote (u daljem tekstu "ZUT"). Tokom zavarivanja, potrebno je smanjiti sadržaje i uticaje navedenih gasova i to kiseonika (O_2) do 0,15%, azota (N_2) do 0,04% i vodonika (H_2) do 0,1%, koji

se intersticijski rastvaraju u titanijumu i time povećavaju čvrstoću, ali i krtost. Titanijum ima veliki afinitet posebno prema kiseoniku na povišenim temperaturama (iznad $400^\circ C$) što prouzrokuje velike probleme prilikom zavarivanja [1]. Uticaji sadržaja kiseonika i azota na mehanička svojstva čistog titanijuma su data na slici 2.



Slika 2: Uticaj sadržaja kiseonika i azota na mehanička svojstva čistog titanijuma [9]

Figure 2: Influence of oxygen and nitrogen content on the mechanical properties of pure titanium [9]



3. Podela i grupisanje titanijuma i njegovih legura

Titanijum i njegove legure su podeljene u 4 grupe prema SRPS CEN ISO/TR 15608 [11], prema njihovim hemijskim sastavima, odnosno fazama u kojima se mogu javiti i to:

- Grupa 51: U ovu grupu spadaju čist titanijum kao i titanijum sa primesama kiseonika i to:
 - Podgrupa 51.1, titanijum sa maksimalnim udelom kiseonika $O_2 \leq 0,20\%$,
 - Podgrupa 51.2, titanijum sa maksimalnim udelom kiseonika $0,20\% < O_2 \leq 0,25\%$,
 - Podgrupa 51.3, titanijum sa maksimalnim udelom kiseonika $0,25\% < O_2 \leq 0,35\%$,
 - Podgrupa 51.4, titanijum sa maksimalnim udelom kiseonika $0,35\% < O_2 \leq 0,40\%$,
- Grupa 52: legure titanijuma sa α -fazom.

Legure ove podgrupe imaju dobru čvrstoću i žilavost i smatraju se lako zavarljivim, i najčešće su legirane aluminijumom (legiranje Al oko 5%). Legure koje podpadaju pod ovu grupu su: Ti-0,2Pd; Ti-2,5Cu; Ti-5Al-2,5Sn; Ti -8Al-1Mo-1V; Ti-6Al-2Sn-4Zr-2Mo; Ti-6Al-2Nb-1Ta-0,8Mo.

- Grupa 53: legure titanijuma sa α -fazom i β -fazom.

Legure ove podgrupe mogu ojačati termičkom obradom i čvrstoća im je između 1000 i 1300 MPa, a izduženje je $A=16\%$ (legirajući elementi: Al, V, Mo, Cr). Legure koje podpadaju pod ovu grupu su: Ti-3Al-2,5V; Ti-6Al-4V; Ti-6Al-6V-2Sn; Ti-7Al-4Mo. Od svih legura iz ove grupe najviše se koristi Ti-6Al-4V.

- Grupa 54: legure titanijuma sa β -fazom.

Legure ove podgrupe se legiraju elementima: V, Nb, Cr i legure koje podpadaju pod ovu grupu su: Ti-10V-2Fe-3Al; Ti-13V-11Cr-3Al; Ti -11,5Mo-6Zr-4,5Sn; Ti-3Al-8V-6Cr-4Zr-4Mo.

4. Eksperimentalni deo – zavarivanje ispitnog uzorka

Zavarivanje je izvedeno na ispitnim uzorcima, cevima, prečnika $\varnothing 48,26\text{mm}$ i debljine zida $3,68\text{mm}$. Cevi su izrađene od materijala koji pripada grupi 51.1 prema SRPS CEN ISO/TR 15608 [11], i kvaliteta prema normi ASTM B861-19 – Grade 1, čiji je hemijski sastav za navedenu šaržu br. 2022300145 dat u tabeli 2.

Tabela 2: Hemijski sastavi osnovnog i dodatnog materijala

Table 2: Chemical compositions of basic and additional material

Šarža br.	Kvalitet	Hemijski sastav						
		% C	% Fe	% Mn	% P	% S	% Cr	% Ni
2022300145	ASTM B861-19 – Grade 1	0,009	0,02	1,037	-	-	-	-
		% Mo	% Al	% Ti	% N	% V	% H	% O
		-	-	Ostalo	0,009	0,005	0,002	0,14
8981574	BÖHLER ER Ti 2-IG	0,01	0,02	-	-	-	-	-
		% Mo	% Al	% Ti	% N	% V	% H	% O
		-	-	Ostalo	0,005	-	0,002	0,01

Zavarivanja je urađeno TIG (tungsten inert gas) postupkom, odnosno zavarivanje netopljivom elektrodom u zaštiti inertnog gasa SRPS EN ISO 4063: 141 [15]. Kao dodatni materijal korišćena je žica za TIG zavarivanje komercijalne oznake „BÖHLER ER Ti 2-IG“, proizvođača „Voestalpine Böhler Welding Austria GmbH“, kvaliteta „EN ISO 24034-A: S Ti 0120 (Ti99,6)“, prečnika $\varnothing 2,0\text{mm}$, čiji je hemijski sastav za navedenu šaržu dat u tabeli 2. Zaštitni gas korišćen za zaštitu zavarenog

spoja sa strane lica i korena (uduvanjem u cevi) je argon, kvaliteta I1-Ar prema standardu SRPS EN ISO 14175 [13], nominalnog sastava 100% Ar, odnosno tehnički argon od 99,99% čistoće. Za zavarivanje je korišćen uređaj oznake „ESAB Orio Tig 3000i“, serijski br.: 802-808-5932.



4.1 Tehnologija zavarivanja (pWPS)

Za potrebe zavarivanja ispitnih uzoraka, sačinjena je preliminarna specifikacija tehnologije zavarivanja, odnosno pWPS (Preliminary Welding

procedure specification), kojom su definisani svi parametri neophodni za potrebe zavarivanja predviđeni standardom SRPS EN ISO 15609-1 [14] (slika 3).

Location: _____	Inspector and inspection location: _____
WPQR: _____	Prep. and cleaning method: Grinding
Made by: _____	Base material specification: ASTM B861-19, Gr.2
Welders name & identification No.: <u>/</u>	Thickness "s"(mm): 3,68
Welding process: 141	Outside diameter (mm): 48,26
Type of welded joint: BW	Welding position: PC, PH
Detail of groove design: Piping	

Joint design		Welding sequence	

Welding parameters								
Run	Process	Filler material (mm)	Current (A)	Voltage (V)	Type of current /polarity	Wire feed	Feed velocity cm/min	Heat input KJ/mm
1-2	141	Ø 2.0	60-90	9-11	DC/-	/	/	0,6-0,8

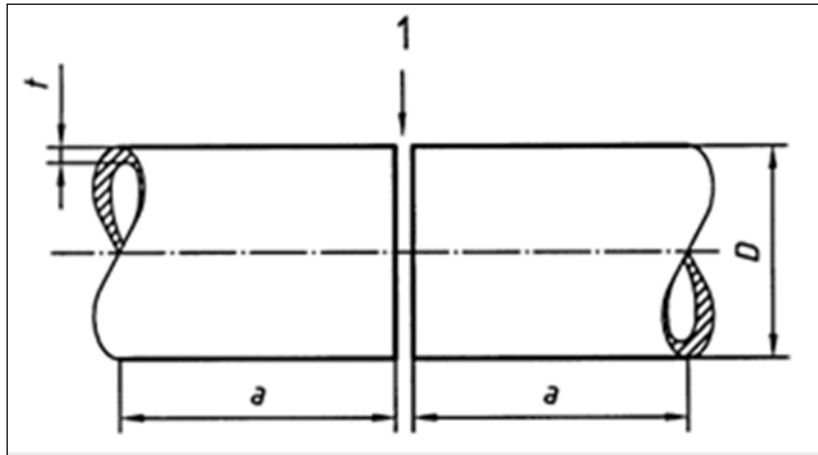
Filler material (class and designation): EN ISO 24034 : S Ti 0120 (Ti99,6)	Preheat temperature: <u>/</u>
Prescribed drying method: <u>/</u>	Interpass temperature: 130°C
Shielding gas / flux	Heat treatment or annealing: <u>/</u>
- face: II(Ar) ISO 14175	Duration of heat treatment: <u>/</u>
- root: II(Ar) ISO 14175	Heating and cooling speed: <u>/</u>
Gas flow l/min	Other data: <u>/</u>
- face: 14-18 l/min	e.g. Weaving (max. bead width): <u>max 3d</u>
- root: 20-30 l/min	Oscillation: amplitude, frequency, holding time: <u>/</u>
Type of tungsten electrode/diameter: WL 15, 2.4 mm	Orifice or gas cup size: <u>/</u>
Gouging detail:	Details of plasma weld.: <u>/</u>
	Torch adjustment angle: <u>/</u>

Slika 3: Preliminarna specifikacija tehnologije zavarivanja pWPS

Figure 3: Preliminary specification of pWPS welding technology

Probni uzorak koji je zavarivan je cev prečnika Ø48,26mm, debljine zida 3,68mm. Dužina „a“ je pripremljena na 150mm na svim uzorcima. Spoj je pripremljen u „V“ žljebu, sa zatupljenjem od 2mm i zazorom od 2 do 4mm. Ugao pripreme kosina žljeba je od po 30° po strani, odnosno ukupno od

60°. Zavarivanje je izvedeno u PH i PC položajima prema standardu SRPS EN ISO 6947 [16], sa maksimalnim dopuštenim njihanjem od 3 debljine elektrode od ≈7,5mm. Uzorci su pripremljeni prema slici 4.



Slika 4: Skica pripreme cevi za zavarivanje

Figure 4: Sketch of pipe preparation for welding

Parametri zavarivanja i svi ostali zahtevani podaci koji su zahtevani preliminarnom Specifikacijom tehnologije zavarivanja su prikazani na slici 4, prema čijim podacima i smernicama su testni uzorci i zavareni.

U toku samog zavarivanja, vodilo se računa o vremenima uduvanja zaštitnog gasa sa korene strane i zaštite sa lica šava kako je prethodno i napisano. Nakon zavarivanja, i održavanja zaštite argonom od 25 sekundi i obezbeđenja da temperatura zavarenog uzorka spadne ispod

300°C, pristupilo se i pregledu spoja, čime je i potvrđena svetla i srebrna boja lica šava, kao i zone osnovnog materijala oko zavarenog spoja. Ova boja spoja ukazuje da je zaštita zavarenog spoja adekvatna i da nije došlo do oksidacije zavarenog spoja.

Ukupno je za potrebe svih ispitivanja zavareno 8 uzoraka, od toga 4 u PH položaju i 4 u PC položaju i pojednini od zavarenih uzoraka u PH i PC položaju prikazani na slici 5.



Slika 5: Fotografije zavarenog uzorka u PH (gornji uzorak) i PC položaju (donji uzorak)

Figure 5: Photographs of welded samples in PH (upper sample) and PC position (lower sample)



4.2 Priprema pre zavarivanja, i aktivnosti u toku i nakon zavarivanja

Pored zahtevanih parametara zavarivanja kao što su definisanje jačine struje, napona, brzine zavarivanja, brzine protoka zaštitnog gasa, definisani su i dodatni zahtevi imajući u vidu materijal koji se zavaruje. Posebna se pažnja posvećuje pripremi pre zavarivanja, kao što su čišćenje žljeba i dela osnovnog materijala prohrumskom čeličnom četkom, nove i čiste zavarivačke rukavice i zaštitna oprema zavarivača. Proverena je oprema, polikabl i creva za protog gasa da nisu negde oštećena i kako se ne bi pojavila neželjena curenja i gubici gasa. Osnovni materijal je brušen sa leve i desne strane po 30mm rastojanja od pripremljenog žljeba kako bi se uklonili oksidi i druge kontaminacije sa površine osnovnog materijala. Osnovni materijal je očišćen i acetonom kako bi se otklonile bilo koje nečistoće i masti.

Pre zavarivanja, svaki put je odsecan vrh elektrodne žice pre utapanja dodatnog materijala u rastopljeno tečno kupatilo – kupku.

Kako je u prethodnom delu rada i navedeno, problem pri zavarivanju titanijuma i njegovih legura je pojava degradacije mehaničkih svojstva usled pojave nečistoća najčešće zbog reakcija sa gasovima (O_2 , N_2 i H_2), kao i zbog strukturnih transformacija u ZUT-u. Kako bi se smanjila reakcija sa ovim gasovima, posebno se obraća pažnja na zaštitu zone oko samog zavarenog spoja ne samo za vreme zavarivanja, već pre i posle zavarivanja. Ovo se postiže zaštitom zavarivačke

kupke (štiti se posebno i oblast korena) argonom, koju treba produžiti dok temperatura šava ne bude ispod $300^\circ C$.

Pre samog uspostavljanja električnog luka, podešen je uređaj za zavarivanje tako da se uduvavanje kroz gorionik započne 25 sekundi pre i nastavi 25 sekundi posle prekidanja električnog luka. Protok je podešen na 15 l/min.

Brušenje međuprolaza se obavlja umerenim pritiskom na radni komad kako se ne bi osnovni materijal previše zagrejao za vreme brušenja spoja. Takođe, međuprolazi su čišćeni i prohrumskom čeličnom četkom.

Zaštitni gas koji se koristio za zaštitu sa korene strane je istog kvaliteta kao i sa lica šava, odnosno SRPS EN ISO 14175 – I1-Ar [13], nominalnog sastava od 100% argona prema navedenom standardu, odnosno tehnički argon od 99,99% čistoće. Protok je podešen na 20 l/min., kako bi se obezbedila adekvatna zaštita i sa korene strane, a uzimajući u obzir dužinu pripremljenih pozicija za zavarivanje.

5. Rezultati ispitivanja uzoraka

Nakon zavarivanja uzoraka, a za potrebe kvalifikacije tehnologije zavarivanja, primenjen je standard SRPS EN ISO 15614-5 [10]. Standard za potrebe kvalifikovanja tehnologije zavarivanja propisuje ispitivanje metodama bez razaranja i metode ispitivanja sa razaranjem, gde su vrste ispitivanja sa svojim obimima i definisani prema SRPS EN ISO 15614-5 [10]. U tabeli 3 su navedene metode sa svojim obimima ispitivanja.

Tabela 3: Ispitivanje metodama bez i sa razaranjem

Table 3: Examination by methods without and with destruction

Metodama bez razaranja		Metodama sa razaranjem	
Metoda	Obim ispitivanja	Metoda	Obim ispitivanja
Vizuelna metoda	100%	Transverzalno ispitivanje zatezanjem	2 epruvete
Ispitivanje tečnim penetrantima	100%	Transverzalno ispitivanje savijanjem	4 epruvete
Radiografsko ispitivanje	100%	Makroskopsko ispitivanje	1 epruveta
		Mikroskopsko ispitivanje	1 epruveta



Svaka od navedenih metoda je definisana svojim standardom i nakon zavarivanja reprezentativnih uzoraka, pristupilo se ispitivanju istih u skladu sa navedenim obimima ispitivanja za oba zavarena uzorka.

5.1 Rezultati ispitivanja metodama bez razaranja

U skladu sa Tabelom 3, uzorci su ispitani vizuelnom metodom prema SRPS EN ISO 17637 [17], tečnim penetrantima prema SRPS EN ISO 3452-1 [18] kako bi se površinski proverio kvalitet spoja i radiografskom metodom prema SRPS EN ISO 17636-1 [19] kako bi se zavareni spojevi proverili i zapreminski. Rezultati ispitivanja nisu pokazali neprihvatljive neusaglašenosti i bili su bez

nalaza, odnosno indikacija. **5.2 Rezultati ispitivanja metodama sa razaranjem**

Kako je primenjenim standardom i predviđeno, nakon ispitivanja metodama bez razaranja i pozitivnim rezultatima ispitivanja, pristupilo se ispitivanjem metodama sa razaranjem.

Primenjeno je ispitivanje zatezanjem transverzalno u odnosu na zavareni spoj, prema SRPS EN ISO 4136 [20], pri čemu je zahtevano da zatezna čvrstoća bude ≥ 345 N/mm². Vrednosti rezultata ispitivanja su u skladu sa zahtevima i isti su prikazani u Tabeli 4.

Tabela 4: Rezultati ispitivanja zatezanjem

Table 4: Tensile test results

Oznaka epruvete/ položaj	Dimenzija epruvete [mm]	Rm [N/mm ²]	Mesto loma
763.1 / PC	3,9 x 6,0	470	Osnovni materijal
763.2 / PC	3,9 x 5,95	494	Metal šava
763.1 / PH	4,0 x 5,9	486	Osnovni materijal
763.2 / PH	4,0 x 5,85	495	Metal šava

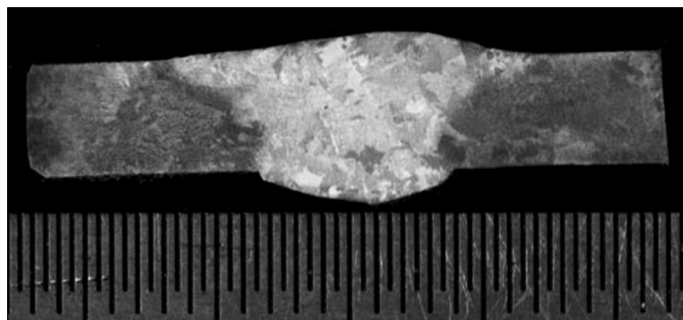
Naredna metoda je ispitivanje savijanjem prema SRPS EN ISO 5173 [21], i rezultati ispitivanja su u skladu sa zahtevima i isti su prikazani u Tabeli 5. Korišćena dimenzija trna je 14mm.

Metode koje su zahtevane standardom primene su i makroskopska i mikroskopska ispitivanja u skladu sa SRPS EN ISO 17639 [22]. Rezultati, odnosno makropreseki su prikazani na slikama 6 i 7.

Tabela 5: Rezultati ispitivanja savijanjem

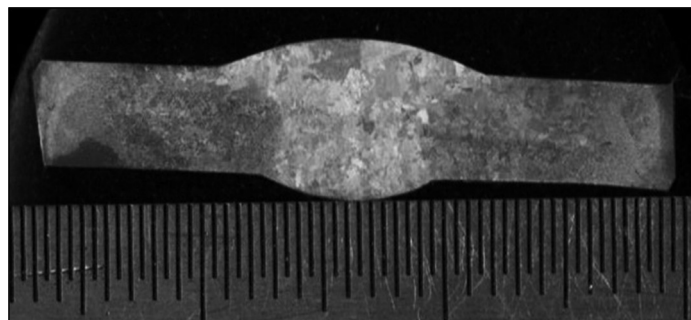
Table 5: Bending test results

Epruvete zavarene u PC položaju				Epruvete zavarene u PH položaju			
Oznaka epruvete/ položaj	Dimenzija epruvete [mm]	Ugao savijanja [°]	Vrsta savijanja	Oznaka epruvete/ položaj	Dimenzija epruvete [mm]	Ugao savijanja [°]	Vrsta savijanja
763.1l / PC	3,68 x 15,0	180	Lice	763.1l / PH	3,68 x 15,0	180	Lice
763.2k / PC	3,68 x 15,0	180	Koren	763.2k / PH	3,68 x 15,0	180	Koren
763.3l / PC	3,68 x 15,0	180	Lice	763.3l / PH	3,68 x 15,0	180	Lice
763.4k / PC	3,68 x 15,0	180	Koren	763.4k / PH	3,68 x 15,0	180	Koren



Slika 6: Makropreseki PC zavarenog uzorka

Figure 6: Macro section of the PC welded sample



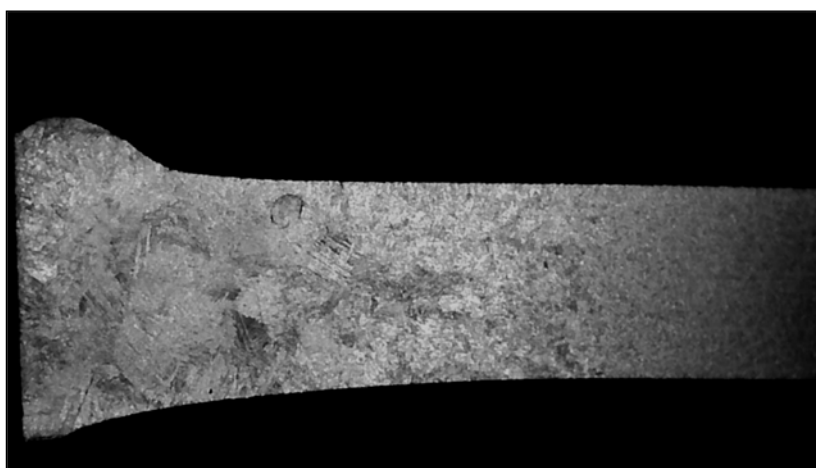
Slika 7: Makropreseki PH zavarenog uzorka

Figure 7: Macro section of the PH welded sample



Makroskopskim ispitivanjem nisu uočene nedozvoljene nepravilnosti i jasno se mogu uočiti linije stapanja, prolazi svakog šava, zone uticaja toplote i sami izgledi lica i naličja spojeva. Makroskopskom analizom uočena je velika širina zone uticaja toplote koja je prisutna na svim makro-uzorcima iako unos toplote na samim uzorcima nije prelazio 0,65 KJ/mm kako je tehnologijom zavarivanja i predviđeno. Usled limita dimenzija prese za toplo zatapanje uzoraka, na prvim uzorcima za analizu makrostrukture zavarenih spojeva (slike 6 i 7) nije bilo moguće videti čitavu

zonu uticaja toplote. Zbog toga su pripremljeni novi uzorci koji su isečeni po sredini metala šava i naknadno pripremani kao dve zasebne polovine i tako analizirani (slika 8). Obradom fotografija makrostrukture i merenjem širine zone uticaja toplote uočeno je da je u PH položaju 10-11mm (slika 8), dok je u PC položaju širina zone uticaja toplote nešto manja (9-10mm) usled razlike u unosu toplote pri zavarivanju u dva navedena položaja.

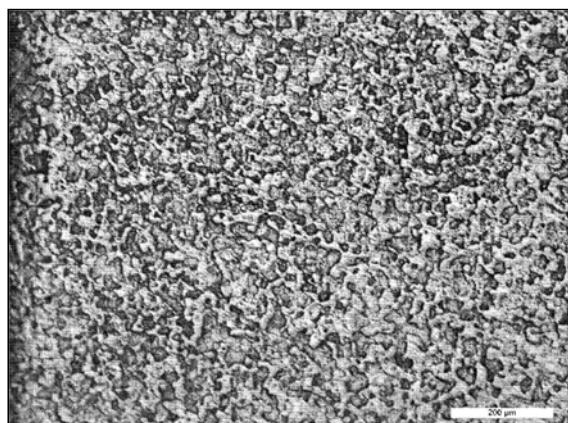


Slika 8: Makropresek PH zavarenog uzorka

Figure 8: Macro section of the PH welded sample

Nakon makroskopskog ispitivanja, pristupilo se mikroskopskim ispitivanjima na uzorcima koji su prethodno makro ispitani. Mikroskopskim ispitivanjem na uzorku zavarenom u PC položaju, utvrđeno je sledeće:

- Struktura osnovnog materijala je α -čvrsti rastvor sa β -fazom (Slika 9),



Slika 9: Mikrostruktura PC uzorka (OM)

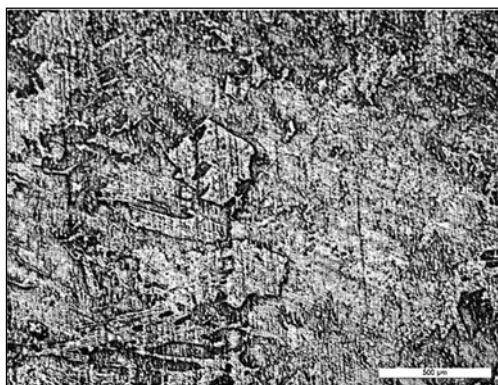
Figure 9: Microstructure of PC sample (BM)

- Mikrostrukturu zone uticaja toplote (ZUT) čini izrazito krupnozrna struktura α -čvrstog rastvora sa β -fazom. Vidmanštetenove morfologije α -čvrstog rastvora mogu se uočiti u zoni uticaja toplote (Slika 10),
- Mikrostrukturu metala šava čini krupnozrna struktura α -čvrstog rastvora sa β -fazom. Vidmanštetenove morfologije α -čvrstog rastvora se mogu uočiti (Slika 11).



Slika 10: Mikrostruktura PC uzorka (ZUT)

Figure 10: Microstructure of PC sample (HAZ)



Slika 11: Mikrostruktura PC uzorka (MŠ)

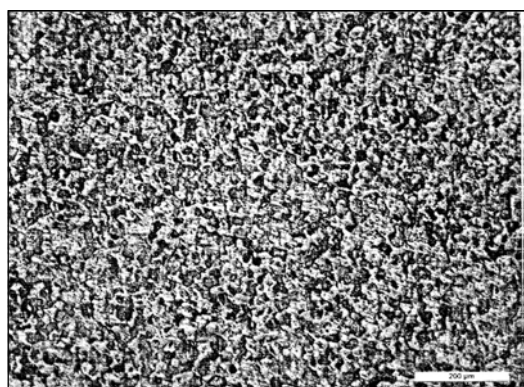
Figure 11: Microstructure of PC sample (WM)

Mikroskopskim ispitivanjem na uzorku u zavarenom u PH položaju, utvrđeno je sledeće:

- Struktura osnovnog materijala je α -čvrsti rastvor sa β -fazom (Slika 12),
- Mikrostrukturu zone uticaja toplote (ZUT) čini krupnozrna struktura α -čvrstog rastvora sa β -fazom.

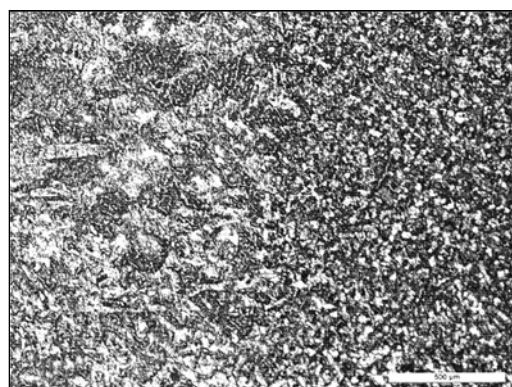
Vidmanštetenove morfologije α -čvrstog rastvora mogu se uočiti u zoni uticaja toplote (Slika 13),

- Mikrostrukturu metala šava čini krupnozrna struktura α -čvrstog rastvora sa β -fazom. Vidmanštetenove morfologije α -čvrstog rastvora se mogu uočiti Slika (14).



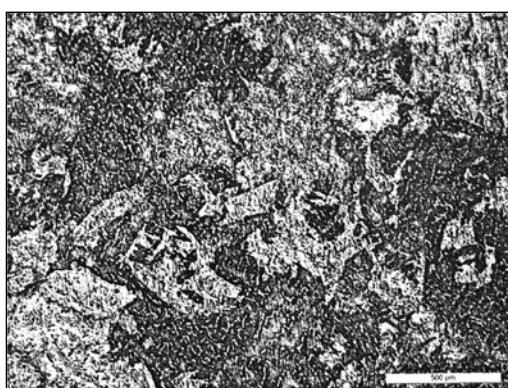
Slika 12: Mikrostruktura PH uzorka (OM)

Figure 12: Microstructure of PH sample (BM)



Slika 13: Mikrostruktura PH uzorka (ZUT)

Figure 13: Microstructure of PH sample (HAZ)



Slika 14: Mikrostruktura PH uzorka (MŠ)

Figure 14: Microstructure of PH sample (WM)

Rezultati ispitivanja mikrostrukture nisu pokazali nedozvoljene nepravilnosti. Kako je već uočeno makroskopskim ispitivanjem i navedeno, potvrđena

je velika širina zone uticaja toplote (ZUT-a). ZUT je po poprečnom preseku imao veću širinu u odnosu na debljinu materijala nego što je očekivano [4-8].



6. Zaključak

Nakon sprovedenih svih predviđenih ispitivanja u skladu sa standarda SRPS EN ISO 15614-5 [10], donet je zaključak da su svi rezultati ispitivanja bez nalaza ili u granicama dozvoljenih odstupanja ukoliko su konstatovana. Može se zaključiti da zavarivanje titanijuma ne mora predstavljati problem ukoliko se ispoštuju smernice i preporuke koje su neophodne u radu i primeni titanijuma i njegovih legura. Pri zavarivanju titanijuma zahtevaju se mere opreza kako bi se izbegla kontaminacija tokom zavarivanja i zaštite kako bi se sprečila pojava oksidacije.

Moraju se obezbediti adekvatni uslovi, oprema i dovoljno obučeno osoblje koji primenom zahtevanih mera pre, za vreme i nakon zavarivanja, odabirom odgovarajuće tehnologije zavarivanja, i tada se može dobiti kvalitetno zavarivanje titanijuma i njegovih legura.

Rezultati ispitivanja na reprezentativnom uzorku i primenom zahteva standarda SRPS EN ISO 15614-5 [10], pokazuju da proizvođači mogu uspešno ovladati zavarivanjem titanijuma grupe 51.1 primenom ove tehnologije.

Dobijene mikrostrukture u zavarenom spoju su bez mikrostrukturnih grešaka i uprkos velikim zrnima u metalu šava i zoni uticaja toplote dobijene mikrostrukture su zadovoljavajuće [3,5,6].

Kao interesantan zaključak se može izdvojiti povećana širina zone uticaja toplote kao i izrazit porast veličini zrna koji se uočavaju na svim uzorcima uprkos malom unos toplote koji na samim uzorcima nije prelazio 0,65 KJ/mm, kako je tehnologijom zavarivanja i predviđeno. Ova pojava utiče na pojavu širu oblast izmenjene mikrostrukture od očekivane, ili bolje reći uobičajne za druge metale i legure ali i sam titanijum i njegove legure. Na ovaj način nastaje degradacija osobina osnovnog materijala u većem delu poprečnog preseka zavarenog spoja, što u zavisnosti od same upotrebe ove legure može dovesti i do narušavanja integriteta i kvaliteta konstrukcije koja se zavaruje uprkos rezultatima koji su zadovoljavajući za kvalifikaciju tehnologije zavarivanja, imajući na umu da se zavarivanje u cilju kvalifikacije tehnologije zavarivanja izvodi u uslovima koji su najčešće bolji u odnosu na radne uslove.

Na kraju, kao rezultat sprovedenih ispitivanja i njihovih pozitivnih nalaza, kao izlazni dokument je i sačinjen Izveštaj kvalifikacije tehnologije zavarivanja ili „Welding Procedure Qualification Report (WPQR)“ u skladu sa SRPS EN ISO 15614-5 [10]. U narednom periodu će biti razmatrane izmene tehnologije zavarivanja koje mogu dovesti

6. Conclusion

After conducting all the planned tests in accordance with the SRPS EN ISO 15614-5 standard [10], it was concluded that all test results were without findings or within the limits of permissible deviations if they were noted. It can be concluded that welding titanium does not have to be a problem if the guidelines and recommendations that are necessary in the work and application of titanium and its alloys are followed. When welding titanium, precautions are required to avoid contamination during welding and protection to prevent oxidation.

Adequate conditions, equipment and sufficiently trained personnel must be provided, so that by applying the required measures before, during and after welding, by choosing the appropriate welding technology, quality welding of titanium and its alloys can be obtained.

The results of testing on a representative sample and applying the requirements of the SRPS EN ISO 15614-5 standard [10], show that manufacturers can successfully master the welding of group 51.1 titanium using this technology.

The obtained microstructures in the welded joint are without microstructural defects and despite the large grains in the weld metal and the heat-affected zone, the obtained microstructures are satisfactory [3, 5, 6].

An interesting conclusion is that the increased width of the heat-affected zone, as well as the marked increase in grain size, are observed on all samples, despite the low heat input, which did not exceed 0.65 KJ/mm on the samples themselves, as predicted by the welding technology. This phenomenon affects the appearance of a wider altered microstructure area than expected, or rather, usual for other metals and alloys, but also titanium itself and its alloys. In this way, a degradation of the properties of the basic material occurs in the greater part of the cross-section of the welded joint, which, depending on the use of this alloy itself, can lead to a violation of the integrity and quality of the structure being welded despite the results that are satisfactory for the qualification of the welding technology, bearing in mind that the welding for the purpose of the qualification of the welding technology is performed in conditions that are usually better than the working conditions.

Finally, as a result of the conducted tests and their positive findings, the welding technology qualification report or "Welding Procedure Qualification Report (WPQR)" was created as an output document in accordance with SRPS EN ISO 15614-5 [10]. In the following period, changes in



do smanjenja širine zone uricaja toplote, uz ispunjenje svih zahteva za kvalitet spoja.

welding technology will be considered, which can lead to a reduction in the width of the heat penetration zone, while meeting all the requirements for the quality of the joint.

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IIW Doc II-C-597-2021 (<https://iiwelding.org>)

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HEAT AFFECTED ZONE FERRITE CONTENT CONTROL OF A NEW DUPLEX STAINLESS STEEL GRADE WITH ENHANCED WELDABILITY KONTROLA SADRŽAJA FERITA U ZONI UTICAJA TOPLOTE NOVIH DUPLEKS NERĐAJUĆIH ČELIKA SA POBOLJŠANOM ZAVARLJIVOŠĆU

Professional paper / Stručni rad

Paper received / Rad primljen:

September 2025.

Paper accepted / Rad prihvaćen:

November 2025.

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Keywords: Duplex stainless steels, weldability, ferrite content, heat affected zone, oil and gas, low temperature

Ključne reči: Dupleks nerđajući čelici, zavarljivost, sadržaj ferita, zona uticaja toplote, nafta i gas, niske temperature

Abstract

Duplex stainless steels have a microstructure consisting of 50% ferrite α and 50% austenite γ . This two-phase microstructure provides the duplex stainless steels with attractive mechanical and corrosion properties and is strongly dependent on the heat treatment and chemical composition. During the welding process, the temperature reached in the heat affected zone (HAZ) retransforms austenite into ferrite. Due to the high cooling rates, only a part of the ferrite is retransformed into austenite. This tends to modify the 50/50 phases equilibrium. Cooling rate is linked to heat input but also to parts thickness and increases with the thickness of the plates. Most of the actual standards limits the ferrite content in the range from 30% to 70% in HAZ. However, the 70% limit for ferrite content in HAZ could be difficult to reach on high thickness plate. To avoid this risk, a new duplex stainless grade, called 2205 Arctic, was developed. This paper will provide details on ferrite content measurement by metallographic method and welding results obtained on industrial welds showing very low and stable ferrite content in HAZ. Mechanical properties obtained on these welds at low temperature will also be reported, pushing the limits of use of duplex from -50°C (-58°F) down to -100°C (-148°F).

Rezime

Mikrostruktura dupleks nerđajućih čelika sastoji se od 50% ferita (α) i 50% austenita (γ). Ova dvofazna mikrostruktura pruža dupleks nerđajućim čelicima atraktivna mehanička i korozivna svojstva, pri čemu jako zavisi od termičke obrade i hemijskog sastava. Tokom procesa zavarivanja, temperatura dostignuta u zoni uticaja toplote (ZUT) dovodi do transformacije austenita u ferit. Zbog visokih brzina hlađenja, deo ferita se ponovo transformiše u austenit. Ovim se menja 50/50 ravnotežni odnos faza. Brzine hlađenja direktno su povezane sa unetom toplotom, kao i sa debljinom delova koji se zavaruju, pri čemu se unos toplote povećava sa debljinom limova. Radi izbegavanja navedenih rizika, razvijena je nova klasa dupleks nerđajućih čelika, pod nazivom 2205 Arctic. Ovaj rad prikazuje detalje u vezi merenja sadržaja ferita metalografskom metodom kao i rezultate na industrijskim zavarenim spojevima, koji pokazuju nizak i stabilan sadržaj ferita u ZUT. Prikazane su i mehaničke osobine na niskim temperaturama dobijene na ovim spojevima, a rezultati pomeraju granicu upotrebe dupleks čelika sa -50°C čak do -100°C .

1. Introduction

Industeel developed a new 25% chromium duplex stainless steel, called 2205 Arctic, with improved toughness down to $-100\text{ }^{\circ}\text{C}$, same tensile properties and corrosion resistance as the standard 2205 duplex material. In the first part, we will explain the chemistry modification which allow better austenite-ferrite balance in base material and in welded joint and the mechanical properties obtained. In a second part, we will come back on the influence of welding and methodology of measurement on ferrite content in HAZ. Last part will gather welding examples performed in partnership with 3 companies: VRV (Italy), Enerfab (USA) and FBM Hudson Italiana (Italy) on 55-mm thick plates with arc processes, where ferrite content and mechanical properties obtained will be presented.

2. A new duplex grade for low temperature conditions

2.1 A new duplex with improved toughness at low temperature

Duplex stainless steels are a balanced mix between austenite phase and ferrite phase. They combine high strength and corrosion resistance compared to standard austenitic stainless steels, which explain their wide use in the energy sector.

To keep optimized corrosion and toughness properties, the ferrite content must be under control either on Base material (BM), Heat Affected Zone (HAZ) or Weld Metal (WM).

A new duplex stainless steel was developed to improve toughness below $-50\text{ }^{\circ}\text{C}$ (-58°F) (1) by reducing the ferrite content.

2.2 Modified chemical compositions to obtain lower ferrite content in HAZ

Duplex stainless steels present a two-phase microstructure consisting generally of 50% austenite and 50% ferrite. This balance is due to the chemical composition between ferrite formers (chromium and molybdenum) and austenite formers (nickel and nitrogen) (2), and to the heat treatment. When it is melted, a duplex stainless steel solidifies from the liquid phase in a fully ferritic microstructure. When it cools down, around half of the ferrite transforms to austenite. Duplex stainless steels have a 50-50 austenite-ferrite microstructure after a solution annealing usually at $1050\text{-}1100^{\circ}\text{C}$ ($1922\text{-}2012^{\circ}\text{F}$) followed by a rapid quenching 2205 Arctic contains more nickel and nitrogen (Table 1) and has a 60-40 austenite-ferrite microstructure after water quenching (Figure 1, Figure 2).

Table 1: Typical chemical composition (weight %) of DSS 2205

Tabela 1: Tipični hemijski sastav (tež. %) legure DSS 2205

Name	UNS	EN	% C	%	%	% Mo	% N	%
Standard	S32205,	1.446	<0.02	22.5	5.3	2.7-	0.16	rest
2205 Arctic	S32205,	1.446	<0.02	22.5	6.0	2.7-	0.19	rest

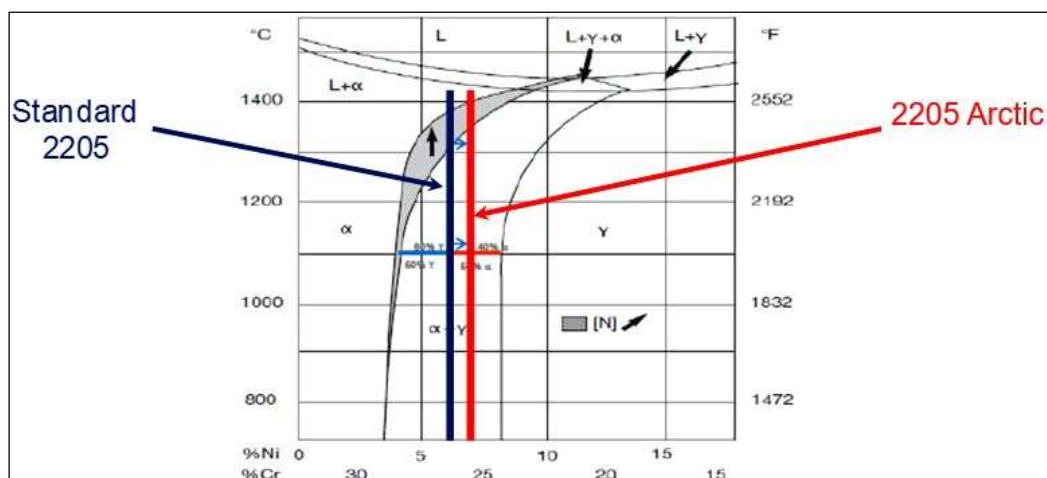


Figure 1: Cr-Ni phase diagram at 68% iron and modification of ferrite content from 50% (Standard 2205) to 40% (2205 Arctic) with Ni and N addition (3)

Slika 1: Cr-Ni fazni dijagram, pri sadržaju Fe od 68% i modifikacija sadržaja ferita od 50% (standardna 2205 legura) do 40% (legura Arctic 2205) dodatkom Ni i N (3)

During welding operation, the thermal cycles induced by welding operations can go up to 1300 °C (2372 °F) and strongly impact the microstructure, by transforming the austenite into ferrite (Figure 2). For instance, nitrogen added (0,14 to 0,21% N₂) into the lean duplex stainless steel 2304 (S32304 / 1.4362) decreases the ferrite content (74 to 65 %) and the width of HAZ (250 to 150 μm) (2).

As the cooling rate is quite high during welding, the re-transformation of ferrite into austenite is not completely achieved and the austenite is made of

needles (Figure 4 in HAZ, Figure 5 in WM). Thus, HAZ and WM of duplex stainless steels are characterized by higher ferrite content than BM.

For the WM, duplex filler metals have high Nickel content (usually 9 to 10% Ni), to promote the austenite and moreover to enhance the toughness in the as-solidified structure. In case of Gas Tungsten Arc Welding or Gas Metal Arc welding, part of nitrogen loss in the arc must be compensated by the nitrogen addition in the shielding gas. It allows to limit the ferrite content in the weld metal (4).

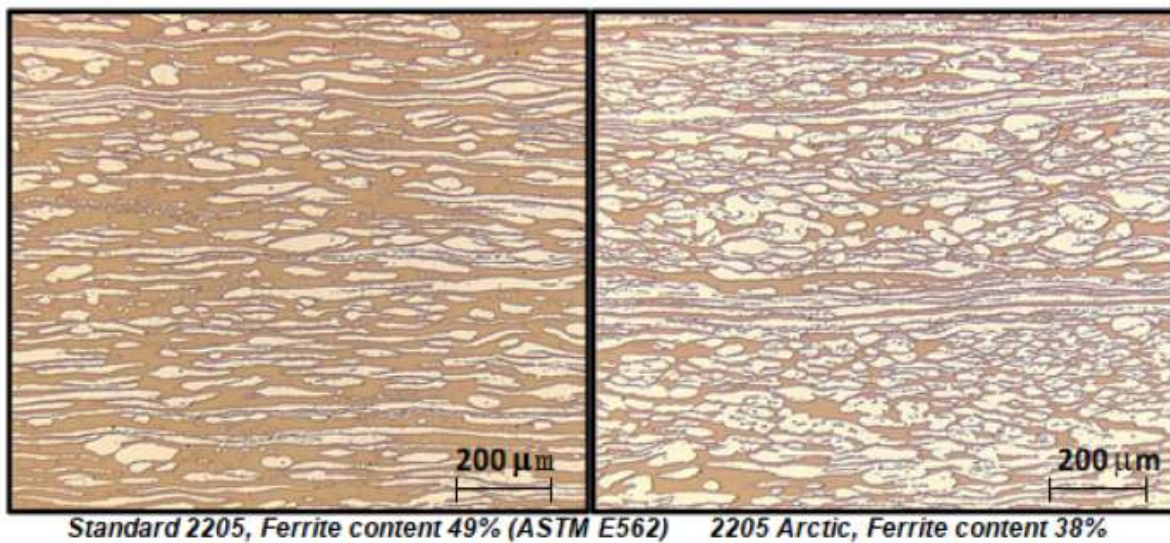


Figure 2: Metallographic examination of a DSS Standard 2205 (left) and 2205 Arctic (right) microstructures (x200) after etching with NaOH 10N (ferrite in brown and austenite in white) (1)

Slika 2: Metalografsko ispitivanje mikrostrukture legura DSS standard 2205 (levo) i 2205 Arctic (desno), x200, posle nagrizanja sa NaOH 10N (braon-ferit, belo-austenit)

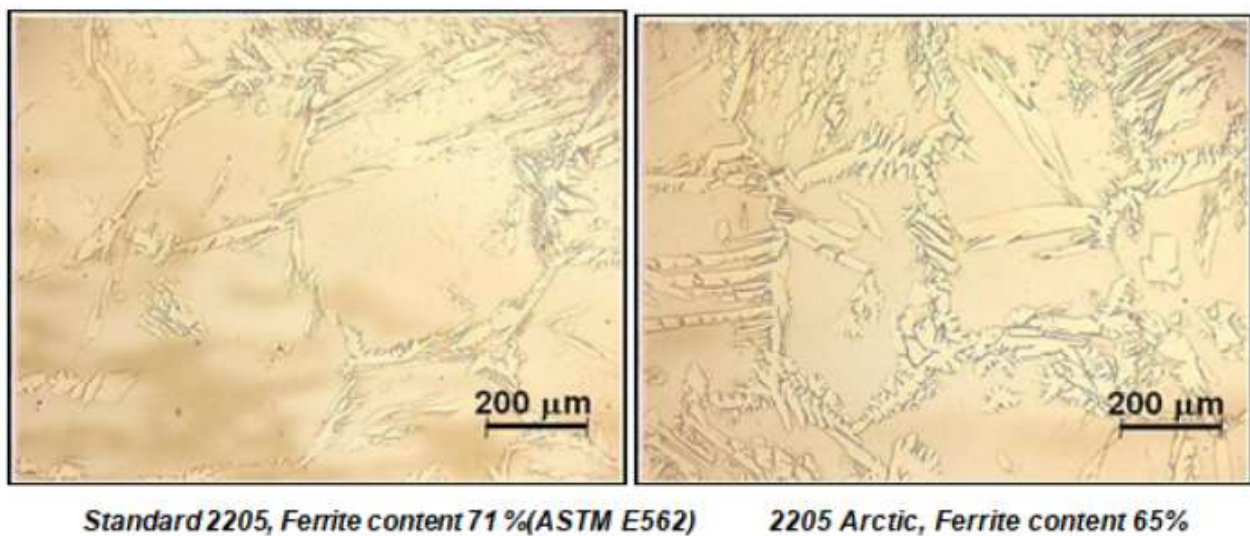


Figure 3: Metallographic examination of a HAZ (single affectation) of a DSS Standard 2205 (left) and 2205 Arctic (right) after etching with NaOH 10N (ferrite in brown and austenite in white) (1)

Slika 3: Metalografsko ispitivanje mikrostrukture u ZUT (jednostruki uticaj) legura DSS standard 2205 (levo) i 2205 Arctic (desno), posle nagrizanja sa NaOH 10N (braon-ferit, belo-austenit) (1)

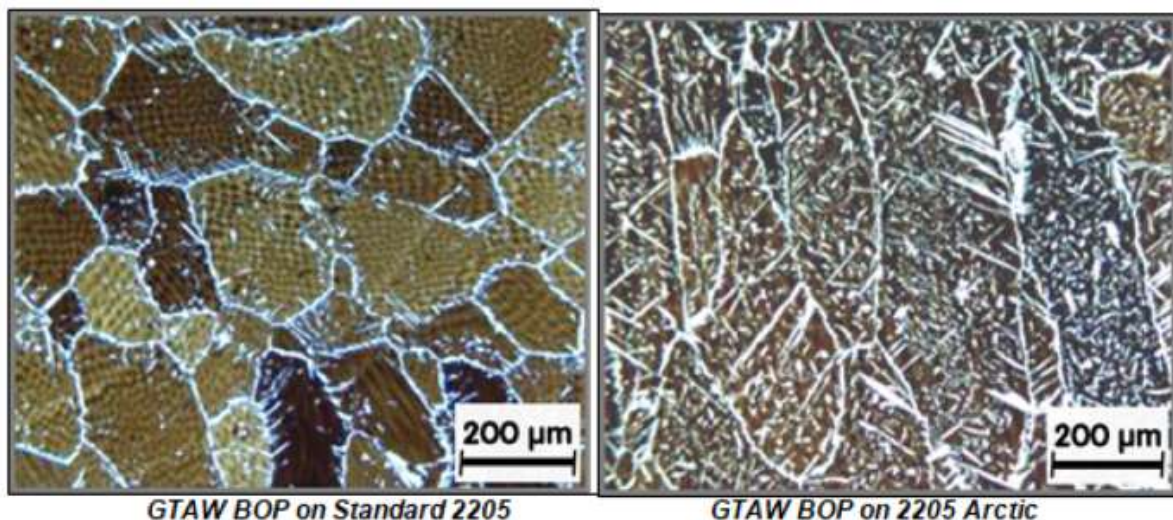


Figure 4: Metallographic examination of a weld metals BOP in GTAW without filler metal on DSS standard 2205 (left) and 2205 Arctic (right) (x200), after Lichtenegger & Bloech etching (ferrite matrix in brown, austenite in white) (1)

Slika 4: Metalografsko ispitivanje metala šava TIG postupak bez dodatnog materijala legura DSS standard 2205 (levo) i 2205 Arctic (desno), x200, nakon nagrizanja Lichtenegger & Bloech reagensom, (braon je matrica ferita, belo je austenit)

2.3 Mechanical properties: same tensile and improved toughness

This two-phases structure gives several attractive properties to the duplex stainless steels, especially in terms of mechanical and corrosion resistance (1) (5). Minimum tensile properties of duplex stainless steels are shown in Table 2.

They present yield strength values twice as high as those of standard austenitic grades which may allow a significant decrease in the thickness of equipment such as storage tanks for instance.

Table 2: Indicative minimum values of YS (Yield Strength), UTS (Ultimate Tensile Strength) and El (Elongation) of duplex 2205 and austenitic grades (6)

Tabela 2: Indikativne minimalne vrednosti YS (granica tečenja), UTS (zatezna čvrstoća) i El (izduženje) za dupleks 2205 i austenitne klase čelika (6)

Name	UNS	YS _{0.2%}		UTS		El, %
		MPa	ksi	MPa	ksi	
Duplex 2205	S31803	460	67	680	98	25
Duplex 2205 Mo	S32205	460	67	680	98	25
Duplex 2205 Arctic	S32205, S31803	460	67	680	98	25
Austenitic 304L	S30403	200	29	520	75	45

Tensile properties between -100 (-148 °F) and 300 °C (572 °F) in base materials are displayed in Figure 5. Samplings were performed from 20-mm thick plates. Results are similar between the grades and above requirements (6) (7). Tensile properties of thicker plates 90 and 150 mm at room temperature are in line with the requirements (5) (6). Toughness properties between -200 °C (-328 °F) and 100 °C (212 °F) in base materials are displayed in Figure 6. Samplings were performed from 20 mm and 90 mm thick plates. Ductile-fragile

transition temperature is shifted to lower temperatures for 2205 Arctic, and in the temperature range [-50; -100 °C] CVN values are significantly enhanced. Requirements of 45J at -46 °C (-50 °F) (8) are fulfilled around -100 °C (-148 °F) for 2205 Arctic instead of -50 °C (-58 °F) for the standard 2205. This increase in toughness values is very interesting especially since the tensile properties as the same as the standard grade (Figure 5).

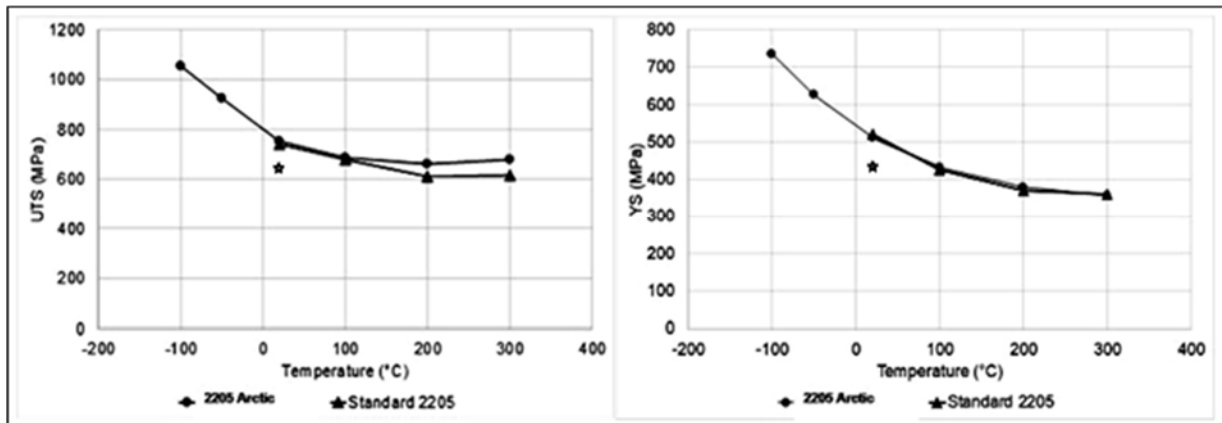


Figure 5: Mechanical properties YS (Yield Strength), UTS (Ultimate Tensile Strength) of standard 2205 and 2205 Arctic; ASTM A240 requirements showed by green stars (5)

Slika 5: Mehanička svojstva YS (granica tečenja), UTS (zatezna čvrstoća) standarda legura 2205 i 2205 Arctic; zahtevi ASTM A240 prikazani zelenim zvezdicama (5)

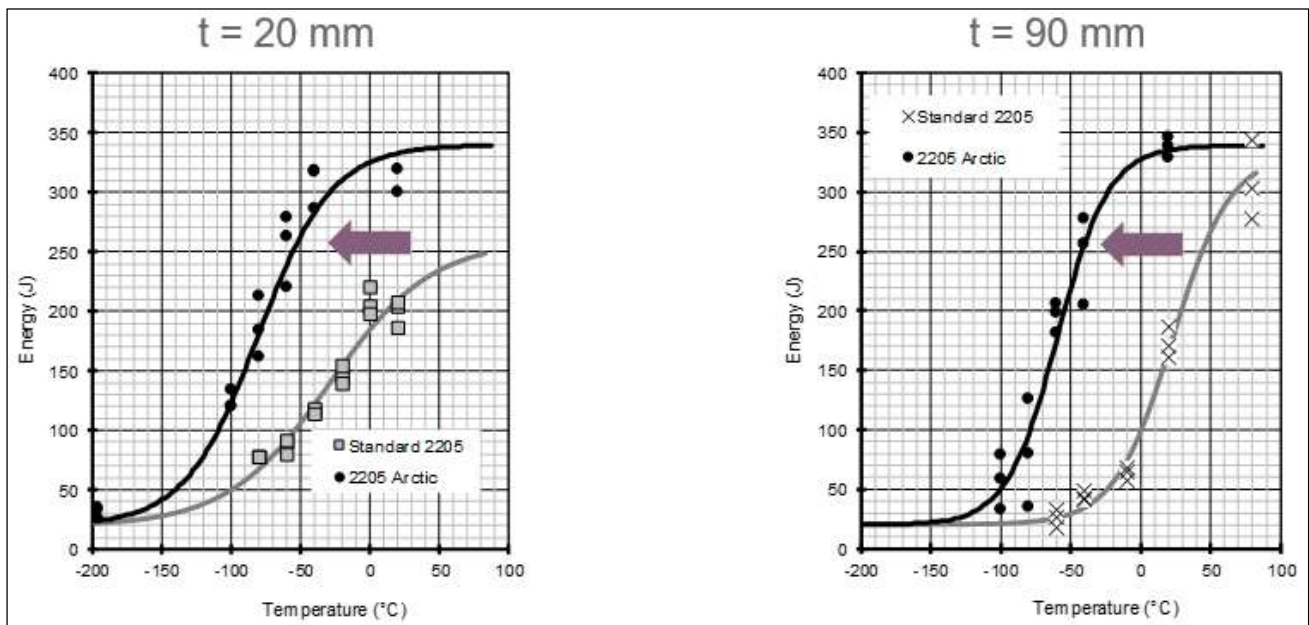


Figure 6: Toughness properties of 2205 Arctic for 20 mm (left) and 90 mm (right) thick plates (5)

Slika 6: Žilavost čelika 2205 Arctic za ploče debljine 20 mm (levo) i 90 mm (desno) (5)

The main conclusion is that 2205 Arctic has the same YS and UTS properties than the standard 2205 grade (Figure 5), and better toughness properties (Figure 6). All results are in line with the most common requirements and specifications (5) (6).

3. Influence on ferrite content of a duplex joint: welding and measurement

The ferrite content after cooling of the weld and HAZ is mainly dependent on the chemical composition of the plate, welding parameters (heat input, welding process...) or configuration (thickness, preparation...).

When measuring the ferrite content on welded joint, it appears clearly that the ferrite / austenite ratio is not only depending on the previous parameters but also on the measurement parameters: method, location or magnification. (2)

3.1 Effect of the welding conditions

On welded joints (HAZ or WM), two areas can be considered: the as-welded condition (single affectation, higher ferrite content) and the re-heated part (multiple affectations which promote the

formation of secondary austenite, lower ferrite content) (1) (2). Maximal ferrite content will be measured in as-welded condition.

In addition to the number of thermal cycles, ferrite content is depending on the welding cooling rate, in other words on the thickness of the plate, the weld preparation (butt weld or fillet), the efficiency of the welding process and the welding heat input.

As the austenite formation occurs at high temperature, preheating, postheating or interpass temperature are not influent parameters.

Based on Industeel database on welded joints, several formulas have been determined to predict

the microstructure and the properties of duplex welded joints (9). The maximal ferrite content

is emphasized by the following graphs depending on the cooling rate (Figure 7). Higher the cooling rate is, higher the ferrite content is. It also highlights the beneficial effect of nitrogen

on the weldability. High nitrogen content at 0.19% allows a ferrite content lower than 70%, whatever the cooling rate.

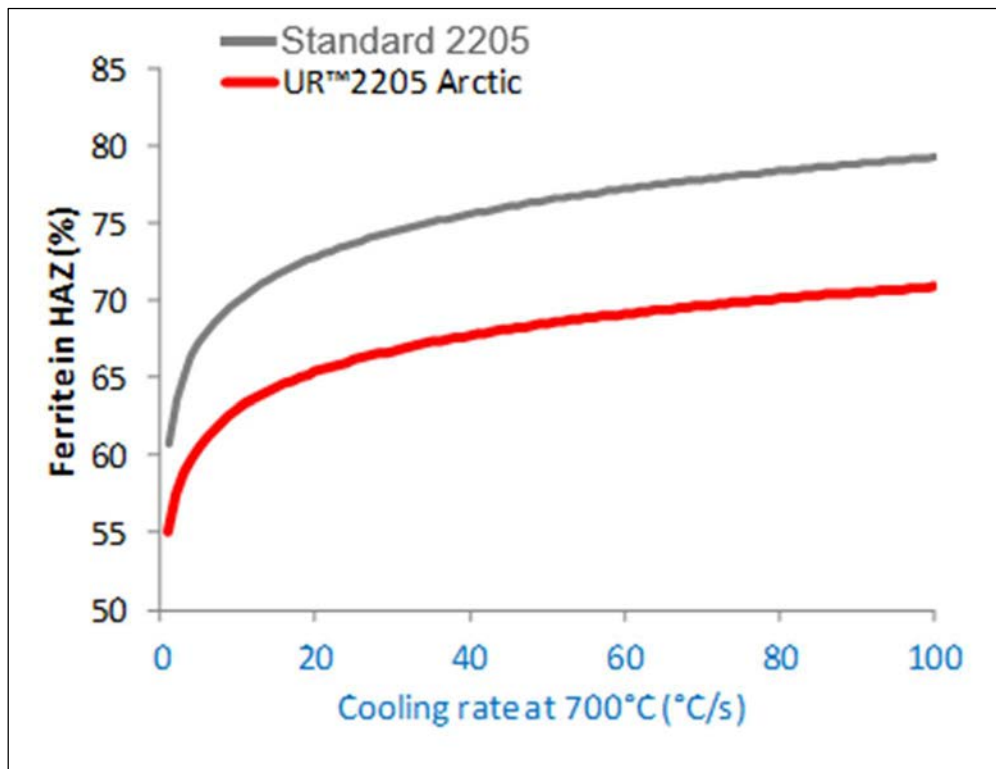


Figure 7: Ferrite content in HAZ of Standard 2205 (0.16%N₂) and 2205 Arctic (0.19%N₂) according to cooling rate of the weld at 700 °C (1292 °F) (°C/s)

Slika 7: Sadržaj ferita u ZUT standardna 2205 (0,16%N₂) i 2205 Arctic (0,19%N₂) u skladu sa brzinom hlađenja zavara na 700 °C (1292 °F) (°C/s)

2205 Arctic shows a very good microstructural stability of HAZ during internal welding tests: BOP with autogeneous GTAW and actual weld in SAW in half V groove with 2209 or nickel base filler metals (1).

3.2 Effect of the methodology of measurement on the ferrite content

Based on API RP 582 guideline (10), maximal ferrite content can be measured in as-welded state (under cap pass) (2) using manual point counting as defined by ASTM E562 (11) or automatic counting defined by ASTM E1245 (7) after

calibration with ASTM E562 method only for base material and weld metal.

Several requirements regarding the ferrite content are observed in standards, guidelines or customers specifications. Those related to the oil & gas industry are summed up in the Table 3.

If the ferrite content requirements are globally common for BM and WM, with an appropriate and representative magnification, the ferrite content requirements in HAZ can evolve in terms of maximal ferrite content and magnification, from 60 to 70% ferrite content and from x400 to x1000 magnification.

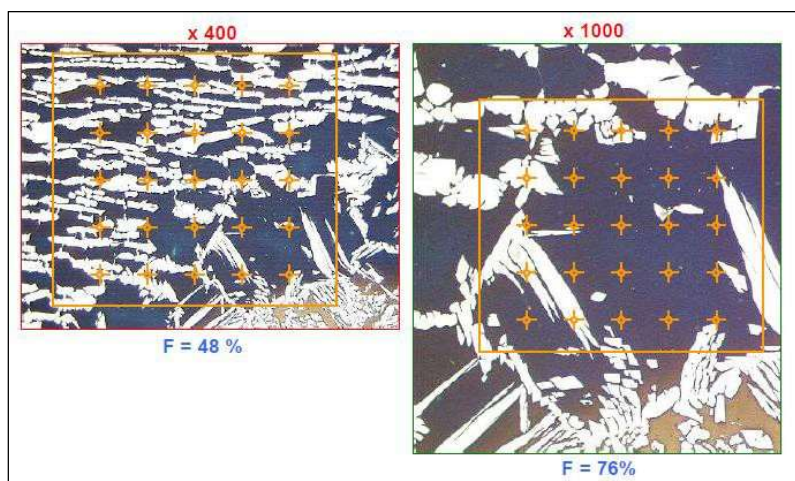
Table 3: Requirements regarding ferrite content and measurement methods (12)**Tabela 3: Zahtevi u vezi sa sadržajem ferita i metodama merenja (12)**

	Base material	Heat Affected Zone	Weld metal
API RP 582 (10) (API A938C)	30 – 65%	30 – 65%	30 – 65%
Method	ASTM E562 Grid : >100 points Magnification : x400	ASTM E562 Grid : >100 points Magnification : x700 – x1000	ASTM E562 Grid : >100 points Magnification : x400
NORSOK M630 D45 (8)	35 – 55%		30 – 70 %
Method	ASTM E562 and ASTM E562 Magnification x400		ASTM E562
Current Oil&Gas specifications	35 – 55 %	< 60 – 65 %	< 60%
Method		ASTM E562 Magnification > x400 or x500	

ASTM E562 is a guideline for phase measurement (duplex and austenite) but does not precisely specify the magnification for the micrographic examination. Consequently, the ferrite content interpretation is strongly dependent on the operator. According to Industeel's experience, a difference of 5 points can be measured from different operators using the same measurement method and the same sample. A difference of 12 points is obtained when considering different operators and different methods. Usually, oil & gas requirements are more precise: x400 for base material and weld metal and higher than x400 or x500 magnification for HAZ. Figure 8 highlights the influence of a ferrite measurement at x400

magnification and x1000 magnification in the same HAZ.

Even with these recommendations, it appears that the ferrite content can evolve from roughly 50% to 75-80% for one microstructure. For instance, a higher magnification allows to place the grid measurement in a high temperature heat affected zone (HTHAZ) characterized by a high temperature and high cooling rate thermal cycle, whereas at x400 magnification the grid is located into a mix between parent material, HAZ and even weld metal. Rationally, the first one is severe but more representative of the HTHAZ and the second one does not represent the HAZ.

**Figure 8: Magnification of x1000 in HTHAZ will give a more representative ferrite content (12)****Slika 8: Uvećanje od x1000 u visokotemperaturnoj ZUT daje reprezentativniji sadržaj ferita (12).**

The magnification rate must be properly chosen to allow a representative measurement of the HAZ. According to Industeel's experience, a x400 magnification is not fully representative whereas a

x1000 magnification is more relevant to evaluate the HAZ ferrite content.

4. Case studies of welding by fabricators

4.1 Example of standard 2205 and 2205 Arctic 55-mm plates welded by VRV in SMAW and SAW: better properties and lower ferrite content with 2205 Arctic VRV company performed welding trials on two materials: the standard 2205 and 2205 Arctic. The

filler material was 2209 and the gas mixture consisted in Ar+2%N₂. The bevel design was U-shape 12 ° opening with a root gap of 3 mm, root face of 2 mm and radius of 8 mm. After root passes in GTAW, filling was performed by 20 passes with SMAW and the rest with SAW. Heat input used were between 0,5 and 1,6 kJ/mm.

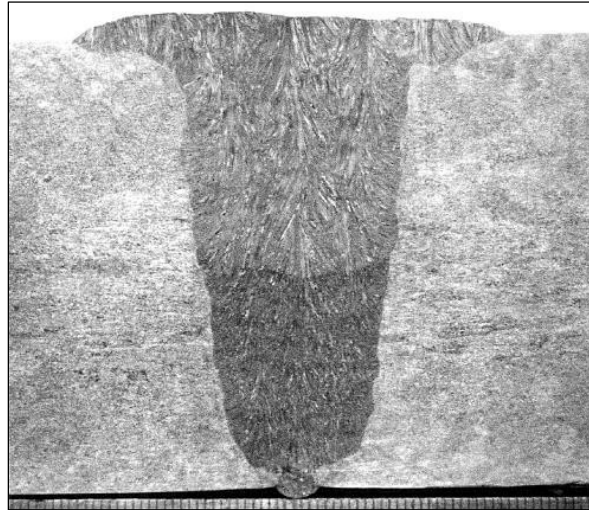


Figure 9: Macrograph on U-shape root GTAW + ½filling SMAW + ½ filling SAW

Slika 9: Makrografija korena u obliku slova U, TIG koreni prolaz + ½ popuna REL + ½ popuna EPP

Microscopic examination Figure 9, show that microstructures are free from precipitate or intermetallic phase according to ASTM A923 method A (13). Ferrite measurements (Table 4) have been performed with micrographic counting

according to the ASTM E1245 standard. Ferrite contents in WM are about 55% in standard 2205 and 50% in 2205 Arctic. Ferrite contents are below 60% as required by oil and gas specifications.

Table 4: Ferrite contents in standard 2205 and 2205 Arctic

Tabela 4: Sadržaj ferita u standardnoj leguri 2205 i 2205 Arctic

Grade	Ferrite cap WM	Ferrite root WM
Standard 2205	55 %	55 %
2205 Arctic	50 %	37 %

Tensile specimens failed in base metal at 750 MPa while bending tests did not lead to cracks in the welds. Impact test results are better for 2205

Arctic HAZ thanks to the lower ferrite content (Table 5). In WM, base material composition impacts more at the root thanks to dilution.

Table 5: Absorbed energy and lateral expansion at -46 °C (-50 °F) are better with 2205 Arctic

Table 5: Apsorbovana energija i bočno širenje na -46 °C (-50 °F) su bolji kod 2205 Arctic legure

Grade	Heat Affected Zone			Weld Metal		
	Top SAW	3/4 SMAW	Root GTAW (subsize samples 2.5x10)	Top SAW	3/4 SMAW	Root GTAW (subsize samples 2.5x10)
Standard 2205	63 J	84 J	28 J	68 J	82 J	31 J
2205 Arctic	122 J	116 J	43 J	74 J	80 J	41 J

4.2 Example of plate 2205 Arctic 55-mm welded by Enerfab in FCAW, SAW: influence of O₂ on WM toughness, ferrite content below 70% in HAZ

Enerfab company performed welding trials on 2205 Arctic and 2209 filler material using two welding processes: FCAW in vertical position with Ar + 18%CO₂ shielding gas on one side and SAW

in flat position on the other side. Welding heat inputs of the two processes were between 1,3 and 1,8 kJ/mm. The bevel design is a symmetric X-shape opened at 60 ° with root gap and root face of 2-3 mm. 17 passes were needed on face side by FCAW and 20 passes on root side by SAW. Macrograph (Figure 10) shows no defect.

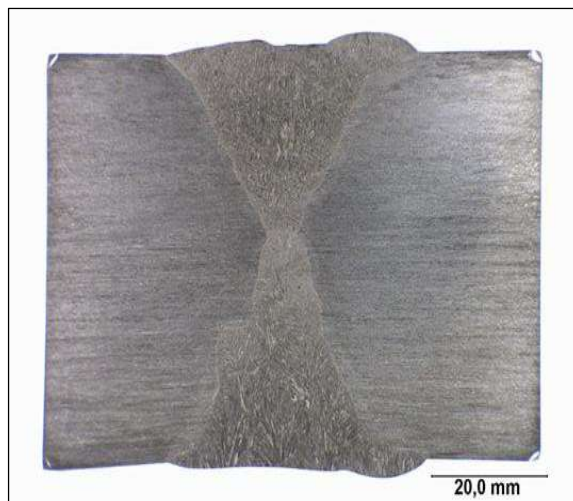


Figure 10: Macrograph of 2205 Arctic 55-mm done by Enerfab

Slika 10: Makro prikaz spoja 2205 Arctic debljine 55mm zavareno u Enefabu

Micrographs (Figure 10) show microstructures free from precipitates and intermetallic phases. Ferrite contents (Table 6) were measured according to the ASTM E562 standard (11) (50 points per grid) in four different locations: in as-welded or reheated parts of WM (at x500, 20 fields)

or HAZ (at x1000 of magnification, 30 fields). Maximal ferrite content in HAZ (which corresponds to as-welded part with lower heat input) is about 63 %. The results are in good agreement with common specifications: below 55% in WM and below 65 % in HAZ.

Table 6: Ferrite measurements in WM and HAZ of 2205 Arctic welded by FCAW and SAW

Tabela 6: Merjenja sadržaja ferita u MŠ i ZUT u materijalu 2205 Arctic zavarenog punjenom žicom i EPP metodama

		Ferrite content (%) ASTM E562	
		Weld metal	HAZ
		x500	x1000
FCAW	As-welded	42	63
	Reheated	37	53
SAW	As-welded	52	62
	Reheated	35	57

It appears that appropriate ferrite content, in accordance with API RP 582 (10) and NORSOK (8), can be achieved using the duplex grade 2205 Arctic. Tensile specimens failed in the base metal in average at 730 MPa, in accordance with typical

values of 2205 Arctic and above requirements. Impact tests at -46 °C (-50 °F) (Table 7) are about 50 J in WM (FCAW or SAW) because of higher O₂ content and 115 J in HAZ.

Table 7: Absorbed energy and lateral expansion at $-46\text{ }^{\circ}\text{C}$ ($-50\text{ }^{\circ}\text{F}$) with 2205 Arctic, influence of O_2 in WM

Tabela 7: Apsorbovana energija i bočno širenje na $-46\text{ }^{\circ}\text{C}$ ($-50\text{ }^{\circ}\text{F}$) legura 2205 Arctic, uticaj O_2 u MŠ

	WM		HAZ	
	Charpy test (J)	Lateral expansion (mm)	Charpy test (J)	Lateral expansion (mm)
Face side FCAW	58	0.77	108	1.18
¼ upper thickness FCAW	42	0.50	115	1.28
¼ lower thickness SAW	58	0.68	129	1.41
Root side SAW	55	0.68	107	1.24

To be able to use the full capacity of the 2205 Arctic grade, weld metal properties could be

improved to 100 J at $-100\text{ }^{\circ}\text{C}$ ($-148\text{ }^{\circ}\text{F}$) by using processes with low oxygen. This finding will be further described in § 4.3.

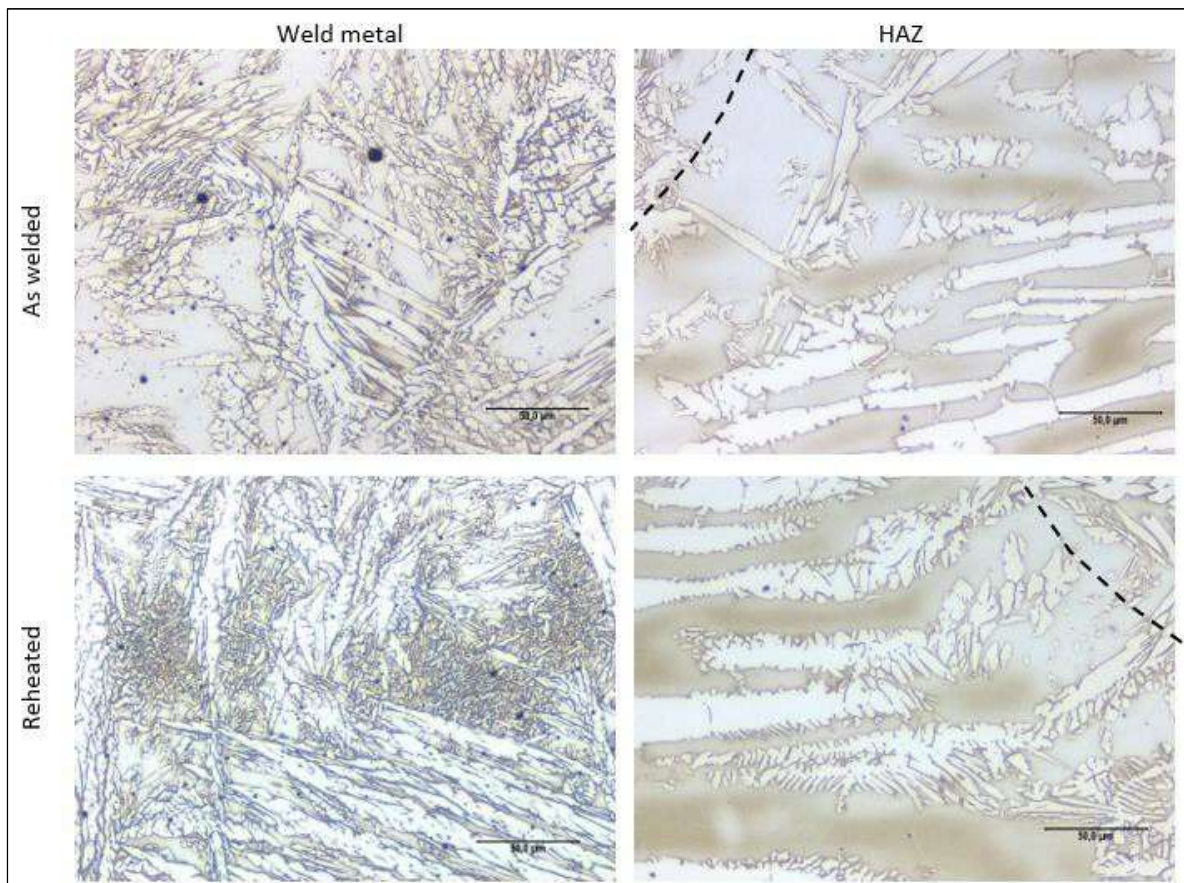


Figure 11: Metallographic examinations of WM and HAZ into FCAW joint on 2205 Arctic, etching NaOH 10N (ferrite brown and austenite white)

Slika 11: Metalografska ispitivanja metala šava (MŠ) i ZUT spoja zavarenog obloženom elektrodom na 2205 Arctic, nagrizanje NaOH 10N (ferit – braon, austenit - bela)

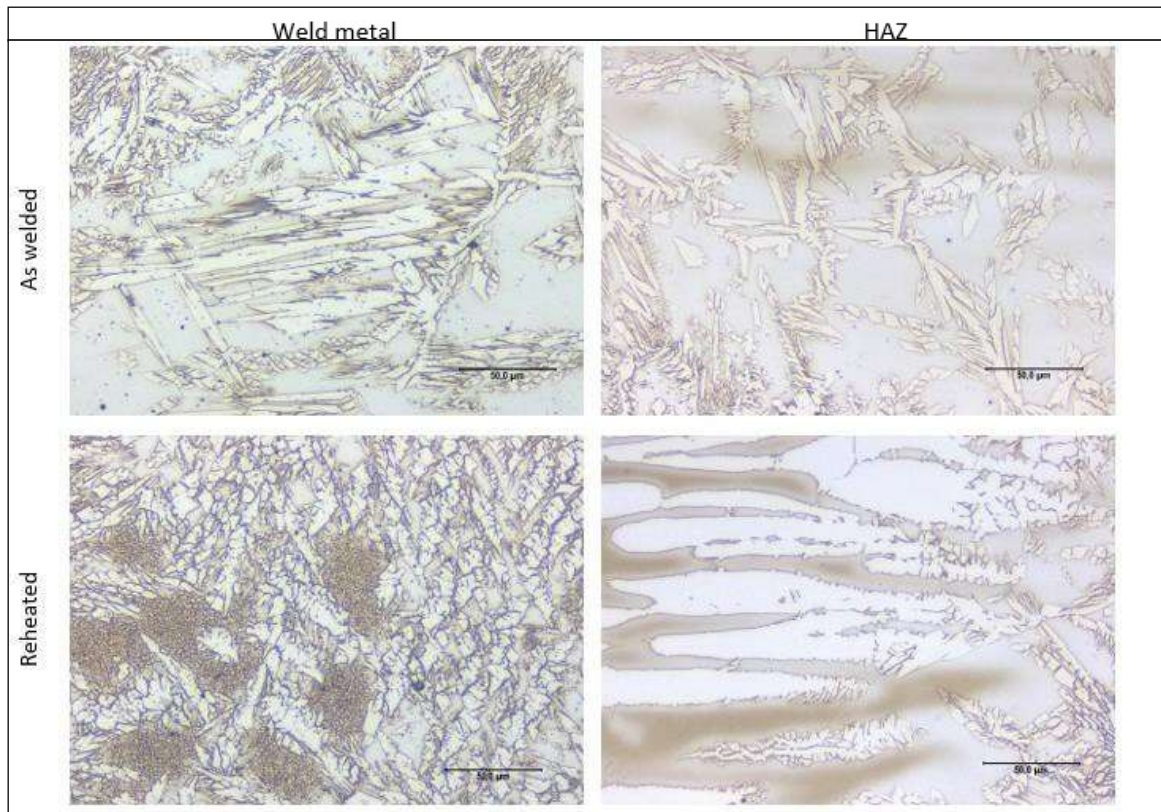


Figure 12: Metallographic examinations of WM and HAZ into SAW joint on 2205 Arctic, etching NaOH 10N (ferrite brown and austenite white)

Slika 12: Metalografska ispitivanja metala šava (MŠ) i ZUT spoja zavarenog EPP postupkom na 2205 Arctic, nagrizanje NaOH 10N (ferit – braon, austenit - bela)

4.3 Example of plate 2205 Arctic 55-mm welded by FBM Hudson Italiana in GTAW Hot wire: improved toughness until $-101\text{ }^{\circ}\text{C}$ ($-150\text{ }^{\circ}\text{F}$)

FBM Hudson Italiana, which has the experience of welding hyperduplex, performed welding trials on

2205 Arctic 55-mm thick and 2209 filler material with Ar + 2%N₂ shielding gas using automatic GTAW Hot Wire process in flat position. Welding heat input was 1,3 kJ/mm. 20 passes were done on each side of the double U-shape bevel 20° (Figure 13).

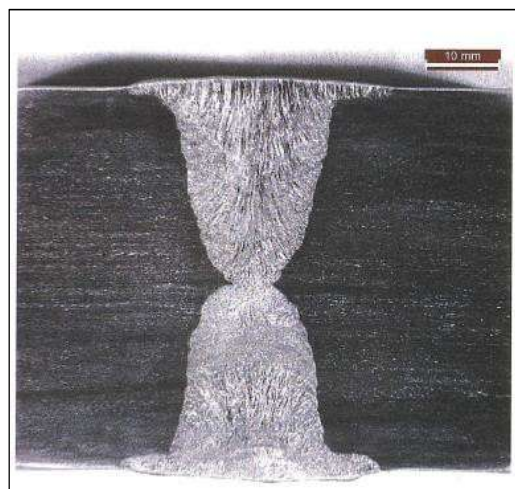


Figure 13: Macrograph of GTAW Hot wire joint 55-mm thick

Slika 13: Makro prikaz spoja dobijenog TIG postupkom sa vrućom žicom, debljina 55mm.

Test method used for ferrite measurements is as following:

- Micrographic counting according to the ASTM E562 standard
- Number of field: 5 fields in the WM: 225 points per grid
- 5fields in the HAZ: Automatic counting

- Magnification: x500 in WM and x500 in HAZ
- Relative accuracy < 10%

Ferrite contents were measured on the same location of impact tests notches. Results are gathered in Table 8. They are well below 70 % and in line with specifications.

Table 8: Ferrite measurements in GTAW hot wire joint

Tabela 8: Merenje sadržaja ferita u spoju dobijenom TIG postupkom sa vrućom žicom

	WM	HAZ
Upper side	38 %	51 %
¼ upper thickness		46 %
½ thickness	36 %	
¾ lower thickness		45 %
Bottom side	35 %	46 %

Toughness are all above 100 J at -101 °C (-150 °F) with GTAW Hot Wire (Table 9). Results are well above requirements. FBM Hudson Italiana will now work to improve productivity.

Table 9: Absorbed energy and lateral expansion at -101°C with 2205 Arctic, influence of low O2 in WM on toughness

Tabela 9: Apsorbovana energija i bočno širenje na -101°C legure 2205 Arctic, uticaj niskog sadržaja O2 u MŠ na žilavost

GTAW Hot Wire	WM		HAZ	
	Charpy test (J)	Lateral expansion	Charpy test (J)	Lateral expansion (mm)
1.3 kJ/mm				
Requirements	Min 27 J	Min 0.38 mm	Min 27 J	Min 0.38 mm
Upper side	188	1.7	146	1.6
½ thickness	196	1.7		
¾ lower thickness			203	1.5
Bottom side	125	1.2	200	1.6

5. Conclusions

Duplex grades are interesting and cost-effective alternatives to equivalent austenitic grades, due to their better mechanical properties and good corrosion resistance.

The duplex stainless steel 2205 Arctic ensures good microstructure stability of base metal and ferrite contents meeting requirements of API 582. The ferrite content is indeed lower than 70% in HAZ without minimal heat input.

This new material presents very good toughness properties even down to -80°C (-112°F) and can even reach 100 J at -100°C (-148°F) when welded with welding processes with low oxygen (GTAW, GTAW with hot wire).

5. Zaključci

Dupleks čelici su zanimljiva i isplativa alternativa ekvivalentnim austenitnim vrstama, zbog svojih boljih mehaničkih osobina i dobre otpornosti na koroziju.

Dupleks nerđajući čelik 2205 Arktik obezbeđuje stabilnu mikrostrukturu osnovnog metala, a sadržaj ferita ispunjava zahteve standarda API 582. Sadržaj ferita je zaista niži od 70% u ZUT kada nije ostvaren minimalan unos toplote.

Ovaj novi materijal pokazuje veoma dobru žilavost čak i do -80°C (-112°F) a može dostići čak 100 J na -100°C (-148°F), kada se zavari postupcima sa niskim sadržajem kiseonika (TIG, TIG sa vrućom žicom).

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