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WELDING DUPLEX STAINLESS STEELS – A REVIEW OF CURRENT RECOMMENDATIONS
ZAVARIVANJE DUPLEKS ČELIKA- PREGLED SADAŠNJIH PREPORUKA

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Recommendations are grade-dependent but vary little within each group with some exceptions. Two major observations are
1) the lower maximum arc energy permitted for the more highly-alloyed grades and
2) the lower minimum arc energy applicable for grades higher in nitrogen.
It can also be noted that there is less agreement on rec- ommendations for newer grades compared to older better established. The very recent 24 % Cr LDX 2404 grade was not launched when the questionnaire was distributed and is consequently not listed in Tables 2 and 3. Producers' data suggest similar weldability as for other high nitrogen grades with low or medium alloy content and the use of 2209-type consumables.
Where recommendations differ between sources upper and lower values have been included. Specific comments on grades have been included where suitable. Interpass temperatures and arc energies, both higher and lower than those indicated in Table 2, are sometimes used in applications where post-weld solution annealing is applied.
Preheating is usually not recommended. However, if weld- ing is performed at temperatures lower than room temperature, it is advisable to preheat to 50-80 ºC to ensure moisture free joint surfaces. In rare cases preheating to maximum 150 ºC is used to minimize the risk of cracking when welding thick and/or heavily restrained work pieces with low arc energy to reduce cooling rate and stress levels.

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Part 2

Preporuke su zavisne od klase, ali se u okviru svake grupe vrlo malo razlikuju uz neke izuzetke. Dva glavna zapažanja su:
1) niža maksimalna energija luka je dopuštena za više visoko-legirane i
2) niža minimalna energija luka koja se primjenjuje za klase sa više azota.
Takođe se može primetiti da postoji manje saglasnosti sa preporukama za novije klase u odnosu na starije- bolje uspostavljene. Nedavna klasa 24% Cr LDX 2404 nije obuhvaćena upitnikom i posledično nije navedena u tabelama 2 i 3. Podaci proizvođača ukazuju na sličnu zavarljivost kao i kod drugih visoko azotnih klasa sa nižim i srednjim sadržajem legurajućih elemenata i upotrebom potrošnog materijala tipa 2209.
Kada se preporuke razlikuju između izvora, uključene su gornje i niže vrednosti. Specifični komentari o klasama su uključeni gde je to prikladno. Međuslojne temperature i energija luka, i više i niže od onih navedenih u Tabeli 2, ponekad se koriste tamo gde se primjenjuje rastvarajuće žarenje nakon zavarivanja.
Predgrevanje se obično ne preporučuje. Međutim, ako se zavarivanje vrši na temperaturama nižim od sobne temperature, preporučljivo je da se zagreje do 50-80 ºC kako bi se obezbedile površine spoja bez vlage. U retkim slučajevima, predgrevanje do maksimalno 150ºC koristi se da bi se smanjio rizik od prslina pri zavarivanju debelih i / ili jako uklještenih radnih komada sa niskom energijom luka kako bi se smanjile brzine hlađenja i nivoi napona.

3.2.Welding methods

The choice of welding method is governed by several factors, but generally the aim to produce a weld with desired properties with the highest possible productivity High productivity in welding is usually synonymous with one or more of the following: high arc energy, high welding speed and narrow joint configuration. As pointed out above, welding of duplex stainless steels has to be performed in such a way that a suitable ferrite content and freedom from deleterious phases is ensured. This therefore imposes some restrictions in the use of welding methods, which to some extent is dependent on joint configuration, steel grade and thickness.

To generalize, all welding methods commonly used for stainless steels are usually well suited for duplex stainless steels. However, welding with low energy input methods should be used with caution and welding without filler material is generally not recommended, unless full solution heat treatment is to be performed [12]. As always there are no rules without exceptions as illustrated in Table 3. It can be noted that grades higher in nitrogen generally seem better suited for low arc energy/high dilution welding methods. Recommendations given within brackets in Table 3 indicate that caution has to be applied, opinions vary or that suitability depends on thickness. The fact that a certain welding method is not recommended is either due to lack of information or because it can result in a weldment with unsuitable microstructure and thereby less good properties. Readers are referred to steel producers for further details for specific grades.

Some comments received (slightly edited) regarding the choice of welding method are listed below.

TIG: Nitrogen additions in shielding and backing gas are beneficial to compensate for losses.

MIG/MAG: Synergic pulse machines recommended for best results.

Autogenous welding: Only recommended for thin material with special welding gas. Maximum 1.5 mm plate thickness is e.g. recommended for S32101/1.4162.

High power density welding processes: Risk of nitrogen loss and high ferrite contents.

Laser: CO2 laser welding permits formation of more austenite contents compared to welding with highbrightness lasers such as fibre- and disk-lasers. PWHT is preferred.

Resistance welding: A double pulse technique reheating the weld is beneficial for improved austenite formation.

3.2 Metode-postupci zavarivanja

Izbor metoda-postupaka zavarivanja reguliše nekoliko faktora, ali uopšteno, cilj je stvaranje šava sa željenim svojstvima uz najvišu moguću produktivnost. Visoka produktivnost u zavarivanju je obično sinonim za jedno ili više od sledećeg: velika energija luka, velika brzina zavarivanja i konfiguracija uskog spoja. Kao što je već istaknuto, zavarivanje dupleks nerđajućih čelika mora biti izvedeno na način koji obezbeđuje odgovarajući sadržaj ferita i slobodu od štetnih faza. Ovo stoga nameće određena ograničenja u korišćenju postupaka zavarivanja, što u izvesnoj meri zavisi od konfiguracije spojeva, klase čelika i debljine.

Za generalizaciju, sve metode-postupci zavarivanja koje se najčešće koriste za nerđajuće čelike su obično pogodne za dupleks nerđajuće čelike. Međutim, zavarivanje sa niskom unetom energijom treba koristiti pažljivo, a ne preporučuje se zavarivanje bez dodatnog materijala, osim ako se ne izvodi termička obrada s potpunim rastvaranjem [12]. Kao i uvek, nema pravila bez izuzetaka kao što je ilustrovano u Tabeli 3. Može se primetiti da su klase sa više azota, uglavnom pogodnije za zavarivanje sa malom unetom energijom/velikim mešanjem. Preporuke navedene u zagradama u tabeli 3 pokazuju da se mora biti oprezan, mišljenja se razlikuju ili da pogodnost zavisi od debljine. Činjenica da se ne preporučuje određeni postupak zavarivanja je ili zbog nedostatka informacija ili zbog toga što može dovesti do zavarenog spoja sa neadekvatnom mikrostrukturom, a time i manje dobrim osobinama. Čitaoci se upućuju na proizvođače čelika za više detalja za određene klase.

Neki primljeni komentari (malo izmenjeni) u vezi sa izborom postupka zavarivanja su navedeni ispod.

TIG: Dodavanje azota u zaštitnom i podložnom gasu korisno je da se nadoknade gubici.

MIG / MAG: Sinergijske impulsne mašine se preporučuju za najbolje rezultate

Autogeno zavarivanje: preporučuje se samo za tanke materijale sa posebnim gasom za zavarivanje. Debljina ploče debljine 1,5 mm je npr. preporučuje se za S32101 / 1.4162.

Postupci zavarivanja visoke gustine energije: rizik gubitka azota i visok sadržaj ferita.

Laser: CO_2 lasersko zavarivanje dozvoljava stvaranje većeg sadržaja austenita u poređenju sa zavarivanjem sa laserima visoke osvetljenosti kao što su laser sa vlaknima i disk laseri. PWHT (TOPZ) je poželjna.

Elektrootporno zavarivanje: tehnika dvostrukog pulsiranja za zagrevanje šava je korisna za poboljšanje formiranja austenita.

UNS No. UNS br.	EN No. EN br.	Common steel designation Uobičajena oznaka čelika	Welding method											Comments/ Other methods Komentari
			MMA/REL	MIG/MAG Solid wire	MIG/MAG Cored wire	TIG	SAW /EPP	PAW/plazma	Autogenous	Laser	Hybrid	Electron beam/ES	Resistance welding	
		Early grades / Ranije klase												
S31500	1.4424	3RE60	x	x		x								
		Contemporary grades / Savremene klase												
		Lean duplex, $PRE_{N/W}$ ~ 20-30 /Siromašni dupleks												
S32101	1.4162	LDX 2101	x	x	x	x	x	x	(x)	(x)	x	(x)	(x)	SAW not first choice EPP nije prvi izbor
S32202	1.4062	UR2202	x	x	x	x	x	x	(x)	(x)	x	(x)	(x)	
S82011		ATI 2102	(x)	x	(x)	x	x	x	(x)	(x)	x	(x)		
S32304	1.4362	2304	x	x	x	x	x	x	(x)	(x)	(x)	(x)	(x)	ESW/SAW strip cladding/trakom
S32003		ATI 2003		x		x	x	x	(x)	(x)	x	(x)		
		Standard 22 % Cr duplex, $PRE_{N/W}$ ~ 35												
S31803	1.4462	2205	x	x	x	x	x	x	(x)	(x)	(x)	(x)	(x)	ESW/SAW strip cladding/trakom
S32205	1.4462	2205	x	x	x	x	x	x	(x)	(x)	(x)	(x)	(x)	ESW/SAW strip cladding/trakom
		25 % Cr duplex, $PRE_{N/W}$ ~ 35-40												
S32550	1.4507	255	x	x	x	x	x	x	x	x	x	x	x	
		Superduplex, $PRE_{N/W}$ ~ 40-50												
S32520	1.4507	2507Cu	x	x	x	x	x	x	(x)	(x)	(x)	(x)	(x)	
S32750	1.4410	2507	x	x	x	x	x	x	(x)	(x)	(x)	(x)	(x)	FSW possible -moguće
S32760	1.4501	Zeron 100	x	x	x	x	x	x	(x)	(x)	(x)	(x)	(x)	
S32906	1.4477	SAF 2906®	x		x	x	x	(x)						ESW strip cladding/trakom
		Hyperduplex, $PRE_{N/W}$ ~ > 50												
S32707		SAF 2707 HD®				x	x							
S33207		SAF 3207 HD®				x								

***"x" = recommended.* –preporučuje se**
"(x)" = caution has to be applied, opinions vary or recommendations depend on thickness.
-oprez, mišljenja su različita ili preporuke zavise od debljine
***" " = not recommended or lack of information.*- ne preporučuje se ili nedostatak informacija**

***Table 3**. Recommended welding methods for a selection of duplex stainless steel grades*
***Tabela 3.** Preporučeni postupci zavarivanja za izbor klasa dupleks nerđajućih čelika*

3.3 Welding consumables

The choice of welding consumables is largely governed by the need to match base material strength, achieve sufficient toughness and ensure that corrosion properties meet requirements. Although welds often have very good corrosion resistance, it is hardly realistic to require matching properties unless a full solution treatment is performed after welding.

3.3. Potrošni materijali za zavarivanje

Izbor potrošnih materijala za zavarivanje je u velikoj meri regulisan potrebom za usklađivanjem čvrstoće osnovnih materijala, postizanjem dovoljne žilavosti i obezbeđenjem korozionih svojstava tako da ispunjavaju zahteve. Iako zavareni često imaju vrlo dobru otpornost na koroziju, teško je zahtevati podudaranje svojstava, osim ako se ne sprovede termička obrada potpunog rastvaranja nakon zavarivanja.

In terms of guaranteeing good corrosion resistance, the choice of filler material and shielding/backing gas is dictated by insuring that the weld metal will have similar or higher contents of critical alloying elements such as Cr, Mo + W, N and for some applications Cu. In addition they need to be higher in elements promoting austenite formation, usually Ni, to avoid excessively high weld metal ferrite contents [12]. Filler materials for duplex stainless steels are therefore different in composition compared to the corresponding steel grade.

3.3.1 Filler materials

The standard recommendation is usually to use a "matching consumable". Matching should here be understood as matching in elements critical for corrosion resistance (Cr, Mo + W, N and sometimes Cu). The Ni-content is always higher compared to the steel, except for consumables designed for applications where a solution heat treatment is to follow the welding operation. Matching consumables are available for most major steels grades.

Within each group of duplex stainless steels, as defined in Table 1, experience has shown that consumables for grades with similar $PRE_{N/W}$ values in practice are interchangeable although different opinions exist. The need for Cu-containing consumables for welding Cu-alloyed steels is sometimes disputed. A rational approach seems to be to use Cu-alloyed consumables whenever steels are specifically selected for applications where Cu is desired. Cu-alloyed consumables can, without any known deleterious effects, be used also for Cu-free steels.

The need for W additions to fillers when welding W-alloyed steels is another issue. W is basically added for three reasons, to differentiate grades for patent and licensing reasons, to improve corrosion resistance in the same manner as Mo and it is also claimed that W slows down precipitation of intermetallics in steels. Studies of weld metals have however not conclusively shown any beneficial effect of W on precipitation behaviour in weld metals [14-17]. As the PR_{EW} formula suggests, consumables with or without W can therefore be used to weld W-containing or W-free steels, as long as the total W+Mo-content is sufficient to provide the desired corrosion resistance. It should be noted, however, that it is sometimes claimed that joining different superduplex grades, e.g. where W content differs, may increase the risk of intermetallic formation.

Što se tiče garantovanja dobre otpornosti na koroziju, izbor dodatnog materijala i zaštitnog / podložnog gasa diktiran je osiguranjem da će metal šava imati sličan ili viši sadržaj kritičnih legirajućih elemenata kao što su Cr, Mo + V, N i za neke primene Cu. Pored toga, oni moraju imati više elemenata koji promovišu formiranje austenita, obično Ni, kako bi se izbegao preterano visok sadržaj ferita u metalu šava.[12]. Zbog toga se dodatni materijali za dupleks nerđajuće čelike razlikuju u odnosu na odgovarajuću klasu čelika.

3.3.1 Dodatni materijali

Standardna preporuka je obično da se koristi "usklađeni potrošni materijal". Ovde treba podudaranje shvatiti tako da se uklapaju u elementima kritičnim za otpornost na koroziju (Cr,Mo + V, N i ponekad Cu). Ni-sadržaj je uvek veći u odnosu na čelik, osim potrošnih materijala dizajniranih za aplikacije gde je rešenje termička obrada koja prati operaciju zavarivanja. Uparivanje potrošnih materijala je dostupno za većinu glavnih klasa čelika.

U okviru svake grupe dupleks nerđajućih čelika, kako je definisano u Tabeli 1, iskustvo je pokazalo da su potrošni materijal za klase sa sličnim $PRE_{N/W}$ vrednostima u praksi zamenljivi iako postoje različita mišljenja. Ponekad je sporna potreba za potrošnim materijalima koji sadrže Cu za zavarivanje čelika legiranih Cu. Izgleda da racionalni pristup koristi potrošne materijale sa Cu kad god su čelici posebno odabrani za primene gde je Cu poželjan. Cu-legirani potrošni materijal mogu se, bez ikakvih poznatih štetnih efekata, koristiti i za čelike bez Cu.

Druga stvar je potreba za dodacima W u dodatnim materijalima pri zavarivanju čelika legiranih sa W. W se u osnovi dodaje iz tri razloga, kako bi se razlikovale klase zbog patentnih razloga i razloga za licenciranje, kako bi se poboljšala otpornost na koroziju na isti način kao i Mo, a takođe se tvrdi da W usporava precipitaciju intermetalida u čeliku. Studije o metalu šava, međutim, nisu pokazale nikakav povoljan uticaj W na taloženje u metalu šava [14-17]. Kao što sugeriše PR_{EW} formula, potrošni materijal sa ili bez W može se koristiti za zavarivanje čelika sa W ili čelika slobodnih od W, sve dok ukupni V + Mo-sadržaj bude dovoljan da obezbedi željenu korozionu otpornost. Treba istaći, međutim, da se ponekad tvrdi da se spajanjem različitih superdupleks klasa, npr. gde se sadržaj W razlikuje, može povećati rizik od intermetalnih formacija.

To summarize current practice without going into grades or specific fillers, typical recommendations are:

– *Early grades*: Matching consumables are used when required and available. The standard recommendation is however typically to use 22Cr9Ni3Mo+N type fillers.

– *Lean duplex stainless steels*: All lean duplex grades can, with few exceptions, be welded with fillers for 22 % Cr providing excellent mechanical and corrosion properties. However, lean duplex fillers (typically 23Cr7Ni+N) are more cost efficient and metallurgically designed to give the weld properties similar to the base material. There are some applications where Mo has a negative effect on corrosion resistance making 22Cr9Ni3Mo+N type fillers less suitable. The Mo-alloyed lean grade S32003 is preferably welded with Mo-containing 22 %Cr fillers to ensure matching corrosion resistance.

– *22 % Cr standard duplex stainless steels (including LDX 2404)*: These grades are welded with the wellestablished 22Cr9Ni3Mo+N type matching filler materials. Over-alloyed (superduplex) fillers are often recommended for root passes in single-side welds where corrosion resistance of the root is critical.

– *25 % Cr duplex stainless steels*: Common recommendations are, depending on grade, 25Cr7Ni2Mo+N type consumables or superduplex 25Cr fi llers with or without Cu.

– *Superduplex stainless steels*: Superduplex grades are commonly welded with matching consumables. A number of filler grades are available with or without Cu and W. As discussed above these are in most cases interchangeable depending on requirements and application.

The S32906/1.4477 grade is due to its different alloying concept preferably welded with 29Cr8Ni2Mo+N fillers. Highly corrosion resistant Ni-base filler are sometimes used but Nb-alloyed grades should be used with care due the strong tendency of N and Nb to form nitrides thereby lowering corrosion resistance and toughness (Figure 3) [18-20]. Strength will also be undermatching compared to the steel. With the introduction of hyperduplex steels, and corresponding 27Cr9Ni5Mo+N fillers, these could be an alternative when overalloying is needed. However, there is little or no documented experience of this approach.

Hyperduplex stainless steels: These should be welded with hyperduplex fillers of the 27Cr9Ni5Mo+N type. Highly-alloyed Ni-base filler materials could in theory be used if lower strength is acceptable. The high N-content of the steels might however cause problems with porosity.

Da sumiramo dosadašnju praksu bez ulaska u klase ili specifične dodatne materijale, tipične preporuke su:

- *Ranije klase*: Usklađeni potrošni materijal se koristi kada je to potrebno i dostupno. Standardna preporuka je međutim uobičajeno korišćenje dodatnih materijala tipa 22Cr9Ni3Mo + N.

- *Siromašni dupleks nerđajući čelici*: Svi siromašni dupleks čelici mogu, uz nekoliko izuzetaka, biti zavareni dodatnim materijalom za 22% Cr pružajući odlične mehaničke i korozione osobine. Međutim, siromašni dupleks dodatni materijali (obično 23Cr7Ni + N) su efikasniji i metalurški dizajnirani da daju karakteristike slične osnovnom materijalu. Postoje neke primene u kojima Mo ima negativan uticaj na otpornost na koroziju, čime su dodatni materijali tipa 22Cr9Ni3Mo + N manje pogodni. Mo-legiranu klasu S32003 je poželjno zavarivati 22% Cr dodatnog materijala sa sadržajem Mo, kako bi se osigurala odgovarajuća otpornost na koroziju.

- *22% Cr standardni dupleks nerđajući čelici (uključujući LDKS 2404):* Ove klase se zavaruju pomoću usaglašenih dodatnih materijala tipa 22Cr9Ni3Mo + N. Prekomerno legirani (superdupleks) dodatni materiali se često preporučuju za korene zavare kod jednostranih zavarenih spojeva gde je otpornost na koroziju korena kritična.

- *25% Cr dupleks nerđajući čelici*: Uobičajene preporuke su, zavisno od kvaliteta, potrošni materijal 25Cr7Ni2Mo + N ili superdupleks 25Cr dodatni materijal sa ili bez Cu.

- *Superdupleks nerđajući čelik*: Superdupleks klase se često zavaruju sa odgovarajućim potrošnim materijalom. Dostupne su brojne vrste dodatnih materijala sa ili bez Cu i W. Kao što je već rečeno, u većini slučajeva su zamenljive u zavisnosti od zahteva i primene. Klasu S32906 / 1.4477 je, zbog svog različitog koncepta legiranja, poželjno zavariti sa 29Cr8Ni2Mo + N dodatnim materijalima. Ponekad se upotrebljava dodatni materijal na bazi Ni, otporniji na koroziju, ali za klase legirane sa Nb ga treba koristiti pažljivo zbog jake tendencije N i Nb da formiraju nitride čime se smanjuju otpornost na koroziju i žilavost (slika 3) [18-20]. Čvrstoća će takođe biti manja u odnosu na čelik. Uz uvođenje hiperdupleks čelika i odgovarajućih dodatnih materijala 27Cr9Ni5Mo + N, to bi mogla biti alternativa kada je potrebno. Međutim, malo ili ne postoji dokumentovanno iskustvo ovakvog pristupa.

Hiperdupleks nerđajući čelici: Njih treba zavarvaiti sa hiperdupleks dodatnim materijalom tipa 27Cr9Ni5Mo + N. Visokolegirani materijali na bazi Ni mogu se teorijski koristiti ukoliko je prihvatljiva niža čvrstoća. Međutim, visok sadržaj N u čeliku može uzrokovati probleme sa poroznošću.

Dissimilar joining: Joining duplex stainless to unalloyed, low alloyed or to other stainless steels is rarely a problem as long as a post-weld heat treatment is not required. Usually the duplex consumable recommended for the particular duplex stainless steel grade is used. A standard 22Cr9Ni3Mo+N type or over-alloyed stainless fillers such as 23Cr12Ni or 23Cr12Ni+Mo are also common choices. Ni-base consumables, preferably Nb-free, are recommended for joining duplex to Ni-base alloys.

Raznorodni spojevi: Spajanje dupleks nerđajućeg čelika sa nelegiranim, nisko legiranim ili drugim nerđajućim čelikom retko je problem dokle god nije potrebna termička obrada posle zavarivanja. Obično se preporučuje dupleks potrošni materijal za poseban dupleks čelik koji se koristi. Standardni tip 22Cr9Ni3Mo+N ili vise legirani nerđajući dodatni materijali kao 23Cr12Ni ili 23Cr12Ni+Mo su takođe čest izbor.Potrošni materijali na bazi Ni, poželjno bez Nb, se preporučuju za spajanje dupleks čelika sa legurama na bazi Ni.

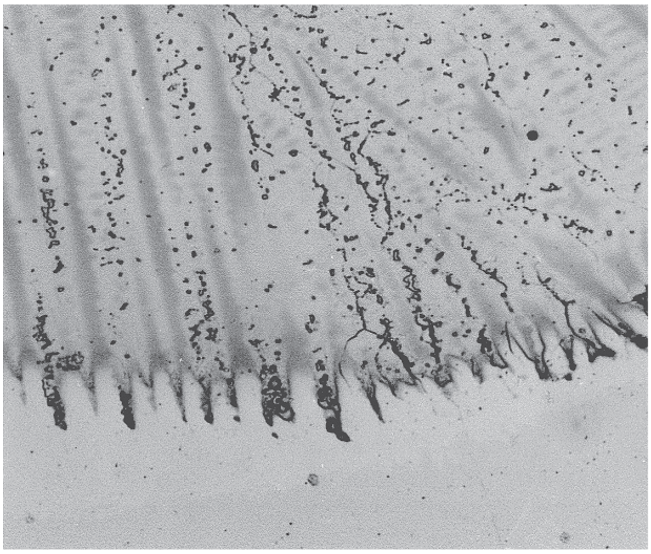


***Figure 3**. Nb- and N-rich precipitates next to fusion boundary in superduplex steel TIG-welded with an alloy 625 type Ni-base filler wire*

***Slika 3.** Precipitati bogati Nb i N u blizini linije stapanja kod superdupleks čelika zavarenog TIG postupkom sa žicom na bazi Ni legure tipa 625*

3.3.2 Shielding and backing gases

Two trends emerge when comparing typical recommendations today and at the time of the duplex conference in Beaune in 1991 [4]. Firstly nitrogen-containing gases are today commonly used for shielding and purging. Nitrogen additions are more or less standard practice in TIG welding but also used in plasma welding. However, MIG/ MAG welding with nitrogen containing shielding gases is generally not recommended due to the risk of porosity. The second trend is to use multicomponent gases with He-additions to improve weld pool fluidity and to permit higher welding speeds.

Recommendations vary somewhat between grades depending on the need to compensate potential losses of nitrogen or improve austenite formation. The dividing line is therefore usually between

3.3.2 Zaštitni i podložni gasovi

Dve trenda se pojavljuju kada se upoređuju tipične preporuke danas i u vreme konferencije o dupleks čelicima u Beaune-u, 1991.[4]. Prvo, gasovi koji sadrže azot se danas često koriste za zaštitu i čišćenje. Dodavanje azota je više ili manje standardna praksa kod TIG zavarivanja, ali se takođe koristi u plazma zavarivanju. Međutim, MIG / MAG zavarivanje sa zaštitnim gasovima koji sadrže azot se generalno ne preporučuje zbog rizika od poroznosti. Drugi trend je korišćenje višekomponentnih gasova sa dodatkom He za poboljšanje tečljivosti zavarivačke kupke i omogućavanje veće brzine zavarivanja.

Preporuke se delimično razlikuju između klasa u zavisnosti od potrebe za kompenzacijom potencijalnih gubitaka azota ili poboljšanjem formiranja austenita. Zbog toga je linija razdvajanja, najčešće između novijih klasa sa visokim newer high-nitrogen grades and older grades lower in nitrogen rather than between groups as presented in Table 1. Typical recommendations are consequently summarized in Table 4 based on welding methods rather than groups of steels. Brackets indicate the second choice, where practices vary or where recommendations depend on steel grade.

Root shielding with a purging gas is, as always in welding of stainless steels, critical for optimum corrosion resistance in particular for single sided welds. Ar, He or mixtures there of can be used but He is seldom an option for cost reasons.

Nitrogen containing purging gases are often recommended for best corrosion resistance but is sometimes claimed to give rise to a yellow discoloration that is not found with Ar. Addition of hydrogen to the purging gas is effective at reducing oxidation and 90 % N_2 + 10 % H_2 is therefore sometimes recommended. However, gases including hydrogen are not always allowed due to the risk of hydrogen embrittlement [7].

3.4 General recommendations

In most respects duplex should be treated similar to any stainless steel when it comes to handling and preparation for welding. A few points not discussed above are listed below for completeness.

– *Joint design*: To achieve good penetration a slightly wider root gap, a smaller land and a joint angle about 10° larger than for standard stainless joints, should be used.

– *Joint preparation*: Standard joint preparation methods used for stainless steels are suitable also for duplex stainless steels. Oxides resulting from thermal cutting shall be removed before welding.

– *Tack welding*: Tacks shall be longer and they should have a shorter distance compared to tacks in austenitic stainless steel grades.

– *Cleaning*: Cleaning joints, before and after welding, follows standard stainless practice.

sadržajem azota i starijih klasa sa nižim sadržajem azota, a ne između grupa kao što je prikazano u tabeli 1. Tipične preporuke su dakle rezimirane u tabeli 4 na postupke zavarivanja, a ne prema grupama čelika. Podaci u zagradama ukazuju na drugi izbor, gde se prakse razlikuju ili gde preporuke zavise od klase čelika.

Zaštita korena gasom za čišćenje je, kao i uvek kod zavarivanja nerđajućih čelika, kritična za optimalnu otpornost na koroziju, posebno za jednostrano zavarene spojeve. Ar, He ili njihove mešavine mogu se koristiti, ali He retko predstavlja opciju zbog troškova.

Gasovi za čišćenje koji sadrže azot, često se preporučuju, ali se ponekad tvrdi da dovode do promene boje u žuto koje nije pronađeno sa Ar. Dodavanje vodonika u gas za čišćenje je efikasno u smanjenju oksidacije, pa se ponekad preporučuje 90% N_2 + 10% H_2. Međutim, gasovi, uključujući vodonik, nisu uvek dozvoljeni zbog rizika od nastanka vodonične krtosti [7].

3.4. Opšte preporuke

U većini aspekata duplekse treba tretirati slično bilo kojem nerđajućem čeliku kada je u pitanju rukovanje i priprema za zavarivanje. Nekoliko tačaka koje nisu gore navedene, date su zbog kompletnosti.

-*Oblik spoja*: Da bi se postiglo dobro uvarivanje, trebalo bi koristiti nešto veći zazor u korenu, manju površinu i ugao spoja veći za oko 10 ° nego kod standardnih nerđajućih spojeva.

- *Priprema spoja*: Standardne metode pripreme spojeva za nerđajuće čelike pogodne su i za dupleks nerđajuće čelike. Okside nastale usled termičkog rezanja, treba ukloniti pre zavarivanja.

- *Pripojni zavari*: Pripoji treba da budu duži i da imaju kraće rastojanje u poređenju sa pripojima u austenitnim klasama nerđajućih čelika.

- Čišćenje: Čišćenje spojeva, pre i posle zavarivanja, prati standardnu praksu za nerđajuće čelike.

Shielding gas Zaštitni gas	Welding method-Postupak zavarivanja						Root shielding-Zaštita korena
	MIG/MAG		TIG	PAW	Laser[c]	Hybrid	
	Solid wire	Cored wire					
Ar			(x)	(x)[b]	x	(x)	x
He					x	x	(x)
CO_2		(x)					
N_2					x		x
Ar + 1-2 % O_2	x				(x)	(x)	
Bban Ar + 2-3 % CO_2	x				(x)	(x)	
Ar + 16-25 % CO_2		x					
Ar + 1-3 % N_2	(x)[a]		x	x[b]	(x)		x
Ar + 20-30 % He				(x)[b]	x	x	(x)
Ar + 30 % He + 1-3 % CO_2	x				(x)		
Ar + 30 % He + 2 % N_2	(x)[a]		x	x[b]	(x)	x	(x)
Ar + 30 % He + 1-2 % N_2 + 1-2 % CO_2	(x)[a]						

[a] Generally not recommended due to risk of porosity.- Generalno se ne preporučuje zbog rizika od poroznosti
[b] Typically the same gas is used as plasma and shielding gas.-Obično se isti gas koristi I kao plazma I kao zaštitni gas
[c] Depends on type of laser and laser power.-Zavisno od tipa i snage lasera
"x" = recommended.-Preporučuje se
"(x)" = caution has to be applied, opinions vary or recommendations depend on thickness.- Potreban oprez, mišljenja se razlikuju ili preporuke zavise od debljine
" " = not recommended or lack of information- Ne preporučuje se ili nedostatak informacija

***Table 4**. Examples of recommended shielding gases*
***Tabela 4.** Primeri preporučenih zaštitnih gasova*

4 Welding related problems

Overall modern duplex stainless steels have good weldability and welding is generally seen as much less of a problem when compared to the time of the duplex conference in Beaune in 1991. Nevertheless welding has to be performed in such ways that weld imperfections are avoided. As most grades are high in nitrogen, porosity can occur and is most commonly observed with thick beads and high welding speeds. Welding duplex stainless steels also require understanding of the need to weld in such a way that a balanced microstructure free from deleterious phases is achieved. Problems therefore typically occur due to lack of knowledge and training, or due to neglecting the need to follow recommendations. One such example is TIG re-melting to improve weld profiles, which inevitably leads to poor corrosion resistance due to high ferrite content unless filler is added or nitrogen containing shielding is used.

Most problems are commonly seen when either too low or excessively high heat input is used, when dilution is too high and when too much nitrogen is lost from the weld pool.

4 Problemi vezani za zavarivanje

Svi savremeni dupleks nerđajući čelici imaju dobru zavarljivost i zavarivanje se uopšteno vidi kao manji problem u poređenju sa vremenom održavanje konferencije o dupleks čelicima u Beaune-u, 1991. godine. Bez obzira na to, zavarivanje se mora izvoditi na takav način da se izbegnu nesavršenosti u zavarenim spojevima. Pošto većina klasa ima visok sadržaj azota, može doći do poroznosti i najčešće se javlja na debelim zavarima i pri velikim brzinama zavarivanja. Zavarivanje dupleks nerđajućih čelika takođe zahteva razumevanje potrebe za postizanjem uravnotežene mikrostrukture, bez štetnih faza. Zbog toga se problemi obično javljaju zbog nedostatka znanja i obuke, ili zbog zanemarivanja potrebe da se prate preporuke. Jedan od takvih primera je TIG pretapanje radi poboljšanja profila šava, što neizbežno vodi do loše otpornosti na koroziju usled visokog sadržaja ferita, osim ako se ne koristi dodatni materijal ili zaštitni gas koji sadrži azot. Većina problema se najčešće javlja kada se koristi previše niska ili prekomerno velika količina unete toplote, kada je mešanje preveliko i kada se previše azota izgubi iz zavarivačke kupke.

4.1 Loss of nitrogen and low energy input

In the author´s experience the most frequent problem is poor corrosion resistance, typically in ASTM G48 testing of TIG welds. Examples of pitting attack in weld metal are shown in Figure 4.
The common denominator of these problems is loss of nitrogen and/or too rapid cooling. As shown in Figure 5 this results in a highly ferritic as-deposited microstructure and copious amounts of secondary austenite in reheated regions, sometimes together with nitride formation. The secondary austenite is low in nitrogen and hence pitting corrosion resistance will be poor in these regions [9].
The remedy is to use higher energy input often in combination with an N-containing shielding gas to enhance austenite formation. In 22 % Cr steels, root passes are often welded with superduplex filler to further improve the root side corrosion resistance.

4.2 Intermetallic phase formation

In superduplex and hyperduplex grades intermetallic phase formation (Figure 6) can occur if cooling is too slow or if a weld region is reheated repeatedly in the range of approximately 600-1000 ºC [11]. Whenever intermetallic phases, such as sigma and chi, form toughness and corrosion resistance will suffer. A strict control of welding procedure is therefore required for highly-alloyed grades.
Not only must the upper recommended energy input and interpass temperature limits be adhered to, it is also important to plan the bead sequence to avoid unnecessary repeated reheating of preceding beads. A too small root bead followed by a larger “hot pass” should normally be avoided.

4.1 Gubljenje azota i mali unos energije

Prema autorovom iskustvu, najčešći problem je loša otpornost na koroziju, obično pri ispitivanju prema ASTM G48 TIG-om zavarenih spojeva. Primeri pitinga u metalu šava su prikazani na slici 4. Zajednički imenitelj ovih problema je gubitak azota i / ili suviše brzo hlađenje. Kao što je prikazano na slici 5, ovo rezultuje u visoko feritnoj mikrostrukturi koja je deponovana kao i na velikim količinama sekundarnog austenita u ponovno zagrevanim oblastima, ponekad zajedno sa formiranjem nitrida. Sekundarni austenit ima nizak sadržaj azota, a samim tim i otpornost na koroziju će biti loša u ovim regionima [9].
Lek je korišćenje veće energije često u kombinaciji sa zaštitnim gasom koji sadrži N za poboljšanje formiranja austenita. Kod 22% Cr čelika, koreni prolazi se često zavaruju superdupleksnim dodatnim materijalima kako bi se dodatno poboljšala otpornost na koroziju na strani korena.

4.2 Stvaranje intermetalnih faza

Kod superdupleksa i hiperdupleksa može doći do stvaranja intermetalne faze (slika 6) ako je hlađenje suviše sporo ili ako se oblast zavarivanja ponovo zagreva u opsegu od oko 600-1000 ºC [11]. Kad god postoje intermetalne faze, kao što su sigma i chi, žilavost i otpornost na koroziju će se umanjivati. Zbog toga je stroga kontrola tehnologije zavarivanja potrebna za visokolegirane klase.
Ne samo da se mora pridržavati gornjih preporučenih granica unete energije i međuslojne temperature, već je važno i planirati redosled zavara kako bi se izbeglo nepotrebno ponovljeno grejanje prethodnih zrna. Uobičajeno treba izbegavati premali koreni zavar praćen većim "toplim prolazom".

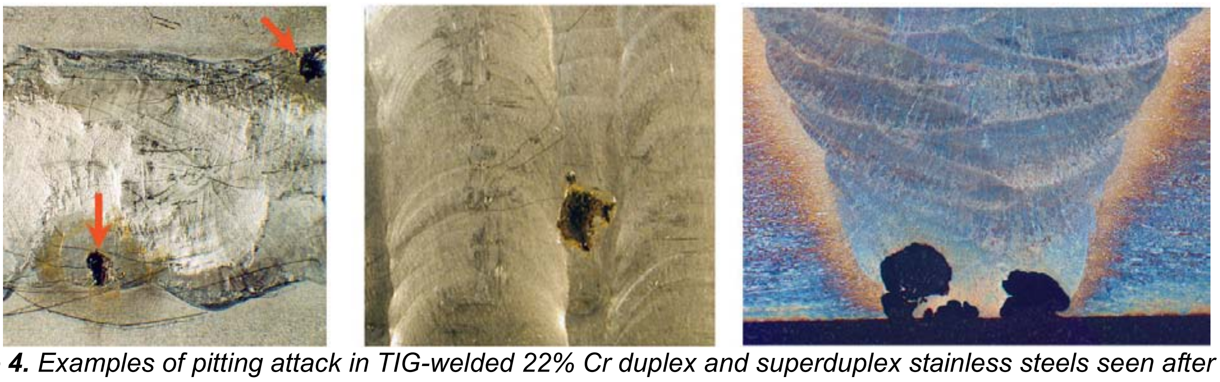
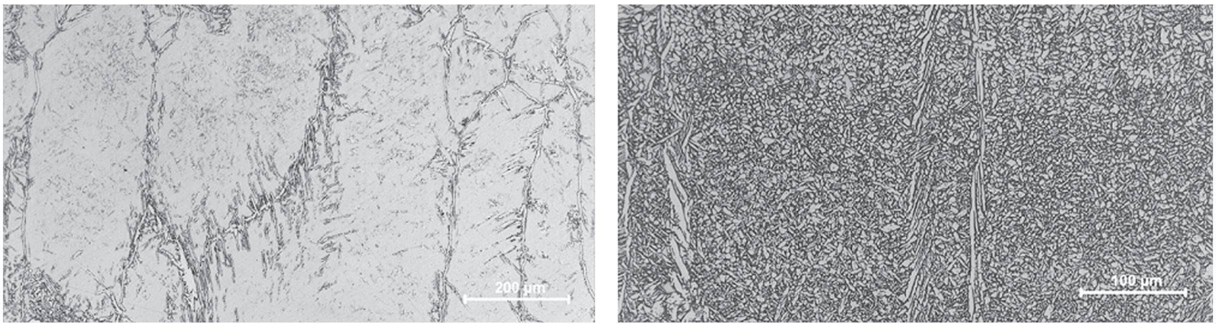


Figure 4. *Examples of pitting attack in TIG-welded 22% Cr duplex and superduplex stainless steels seen after ASTM G48 testing*

Slika 4. *Primeri piting korozije na TIG-om zavarenom 22% Cr dupleks I superdupleks nerđajućem čeliku posle ispitivaja prema ASTM G-48*



Massive formation of secondary austenite can be seen in the reheated bead
Masivna formacija sekundarnog austenita se može videti u ponovo zagrejanom zavaru
a) Last bead - Poslednji zavar *b) Reheated beads-Ponovno zagrejani zavar*

Figure 5. *Microstructure of last and reheated beads in 22% Cr duplex stainless steel TIG-welded with a 22Cr9Ni3Mo+N type filler*
Slika 5. *Mikrostruktura poslednjeg I ponovo zagrevanog zavara na 22% Cr dupleks nerđajućem čeliku zavarenom TIG-postupkom sa dodatnim materijalom tipa 22Cr9Ni3Mo+N*

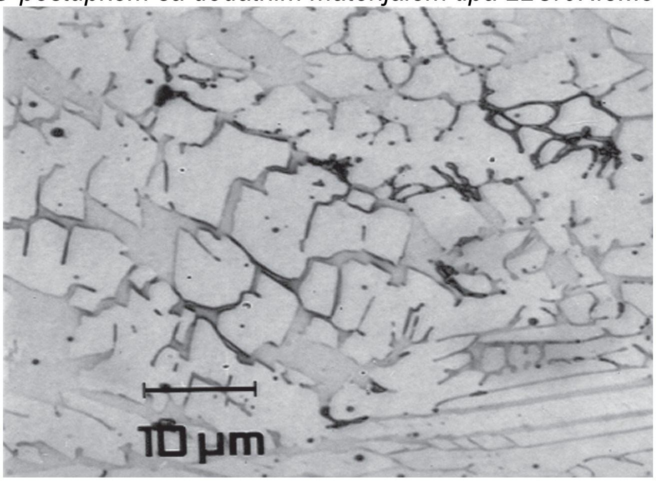


Figure 6. *Intermetallic phase (dark etching) formation in a repeatedly reheated region of a superduplex weld*
Slika 6. *Intermetalna faza (tamno nagrižena) stvorena na ponovno zagrejanoj zoni superdupleks metala šava*

4.3 Solidification cracking

Solidification cracking is a minor problem in welding of duplex stainless steels. However, this is not to say it cannot occur under certain conditions. A high restraint in combination with deep and narrow beads is a classical condition when cracking can become a problem with conventional arc welding methods. This tendency is generally counteracted by modifying the bead profile and for thick material sometimes using a moderate preheat.
Two less well-known situations when hot cracking sometimes is observed is with very shallow beads or in highly ferritic welds. The first case is illustrated in Figure 7 for a submerged arc weld in 22 % Cr duplex material. Typically hot cracks appear under high restraint situation, with shallow beads forming “wings”. Cracking is either found in the “wing” region where stresses will act perpendicular to the vertical ferrite grains or in the transition region between the “wing” and the central penetrating portion of the weld. These cracks can be avoided

4.3 Solidifikacione prsline

Solidifikaciona prslina je manji problem kod zavarivanja dupleksnih nerđajućih čelika. Međutim, to ne znači da se to ne može dogoditi pod određenim uslovima. Visoka ograničenost u kombinaciji sa dubokim i uskim zavarima je klasično stanje kada prslina može postati problem konvencionalnim metodama elektrolučnog zavarivanja. Ova tendencija se generalno suprotstavlja modifikacijom profila zavara i ponekad kod debelih materijala uz umereno zagrevanje.
Dve manje poznate situacije kada se ponekad primećuje vruća prslina su vrlo plitki zavari, ili kod zavarenih spojeva sa visokim feritom. Prvi slučaj je ilustrovan na slici 7 za EPP šav od 22%Cr dupleks materijala. Tipične vruće pukotine pojavljuju se pod visokim uslovima ukrućenja, sa plitkim zavarima koji formiraju "krila". Prsline se nalaze ili u oblasti "krila" gde će naponi delovati normalno na vertikalna feritna zrna ili u prelaznoj oblasti između "krila" i centralnog prodirućeg dela zavara. Ove

by modifying welding parameters to avoid “wing” formation.

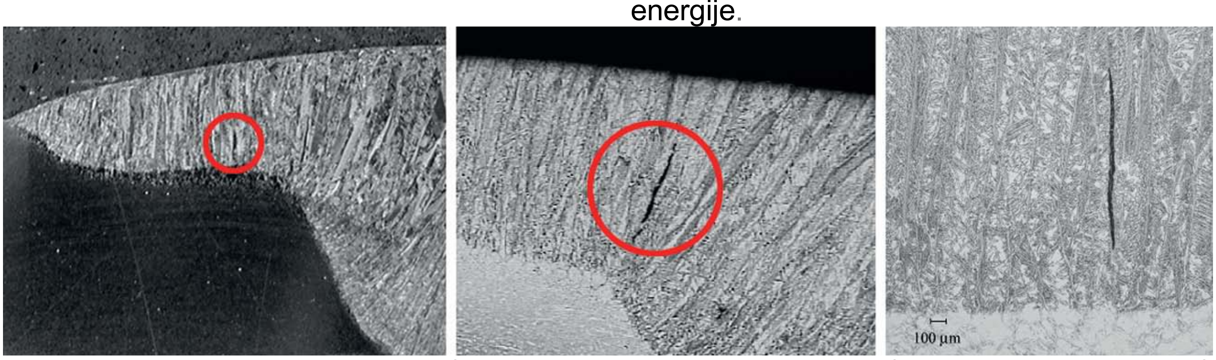
The second condition when hot cracks appear is most commonly seen with low energy input and high dilution welding situations. Two examples are shown in Figure 8 for autogenous laser welding and hybrid welding of 22 % Cr duplex material. It is well-known that hot cracking resistance decreases when going from austenitic weld metals with some ferrite towards fully ferritic compositions [21].

The common solution is therefore to modify the welding procedure, to permit formation of more austenite, by adding more austenite promoting elements through shielding gas and filler wire and by increasing the energy input.

prsline se mogu izbeći modifikacijom parametara zavarivanja radi izbegavanja nastanka krila.

Drugi uslov kada se pojavljuju vruće prsline se najčešće vide pri malom unosu energije i velikim mešanjem. Dva primera su prikazana na slici 8 za autogeno lasersko zavarivanje i hibridno zavarivanje 22%Cr dupleks materijala. Poznato je da se otpornost na vruće prsline smanjuje pri izlasku iz austenitnog metala šava sa nešto ferita prema potpuno feritnim sastavima [21].

Zbog toga je zajedničko rešenje, modifikovati postupak zavarivanja, kako bi se omogućilo formiranje više austenita, dodavanjem više elemenata koji promovišu austenit kroz zaštitni gas i dodatni materijal i povećanjem količine unete energije.

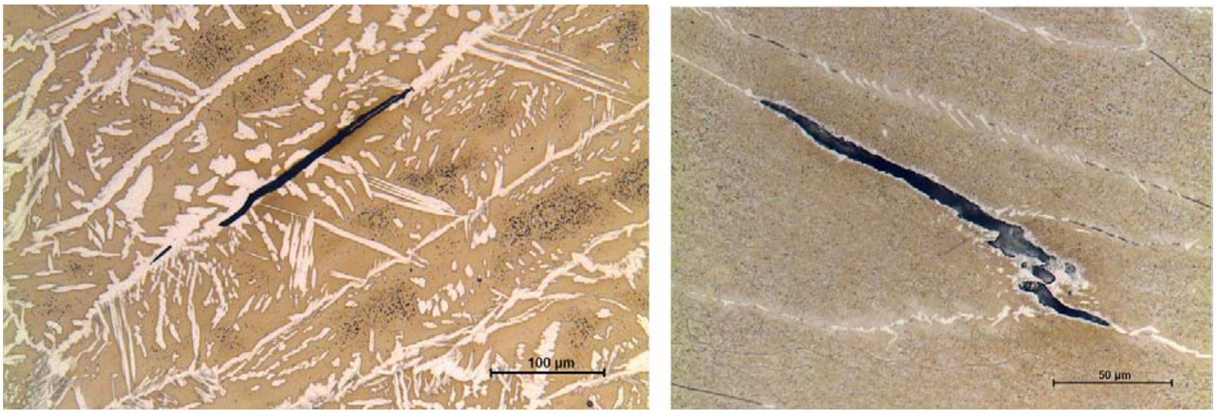


The red circles show regions with solidifi cation cracks in the macrographs (left and centre). A close-up of a crack is seen in the micrograph (right).

Crveni krugovi pokazuju regione sa solidifikacijskimprslinama na makrografima (levo i centar). Na mikrofotografiji (desno) vidi se krupna prslina.

Figure 7. *Hot cracks in submerged arc welds in 22 % Cr duplex stainless steel*

Slika 7. *Vruće prsline kod EPP zavarenih spojeva na dupleksnerđajućem čeliku 22% Cr*



The energy input was 0.6 kJ/mm.
Uneta energija 0,6kJ/mm
a) Hybrid weld -Hibridno zavareni spoj

The energy input was 0,1 kJ/mm
Uneta energija 0,1kJ/mm
b) Laser weld –Laserom zavareni spoj

Figure 8. *Hot cracks in hybrid and laser welds in 22 % Cr duplex stainless steel*

Slika 8. *Vruće prsline kod hibridno i laserom zavarenih spojeva od dupleks nerđajućih čelika 22%Cr*

5. Concluding remarks

Many important aspects of welding duplex stainless steels have not, or only briefly, been touched on. These include for example standardization, suitability and reliability of various test methods, hydrogen effects, postweld straightening and cleaning, characterization and prediction of microstructures and properties [22-25].

Many of these aspects were discussed in papers at the recent conference on duplex stainless in Beaune, France, in 2010 and the reader is referred to the proceedings for more detail [4].

Generally the knowledge about what can be done and what should be avoided is at a high level among experienced users and these consequently report very few welding related problems. Nevertheless, as discussed above, duplex stainless steels require understanding of how welding will affect the microstructure and properties.

New users/fabricators therefore occasionally experience problems when cutting corners to save time.

The following is the summary of some of the more important aspects discussed in the paper:

– The range of duplex grades has in recent years been extended both with lean less-alloyed grades

– The newer as well as more established grades are welded with excellent result provided basic rules and recommendations are followed.

– Generally there is consensus on welding recommendations but variations reflecting differences in practices exist in particular for newer steel grades.

– Limits in allowable energy inputs are less well documented for some of the newer grades.

– Welding related problems are most commonly encountered when too low or excessively high heat input is used, when dilution is too high or when too much nitrogen is lost from the weld pool. In particular resistance to localized corrosion and impact toughness is affected.

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5. Završne napomene

Mnogi važni aspekti zavarivanja dupleks nerđajućih čelika nisu ili su samo kratko dodirnuti. Ovo uključuje, na primer, standardizaciju, pogodnost i pouzdanost različitih metoda ispitivanja, efekte vodonika, ispravljanje posle zavarivanja i čišćenje, karakterizaciju i predviđanje mikrostruktura i svojstava [22-25].

Mnogi od ovih aspekata diskutovani su u radovima na nedavnoj konferenciji o dupleks nerđajućim čelicima u Beaune-u, u Francuskoj 2010. godine, a čitalac se upućuje na zbornik radova za više detalja [4].

Uopšteno, znanje o tome šta se može uraditi i šta se treba izbegavati je na visokom nivou među iskusnim korisnicima i zbog toga oni prijavljuju vrlo malo problema sa zavarivanjem. Ipak, kao što je već rečeno, dupleks nerđajući čelici zahtevaju razumevanje toga kako zavarivanje utiče na mikrostrukturu i svojstva.

Iz tog razloga, novi korisnici / proizvođači povremeno imaju problema prilikom sečenja uglova kako bi uštedeli vreme.

Sledeće je pregled nekih od najvažnijih aspekata koji su razmatrani u članku:

- Opseg klasa dupleksa se poslednjih godina proširio i sa manje legiranim klasama

- Novije i bolje utvrđene klase su zavarene sa odličnim rezultatom uz poštovanje osnovnih pravila i preporuka.

- Uopšteno postoji konsenzus o preporukama za zavarivanje, ali varijacije koje odražavaju razlike u praksi postoje, posebno za nove klase čelika.

- Granice dozvoljenih ulaza energije su manje dokumentovane za neke od novijih klasa.

- Problemi sa zavarivanjem najčešće se javljaju kada se koristi previše mali ili prekomerni unos toplote, kada je mešanje preveliko ili kada se previše azota izgubi iz zavarivačke kupke. Konkretno je ugrožen otpor lokalizovanoj koroziji i udarna žilavost.

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Additional literature

The interested reader is referred to the Proceedings of Duplex Conferences for further details. These give an excellent overview of the development of steels, applications and welding experiences during the last four decades:

Proceedings Conference Duplex Stainless Steels’82, St Louis, USA (Oct. 1982).
Proceedings Conference Duplex Stainless Steels’86, The Hague, Netherlands (Oct. 1986).
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Dodatna literatura

Zainteresovani čitalac se upućuje na Zbornik radova sa Konferencije o dupleks čelicima za više detalja. Oni daju odličan pregled razvoja čelika, primena i iskustava zavarivanja tokom poslednje četiri decenije:

Proceedings Conference Duplex Stainless Steels’97, Maastricht, The Netherlands (Oct. 1997).
Proceedings International Conference Duplex 2000, Venice, Italy (Oct. 2000).
Proceedings International Conference Duplex 2007, Grado, Italy (June 2007).
Proceedings International Conference Duplex World 2010, Beaune, France (Oct. 2010).