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NEW TOOLS FOR STEELS WELDABILITY MODEL BASED ON THE RISK ASSESSMENT

NOVI ALATI ZA MODEL ZAVARLJIVOSTI ČELIKA ZASNOVAN NA OCENI RIZIKA

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Abstract

In this paper a new weldability model is presented, which can be applied to different steels grades based on a risk analysis, parent and filler materials properties, welding process and welding technology. The previous weldability models based on carbon equivalent formula or on other indirect methods available in the literature have limited applications. This is because it consider only the steel chemical composition, ignoring others process factors over the weldability. The weldability should consider all material and process factors of influence, even for the very same steel grade, which can be welded in different conditions, thus obtaining different weldability results.

1. Introduction

Nowadays, many applications require high strength metallic welded structures, capable to support dynamic loads in different environments and temperature conditions. Such applications require the utilization of advanced high strength steels (AHSS) or even ultrahigh strength steels (UHSS), which beside high strength should present also good weldability properties. Due to exploitation conditions and safety concerning, the weldability property plays a fundamental role in designing and fabrication of modern metallic welded structures. According to American Welding Society (AWS), the weldability is defined as the metal capacity to be welded under the fabrication conditions imposed with a specific suitability and designed structure, which perform satisfactorily in service, [1].

Similarly, DIN 8528 Part 1, is defining the weldability as result of interaction of three main group factors, according to material, manufacture and design characteristics. These factors must be accounted and are summarised in the Table 1.

Rezime

U ovom radu je predstavljen novi model zavarljivosti, koji se može primeniti za različite vrste čelika na osnovu analize rizika, karakteristika osnovnog i dodatnog materijala, postupka i tehnologije zavarivanja. Prethodni modeli zavarljivosti zasnovani na ekvivalentu ugljenika ili na drugim indirektnim metodama dostupnim u literaturi, imaju ograničene primene. Ovo je zato što uzima u obzir samo hemijski sastav čelika, ignorišući druge procesne faktore od kojih zavisi zavarljivost. Zavarljivost treba da uzme u obzir sve faktore materijala i procesa, čak i za istu klasu čelika, koji se mogu zavariti u različitim uslovima, i stoga se dobijaju različiti rezultati zavarljivosti.

1. Uvod

Danas, mnoge aplikacije zahtevaju metalne zavarene konstrukcije visoke čvrstoće, sposobne da izdrže dinamička opterećenja u različitim okruženjima i temperaturnim uslovima. Ovakve primene zahtevaju korišćenje naprednih čelika visoke čvrstoće (AHSS) ili čak čelika visokih čvrstoća (UHSS), koji pored visoke čvrstoće treba da imaju i dobre karakteristike zavarljivosti. Zbog uslova eksploatacije i sigurnosti, svojstvo zavarljivosti igra osnovnu ulogu u projektovanju i izradi modernih metalnih zavarenih konstrukcija. Prema Američkom zavarivačkom društvu (AWS), zavarljivost se definiše kao mogućnost metala da bude zavaren pod uslovima izrade koji su nametnuti specifičnom pogodnošću i projektom konstrukcije, a da zadovolje uslove rada [1].

Slično tome, DIN 8528 deo 1, definiše zavarljivost kao rezultat interakcije tri glavne grupe faktora, u zavisnosti od materijala, proizvodnje i karakteristika projekta. Ovi faktori se moraju uzeti u obzir i prikazani su u tabeli 1.

Welding Suitability Pogodnost za zavarivanje	MATERIAL/MATERIJAL
	Chemical composition, Tendency to hardening, Tendency to ageing, Tendency to hot cracking Melting point, Thermal conductivity, Expansion coefficient, Mechanical properties Segregations, Inclusions, Grain size, Anisotropy
	Hemijski sastav, Sklonost ka otvrdnjavanju, Sklonost ka starenju, Sklonost ka vrućim prslinama, Tačka topljenja, Toplotna provodljivost, Koeficijent širenja, Mehaničke osobine, Segregacije, Uključci, Veličina zrna, Anizotropija
Welding Possibility Mogućnost zavarivanja	MANUFACTURE/IZRADA
	Welding process, Groove shape, Preheating, Susceptibility to cracking, Heat input and dilution, Welding position, Welding sequence, Weld penetration, Post weld heat treatment, Grinding, Pickling
	Postupak zavarivanja, Oblik žljeba, Predgrevanje, Osetljivost na prsline, Uneta toplota I stepen mešanja, Položaj zavarivanja, Uvarivanje šava, Termička obrada posle zavarivanja, Brušenje, Ispiranje
Welding Safety Bezbednost zavarivanja	DESIGN/ Projekat
	Material thickness, Notch effect, Stiffness differences, Joint geometry and displacement, Temperature range, Corrosion resistance, Loads and stress distribution, Weld bead shape
	Debljina materijala, Efekat zareza, Razlika u krutosti, Geometrija spoja i postavljenost, Opseg temperature, Otpornost na koroziju, raspodela opterećenja i napona, Oblik zavara

Table 1. *Groups of weldability factors of influence*
Tabela 1. *Grupe uticajnih faktora zavarljivosti*

Detailed description of each factor influence over weldability exceeds the present purpose of this paper, but a short comment is given for the main factors considered in our weldability model.

1.1 Chemical composition

Parent and filler material chemical composition is a key element that has a great influence over the weldability. Usually, the filler material is selected in order to match the parent material mechanical properties, taking into account the differences in the weld microstructure, as result of the welding thermal cycle applied. In literature, different empirical carbon equivalent formulas can be found, that are used to evaluate the weldability and the tendency of hydrogen induced cracking of the weld. The most frequently formulas used for carbon equivalent calculus are given in the eq. (1)-(5), [3]-[7].

$CEIIW= C + Mn/6 + (Cr+Mo+V)/5 + (Ni+Cu)/15$ (1)
$CET = C + (Mn+Mo)/10 + (Cr+Cu)/20 + Ni/40$ (2)
$CEN= C + k\cdot[Si/24 + Mn/6 + Cu/15 + Ni/20 + +(Cr+Mo+V+Nb)/5 + 5B]$ (3)
where $k = 0.75+0.25\cdot\tanh(20\cdot(C-0.12))$ (4)
$Pcm= C + Si/30 + (Mn+Cu+Cr)/20 + Ni/60 + +Mo/15 + V/10 + 5B$ (5)
$CEq= C + Si/25 + (Mn+Cu)/16 + Ni/40 + Cr/10 + +Mo/15 + V/10$(6)

Each formula has been developed for different steels classes, based on a chemistry that in time has changed for modern steels, in order to obtain a better weldability and superior mechanical properties. These properties are achieved based on the steel microstructure control, rather than by increasing steel carbon equivalent value.

Detaljan opis uticaja svakog faktora na zavarljivost prevazilazi sadašnju svrhu ovog rada, ali je dat kratak komentar za glavne faktore koji se uzimaju u obzir u našem modelu zavarljivosti.

1.1 Hemijski sastav

Hemijski sastav osnovnog i dodatnog materjala je ključni element koji ima veliki uticaj na zavarljivost. Obično se dodatni materijal bira tako da se podesi sa mehaničkim osobinama osnovnog materijala, uzimajući u obzir razlike u mikrostrukturi zavarenog spoja, kao rezultat primenjenog termičkog ciklusa zavarivanja. U literaturi se mogu naći različite empirijske formule za ekvivalent ugljenika, koje se koriste za procenu zavarljivosti i tendenciju stvaranja vodoničnih prslina u zavarenom spou. Najčešće formule koje se koriste za izračunavanje ekvivalenta ugljenika date su u jednačinama. (1) - (5), [3] - [7].

$CEIIW= C + Mn/6 + (Cr+Mo+V)/5 + (Ni+Cu)/15$ (1)
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Svaka formula je razvijena za različite klase čelika, zasnovana je na hemiji koja se vremenom promenila za savremene čelike, kako bi se postigla bolja zavarljivost i vrhunska mehanička svojstva. Ova svojstva se postižu na osnovu kontrole mikrostrukture čelika, a ne povećanja vrednosti ekvivalenta ugljenika čelika.

However, there is no universal carbon equivalent formula that could be applied to all steels grades, some formulas giving better results for low carbon and HSLA steels, equations (4), (5), while others formula are more accurate for steels with higher carbon equivalent content equations (1), (3). Nevertheless, all carbon equivalent formulas are related to the steel cold-cracking susceptibility, being a direct connection between the steel carbon equivalent and the martensite volume or maximum hardness in the HAZ.

1.2 Heat input and cooling cycle

The welding thermal cycle plays also a key factor in the microstructure control in parent material and HAZ. The formation of hard secondary phases depends directly on the carbon equivalent and cooling rates experienced in the 800-500^{0}C temperature range, for structural steels to HSLA and AHSS steels. In order to avoid the stainless steels sensitization the apparition of sigma and chi phases must be avoided. That requires different cooling rates, especially in the maximum temperature transformation range, between 1000-800^{0}C.

Heat input is determined by the welding parameters, I (A), U (V) and welding speed (m/min), while the cooling rate CR (^{0}C/sec) depends on the material thickness, heat flow regime, metallic structure design, material thermal conductivity and welding pool properties.

Međutim, ne postoji univerzalna formula za ekvivalent ugljenika koja bi se mogla primeniti na sve vrste čelika, neke formule daju bolje rezultate za niskougljenične i HSLA čelike, jednačine (4), (5), dok su druge formule tačnije za čelike sa većim sadržajem ugljenika, jednačine (1), (3). Bez obzira na sve, sve formule sa ekvivalentom ugljenika odnose se na podložnost ka hladnim prslinama čelika, što je direktna veza između ekvivalenta ugljenika čelika i zapremine martenzita ili maksimalne tvrdoće u ZUT-u.

1.2 Uneta toplota i ciklus hlađenja

Termički ciklus zavarivanja predstavlja ključni faktor u kontroli mikrostrukture u osnovnom materijalu i ZUT-u. Formiranje tvrdih sekundarnih faza zavisi direktno od ekvivalenta ugljenika i brzine hlađenja u temperaturnom opsegu od 800-500°C, za konstrukcione čelika do HSLA i AHSS čelika. Da bi se izbegla senzitivizacija nerđajućih čelika, mora se izbeći pojavljivanje sigma i hi faza. To zahteva različite brzine hlađenja, posebno u maksimalnom opsegu temperature transformacije, između 1000-800^{0}C.

Unošenje toplote određuje se parametrima zavarivanja I (A), U (V) i brzine zavarivanja (m / min), a brzina hlađenja CR (^{0}C/sec) zavisi od debljine materijala, režima provođenja toplote, projekta metalne konstrukcije, toplotne provodljivosti materijala i karakteristike zavarivačke kupke.

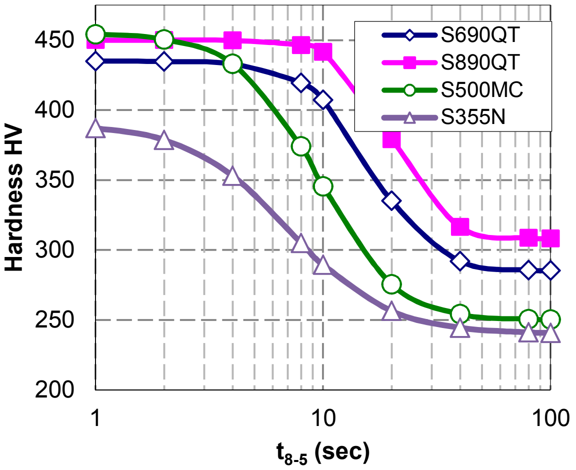


***Figure 1.** HAZ hardening for different materials as a function of cooling time t 8-5 after welding, calculated after [8].*

***Slika 1.** Otvrdnjavanje ZUT kod različitih materijala kao funkcija vremena hlađenja t 8-5 posle zavarivanja [8].*

As the steel's carbon equivalent become higher and cooling rate faster, the tendency to form hard and brittle phases in HAZ get stronger, increasing the weld cracking susceptibility and lowering the weldability. The risk of cracking in HAZ depends on the diffusible hydrogen level, joint restraint and HAZ hardening. The dependence between the maximum HAZ hardness and cooling rate expressed by the t_{8-5} parameter is presented in the Figure 1 for

Kako ekvivalent ugljenika čelika postaje veći i brzina hlađenja raste, tendencija stvaranja tvrdih i krtih faza u ZUT-u postaje sve jača, povećavajući podložnost prslinama i smanjenje zavarljivosti. Rizik od prslina u ZUT-u zavisi od nivoa difundovanog vodonika, krutosti zavarenih spojeva i otvrdnjavanja ZUT-a. Zavisnost između maksimalne tvrdoće ZUT i brzine hlađenja izražena different steels, used frequently in welded structures.

2. Weldability model proposed

The weldability model proposed in this paper is measuring how much the deposited metal and HAZ properties have been negatively affected by the welding process in respect with the parent material properties reference system (MPRS). Practically, in MPRS are included but not limited to: hardness, impact energy, ductility, fatigue strength, creep and corrosion resistance, grain size, microstructure anisotropy, stress distribution and others specific properties.

The weldability is determined based on each property impact analysis, by calculating the weighted arithmetic mean of all negative impacts. The risks and weights factors are arranged in a matrix form, considering normalized values for each risk analysed. Thus, the weldability will result as a number between 0 and 1, representing the weldability number (WN). Mathematically, the weldability could be described by a five-parameter logistic (5PL) function that has two horizontal asymptotes.

parametrom t_{8-5} prikazana je na slici 1 za različite čelike, često se koristi kod zavarenih konstrukcija.

2. Predviđeni model zavarljivosti

Model zavarljivosti predložen u ovom članku meri koliko je na naneti metal i svojstva ZUT negativno uticao proces zavarivanja u odnosu na referentni sistem svojstava osnovnog materijala (MPRS). Praktično, u MPRS su uključeni ali ne i ograničeni na: tvrdoću, energiju udara, duktilnost, zamornu ćvrstoću, otpornost na puzanje i koroziju, veličinu zrna, anizotropiju mikrostrukture, raspodelu napona i druge specifične osobine.

Zavarljivost se određuje na osnovu analize uticaja svake osobine, izračunavanjem ponderisane aritmetičke sredine svih negativnih uticaja. Faktori rizika i težine su raspoređeni u matričnom obliku, uzimajući u obzir normirane vrednosti za svaki analizirani rizik. Prema tome, zavarljivost će rezultovati kao broj između 0 i 1, što predstavlja broj zavarljivosti (WN). Matematički, zavarljivost se može opisati pomoću petoparametarske logističke (5PL) funkcije koja ima dve horizontalne asimptote.

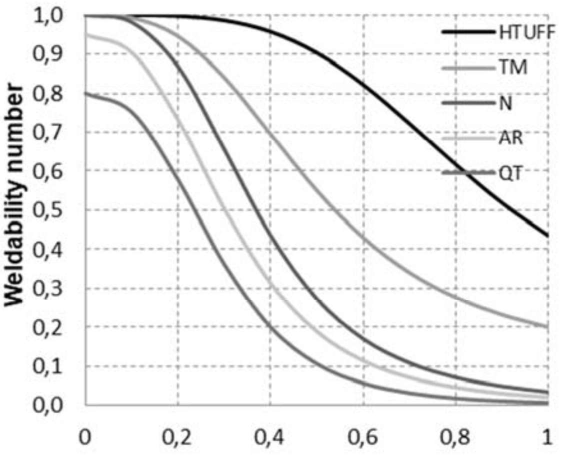


Figure 2 *Weldability vs. Equivalent Risk Factor.*
Slika 2. *Zavarljivost –Ekvivalent faktora rizika*

5PL weldability function has been graphically represented vs. the equivalent risk factor, in the The Figure 2. This representation allows us to obtain a compared view of different steels weldability calculated for the same welding conditions or risk factors. Beside the parent and filler material properties – e.g. carbon equivalent, the weldability is strongly affected by many others factors, like those presented in the Table 1

In the Table 2 are presented the parameters of the 5PL weldability function, which is graphically represented in the Figure 2, for different steels grades, using the equation (7), where RF represent the equivalent risk factor.

Funkcija zavarljivorti 5PL je grafički prikazana u odnosu na ekvivalentni faktor rizika, na slici 2. Ova prezentacija nam omogućava da dobijemo upoređeni prikaz različitih zavarljivih čelika izračunatih za iste uslove zavarivanja ili faktore rizika. Pored karakteristika osnovnog i dodatnog materijala - npr. ugljenični ekvivalent, zavarljivost je snažno pogođena mnogim drugim faktorima, kao što su one prikazane u Tabeli 1

U tabeli 2 prikazani su parametri funkcije zavarljivosti 5PL, koja je grafički prikazana na slici 2, za različite vrste čelika, koristeći jednačinu (7), gde RF predstavlja ekvivalentni faktor rizika.

Parameters 5PL Function Parametri 5PL funkcije	a	d	c	b	e
HTUFF Steels Ultra finozrni čelici visoke čvrstoće	0.1	1	0.8	4	0.8
Thermomechanical steels TM Termomehanički obrađeni čelici	0.1	1	0.5	3	1
Structural steels (N) Konstrukcioni čelici (normalizaciono stanje)	0	1	0.4	3	1.2
Structural steels (AR) Konstrukcioni čelici (vruće valjani)	0	0.95	0.4	2.5	1.6
Structural steels (QT) Konstrukcioni čelici (kaljeni I otpušteni)	0	0.8	0.4	2.5	2

Table 2. *Parameters of 5PL weldability function 5PL*

Tabela 2. *Parametri funkcije zavarljivosti*

$$WN(RF) = a + \frac{d-a}{\left[1+\left(\frac{RF}{c}\right)^{b}\right]^{e}} \quad (7)$$

The equivalent risk factor RF, equation (8) is obtained also by a weighted arithmetic mean of individual risks RFi considered in the Table 3, arranged in five groups, according to the risk level. Each individual risk is normalized and is accounted on equivalent risk number based on an impact factor IFi or weight, given also in the Table 3.

Ekvivalentni faktor rizika RF, jednačina (8) se dobija i ponderisanom aritmetičkom sredinom pojedinačnih rizika RFi razmatranih u Tabeli 3, raspoređenih u pet grupa, prema nivou rizika. Svaki pojedinačni rizik se normalizuje i obračunava se na ekvivalentnom broju rizika zasnovanom na faktoru uticaja IFi ili težini, datom u tabeli 3.

$$RF = \sum_{i=1}^{n} RF_i \cdot IF_i \quad (8)$$

Risk factor RFi Faktor rizika	*Group Risks/ Grupe rizika*					*Weight factor Faktor težine*
	1	*2*	*3*	*4*	*5*	
Groove type Vrsta žljeba	*I, J, Y 0.1*	*V, U, X 0.2*	*2X, 2U 0.5*	*fillet 0.8*	*asym. 1*	*5%*
Weld bead shape Oblik zavara	*Flat/ravno 0.1*	*convex 0.2*	*concave 0.4*	*convex+ 0.8*	*concave+ 1*	*5%*
Weld H/W ratio Odnos H/W u šavu	*<1 0.2*	*1-2 0.3*	*2-3 0.5*	*3-4 0.8*	*>4 1*	*5%*
Joint Restraint Krutost spoja	*no restr./bez 0*	*Low/malo 0.2*	*Medium/srednje 0.5*	*High/veliko 0.8*	*very high/vrlo veliko 1*	*10%*
Welding position Položaj zavarivanja	*PA 0.1*	*PB, PH 0.2*	*PC 0.5*	*PD,PG,PF 0.8*	*PE 1*	*5%*
Material thickness Deljina materijala	*< 10 0.1*	*11-20 0.2*	*21-30 0.4*	*31-40 0.8*	*>40 1*	*5%*
Welding process Postupak zavarivanja	*LW,EBW 0.2*	*GMAW, 0.3*	*SAW 0.5*	*ESW 0.8*	*OAW 1*	*5%*
Cold crack susceptibility Osetljivost na hladne prsline	*very low 0*	*low 0.2*	*medium 0.5*	*high 0.8*	*very high 1*	*25%*
Hot crack susceptibility Osetljivost na vruće prsline	*very low 0*	*low 0.2*	*medium 0.5*	*high 0.8*	*very high 1*	*25%*
Microstructure anisotropy Anizotropija mikrostrukture	*UFG 0*	*FG 0.2*	*AR 0.5*	*AR+PD 0.8*	*CAST 1*	*10%*

Table 3. *Risk factors matrix*

Tabela 3. *Matrica faktora rizika*

Notes: UFG-Ultra Fine Grained; FG-Fine Grained (micro alloyed); AR-As Rolled (hot rolled, conventional structural steels); PD-severe plastic deformation; CAST-cast steel. Convex+ or concave+ means weld surface excessive curvature.

Napomene:UFG-ultrafinozrni; FG-finozrni (mikrolegirani); AR- Kao valjano (vruće valjani, konvencionalni konstrukcioni čelici); PD-značajna plastična deformacija; CAST-čelični liv; Konveksan ili konkavan znači prekomernu zakivljenost površine šava.

3. Weldability measurement

In equation (9), it has been proposed a formula for experimental measuring of weldability. The basic principle is to measure the extension of which the properties of the deposited metal and in HAZ have been affected by the welding process, in respect with the parent material properties reference system. Thus, we can measure the hardening or softening effect, the toughness reduction, heat input effect, changes in microstructure and hardness profile variation across the HAZ and deposited metal, in respect with the parent material hardness, Figure 3 and Figure 4.

3. Merenje zavarljivosti

U jednačini (9) predložena je formula za eksperimentalno merenje zavarljivosti. Osnovni princip je merenje obima nanetog metala i ZUT na koje je uticao proces zavarivanja, u odnosu na referentni sistem svojstava osnovnog materijala. Tako možemo meriti efekat otvrdnjavanja ili omekšavanja, smanjenje žilavosti, uticaj unete toplote, promene u mikrostrukturi i varijacije profila tvrdoće preko ZUT-a i nanetog metala, u odnosu na tvrdoću osnovnog materijala, slika 3 i 4.

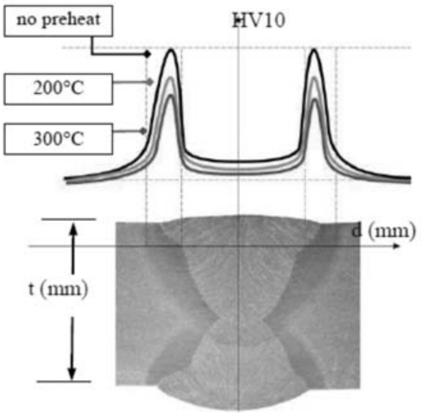


Figure 3 *Hardness profile across the HAZ and deposited metal, for an over-strength weld (Rp0,2 filler > Rp0,2 base)*
Slika 3. *Profil tvrdoće preko ZUT i nanetog metala sa „jačim“ metalom šava (Rp0,2 dodatni > Rp0,2 osnovni)*

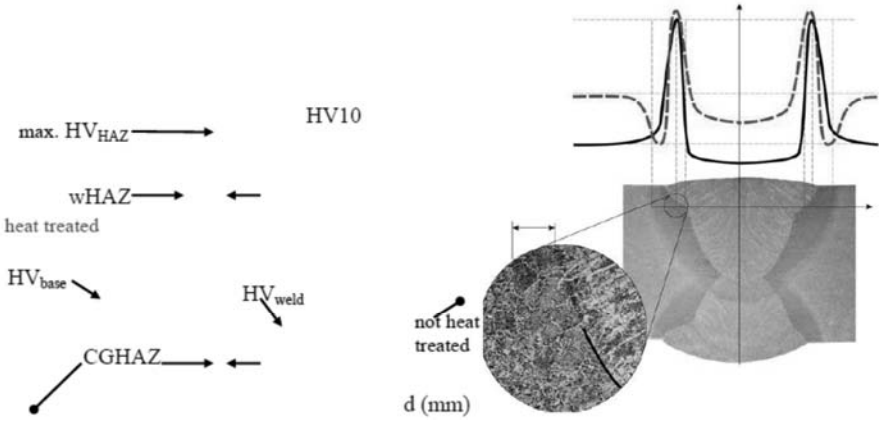
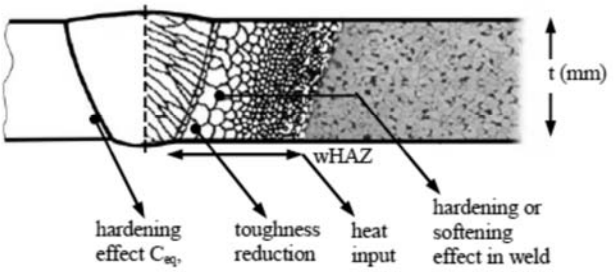


Figure 4 *Hardness profile across the HAZ and deposited metal, for an under-strength weld (Rp0,2 filler < Rp0,2 base)*
Slika 4. *Profil tvrdoće preko ZUT i nanetog metala sa „slabijim“ metalom šava (Rp0,2 dodatni < Rp0,2 osnovni)*



$$V_{HV} = 0.25 \cdot \left[\frac{HV_{base}}{HV_{HAZ}} + \frac{1}{1+\frac{CGHAZ}{wHAZ}} + \frac{1}{1+\frac{wHAZ}{t}} + \frac{1}{1+\frac{|\Delta HV|}{HV_{base}}} \right] \quad (9)$$

Figure 5 *Hardness vector VHV calculus*
Slika 5. *Vektor tvrdoće VHV računski*

The hardness vector VHV depends on parent and filler material chemistry, but also on heat input, dilution and cooling rates. The best weldability scenario is achieved when VHV =1, meaning that there are not any differences between the parent material, HAZ and deposited material, in terms of hardness, tensile strength, impact energy or microstructure. This is a hypothetical positive scenario, but based on the hardness vector VHV, we can estimate how much the weld joint properties are different from that situation.

The hardness vector VHV given in equation (9) has four terms, each one taking values between 0 and 1. The first term is measuring the hardening effect in HAZ, the HVHAZ representing the maximum hardness reached in HAZ. The second term would be proportional with the toughness reduction in the coarse-grained region (CGHAZ), wHAZ representing the width of the HAZ. As the ratio between the two zones (CGHAZ vs. HAZ) grows, more pronounced the toughness reduction would be, Figure 5. This is happening especially when conventional or structural steels are welded with processes characterized by large heat inputs, when the austenite grain pinning effect during heating cycle is no longer effective.

The heat input effect is measured also by the third term, where HAZ width is compared against to welded part thickness. As the HAZ become narrower, the weldability is increased accordingly. Finally, the last term is considering the hardening or softening effect in the deposited metal, according to dilution, parent and filler material properties, where ΔHV=HVweld – HVbase. If ΔHV> 0 we have a hardening effect, while for ΔHV< 0 we have a softening effect, Figure 5.

4. Experimental results

For weldability model validation, we have analysed the data recorded in a welding procedure specification WPS available in a standard form, from a Romanian company. These data can be used in our weldability model in order to build a large database, thus allowing us to refine the 5PL logistic function for the weldability function.

VHV vektor tvrdoće zavisi od hemijskog sastava osnovnog i dodatnog materijala, ali i od količine toplote, stepena mešanja i hlađenja. Najbolji scenario zavarljivosti se postiže kada je VHV = 1, što znači da ne postoje razlike između osnovnog materijala, ZUT-a i nanetog materijala, u smislu tvrdoće, zatezne čvrstoće, energije udara ili mikrostrukture. Ovo je hipotetički pozitivan scenario, ali na osnovu VHV vektora tvrdoće, možemo proceniti koliko su osobine zavarenog spoja različite od te situacije.

Vektor tvrdoće VHV dat u jednačini (9) ima četiri termina, od kojih svaki ima vrednosti između 0 i 1. Prvi izraz je za merenje efekta otvrdnjavanja u ZUT-u, a HVHAZ predstavlja maksimalnu tvrdoću koja je postignuta u ZUT-u. Drugi termin bi bio proporcionalan smanjenju žilavosti grubog zrna (CGHAZ), nasuprot (vHAZ) koji predstavlja širinu ZUT-a. Kako raste odnos između dve zone (CGHAZ vs. HAZ), bilo bi izrazitije smanjenje smanjenja žilavosti, slika 5. Ovo se dešava posebno kada su konvencionalni ili konstrukcioni čelici zavareni postupcima koje karakterišu veliki ulazi toplote, kada efekat zakačinjanja austenitnog zrna tokom ciklusa grejanja, više nije efikasan.

Efekat unete toplote meri se i trećim načinom, gde se upoređuje širina ZUT-a prema debljini zavarenog dela. Kako ZUT postaje uži, zavarljivost se povećava u skladu s tim. Konačno, poslednji termin razmatra efekat otvrdnjavanja ili omekšavanja u nanetom metalu, u skladu sa karakteristikama stepena mešanja osnovnog i dodatnog materijala, gde je ΔHV = HVšav - HVosnovni. Ako je ΔHV> 0, imamo efekt otvrdnjavanja, dok za ΔHV <0 imamo efekat omekšavanja, slika 5.

4. Eksperimentalni rezultati

Za validaciju modela zavarljivosti, analizirali smo podatke iz WPS specifikacije zavarivanja koji su dostupni u standardnom obliku, od rumunske kompanije. Ovi podaci se mogu koristiti u našem modelu zavarljivosti kako bi se izgradila velika baza podataka, što nam omogućava da usavršimo 5PL logističku funkciju za funkciju zavarljivosti.

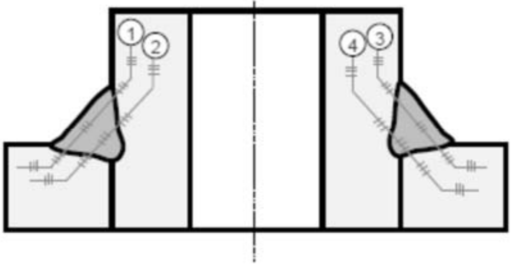


***Figure 6** Hardness vector VHV measurement based on a WPS_1*
***Slika 6.** Merenje vektora tvrdoće VHV zasnovano na WPS 1*

The welding parameters, welding test conditions and material properties are given in the Table 4, while the hardness measurement details and results are presented in the Figure 6 and Figure 7.

Parametri zavarivanja, uslovi ispitivanja zavarivanja i svojstva materijala dati su u tabeli 4, dok su detalji i rezultati merenja tvrdoće prikazani na slikama 6 i 7.

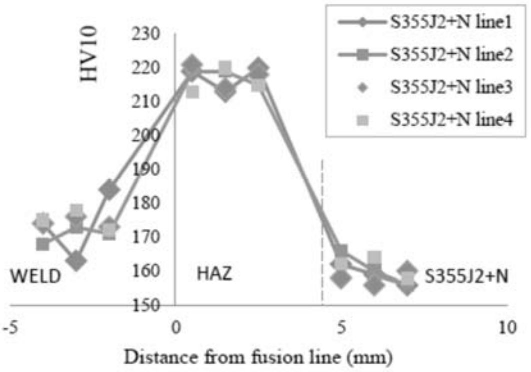


Figure 7 *Hardness profile across the HAZ and deposited metal, measured for welded samples using WPS_1*
Slika 7. *Profil tvrdoće preko ZUT i nanetog metala , mereno na zavarenim uzorcima prema WPS 1*

	Current Jačina struje I [A]	Tension Napon U [V]	Travel speed Brzina w_s (cm/min)	Heat input H Uneta toplota [kJ/mm]
Root pass Koreni zavar	180-181	13.5-14.6	6.5	1.40
Filler pass Zavar ispune	180-181	14.4-15.6	6.3	1.55
Cover Pass Pokrivni zavar	165-166	13.8-15.2	4.8	1.80
Materials: ∅75 x 20 mm t=20 mm Filler material	Welding Dissimilar materials" Zavarivanje raznorodnih materijala EN 10272 – 1.4541 EN 10025 – S355J2+N EN ISO 14343-A-W23 12L Si∅2.0 mm			
Welding process Postupak Welding position Položaj Shielding gas Zaštitni gas Welding current Vrsta struje	141 – TIG PB EN ISO 14175 - I1 - Ar DC^-			

Table 4. *Welding Procedure Specifications, WPS_1*
Tabela 4. *Specifikacija tehnologije zavarivanja WPS 1*

Hardness Vector V_{HV}	Measured Izmeren	Calculated Izračunat
S355J2+N Line 1	0.82	WN=0.88 eq.(7) jed.(7) for a risk factor equivalent za ekvivalent faktora rizika RF=0.20
S355J2+N Line 2	0.84	
S355J2+N Line 3	0.82	
S355J2+N Line 4	0.83	
Average value V_{HV} Srednja vrednost	0.83	
Standard distribution Standardna raspodela	0.009	

Table 5. *Hardness vector VHV results*
Tabela 5. *Rezultati za vektor tvrdoće VHV*

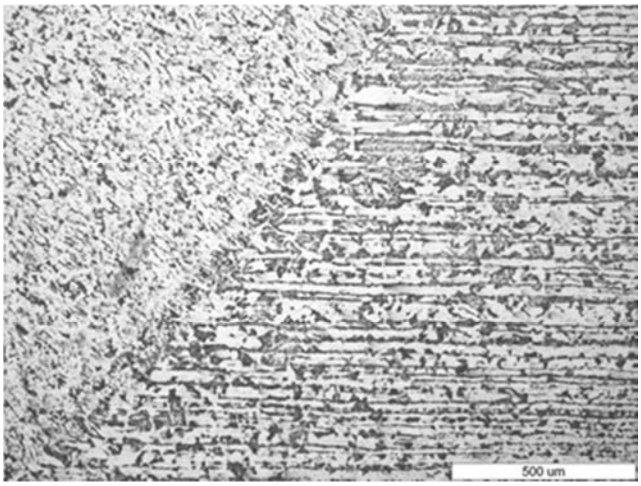


***Figure 8** Fusion line and HAZ for welded sample S355J2+N, WN=0.88, RF=0.2, σ= ± 0.009, X200, nital.*
***Slika 8.** Linija stapanja i ZUT zavarenih uzoraka S355J2+N, WN=0.88, RF=0.2, σ= ± 0.009, X200, nital.*

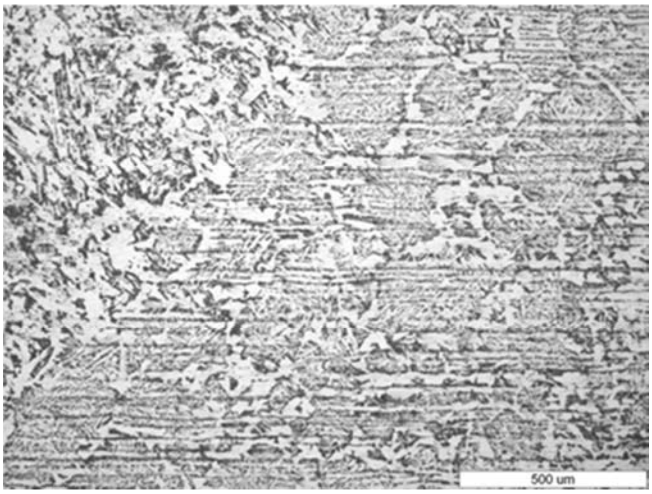


***Figure 9** Fusion line and HAZ for welded sample S355J2+N, CGHAZ = 500 μm, HAZ = 1500 μm (visual delimitation), X500, nital*
***Slika 9** Linija stapanja i ZUT zavarnih uzoraka S355J2+N, CGHAZ = 500 μm, HAZ = 1500 μm (vizuelna razgraničenja), X500, nital*

In Figure 8 and Figure 9 is presented the microstructure near fusion line and in the weld. Just after the fusion line in the metal base, it can be observed large ferrite grains that have coalesced into a continuous network of ferrite grains, which constitute the CGHAZ. The visible HAZ has been considered the microstructure area, which presents visual modifications in respect to parent material microstructure, as, can be seen in the Figure 8 at smaller magnification.

The banded microstructure feature has been preserved in the HAZ, where at larger magnification can be observed predominantly granular bainite morphology.

The weldability is measured based on the hardness vector formula presented in the equation 9, which was applied for each measurement line, illustrated in the Figure 6. The obtained results are given in the Table 5. The average value for hardness vector VHV has been measured to 0.83 with a standard deviation of 0.009 which is in a good agreement with the calculated weldability number WN=0.88 obtained for an equivalent risk factor RF=0.196.

The weldability number WN was calculated with eq.(7) using the 5PL parameters given in the Table 2 for structural steels (N).

Na slikama 8 i 9 prikazana je mikrostruktura u blizini linije stapanja i u metalu šava. Neposredno uz liniju stapanja linije u osnovnom metalu, primećuju se velika feritna zrna koja su se spojila u kontinuiranu mrežu feritnih zrna, koja čine CGHAZ. Vidljiva ZUT se smatra površinom mikrostrukture, koja prikazuje vizuelne modifikacije u odnosu na mikrostrukturu osnovnog materijala, kao što se vidi na slici 8 pri manjim uvećanjima.

U ZUT-u je očuvana trakasta mikrostruktura, gde se kod većih uvećanja može primetiti pretežno granularna morfologija beinita.

Zavarljivost se meri na osnovu formule vektora tvrdoće predstavljene u jednačini 9, koja je primenjena za svaku mernu liniju, ilustrovanu na slici 6. Dobijeni rezultati su dati u tabeli 5. Prosečna vrednost vektora tvrdoće VHV je merena na 0,83 sa standardnim odstupanjem od 0,009, što je u dobroj saglasnosti sa izračunatim brojem zavarljivosti WN = 0,88 dobijenog za ekvivalentni faktor rizika RF = 0,196.

Broj zavarljivosti WN izračunat je prema jednačini (7) korišćenjem parametara 5PL datih u tabeli 2 za konstrukcione čelike (N).

5. Conclusion

1) The weldability number WN has been proposed as a new way for materials weldability assessment. The WN is measuring how much the deposited metal and HAZ properties have been negatively affected by the welding process, in respect with the parent material properties reference system.

2) The weldability model proposed can be applied for different steels grades based on a risk analysis, parent and filler materials properties, welding process and welding technology. Thus, we have a more accurate model that considers the effective welding conditions over the weldability. More important, we obtain a compared view over materials weldability in respect to major risk factors encountered in the welded structures fabrication.

3) The hardness vector VHV can be used for experimentally measurements of the materials weldability. The VHV depends on parent and filler material chemistry, but also on heat input, dilution and cooling rates.

4) The proposed weldability model can be improved and extended further by refining 5PL function parameters for others metallic materials. This can be accomplished by analysing large welding database, or existing WPS in large companies, being very useful in the Industry 4.0 implementation.

5. Zaključak

1) Broj zavarljivosti WN je predložen kao novi način za procenu zavarljivosti materijala. WN meri koliko na svojstva nanetog metala i ZUT negativno utiče proces zavarivanja, u odnosu na referentni sistem svojstava osnovnog materijala.

2) Predloženi model zavarivanja može se primeniti za različite vrste čelika na osnovu analize rizika, osobina osnovnog i dodatnog materijala, postupka i tehnologije zavarivanja. Dakle, imamo tačniji model koji uzima u obzir efektivne uslove zavarivanja. Što je još važnije, dobijamo upoređeni prikaz o zavarljivosti materijala u odnosu na glavne faktore rizika koji se javljaju pri izradi zavarenih konstrukcija.

3) Vektor tvrdoće VHV može se koristiti za eksperimentalno merenje zavarljivosti materijala. VHV zavisi od hemijskog sastava osnovnog i dodatnog materijala, ali i od količine toplote, stepena mešanja i hlađenja.

4) Predloženi model zavarivanja može se unaprediti i proširiti rafiniranjem parametara funkcije 5PL za druge metalne materijale. Ovo se može postići analizom velike baze za zavarivanje ili postojećih WPS u velikim kompanijama, što je veoma korisno u implementaciji industrije 4.0.

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