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Changes of microstructure and mechanical properties of the HAZ of the S960MC steel sheet weld joint

Promene mikrostrukture i mehaničkih svojstava u zoni uticaja toplote zavarenog spoja čeličnih traka klase S960MC

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Abstract

The TMCP (thermo-mechanically controlled processed) steels belong to the group of ultra-high strength steels, which exhibit exceptional combination of high tensile and yield strength, toughness and ductility. These steels were introduced in the heavy machinery constructions, such as heavy mobile cranes, chassis trucks and other to reduce their weight, what increases their loading capacity and ecology of transport. The high tensile and yield strength of this type of steels is obtained by the combination of the chemical composition, heat treatment and the mechanical processing. However, the heat input into the material during the welding significantly affect properties of the steel and the whole joint. In this paper are presented results of mechanical properties evaluation and structural analysis of the welds of the thin sheets made of the S960MC steel, which were welded using the GMAW procedure. The microstructural evaluation referred significant changes in the HAZ. This area contains the three sub-zones, coarse grain (CGHAZ), fine grain (FGHAZ) and intercritical zone (ICHAZ). Analysis of microhardness and the tensile tests results showed, that ICHAZ is the most critical area of the whole welded joint.

Rezime

Termomehanički kontrolisano valjani čelici pripadaju grupi čelika ultra visoke čvrstoće, koji pokazuju izuzetnu kombinaciju visoke zatezne čvrstoće, granice tečenja, žilavosti i duktilnosti. Ovi čelici su prvo počeli da se koriste u teškoj mašinogradnji, za pokretne kranove, šasije kamiona i drugih teških vozila, kako bi smanjili sopstvenu težinu, čime se povećava nosivost i ekološki standardi. Visoka zatezna čvrstoća i granica tečenja u ovim čelicima se postiže kombinacijom odabranog hemijskog sastava, termičke i plastične prerade. U ovakvim strukturama, unos toplote pri zavarivanju značajno utiče na svojstva čelika i zavarenog spoja. U ovom radu su prikazani rezultati ispitivanja mehaničkih osobina i mikrostrukture spojeva dobijenih zavarivanjem tankih ploča kvaliteta S960MC, primenom MAG postupka. Mikrostrukurna analiza ukazuje na značajne promene u ZUT. Ovu zonu čine tri podzone i to: grubozrna zona (CGHAZ), finozrna zona (FGHAZ) i interkritična zona (ICHAZ). Analizom mikrotvrdoće i zateznih ispitivanja utvrdjeno je da je interkritična zona kritično mesto celog spoja.

1. Introduction

Application of high-strength low-alloy (HSLA) steels is related to ensuring a higher strength of the structure and maintaining its weight or reducing it. At the same time, good processing properties are

1. Uvod

Upotreba niskolegiranih čelika visoke čvrstoće (HSLA) je okrenuta obezbedjenju strukture visoke čvrstoće uz zadržavanje ili redukciju težine. U isto vreme, moraju biti ispunjeni tehnološki zahtevi, pre required, mainly formability and weldability. Reducing the weight of transport vehicle leads to fuel savings and consequently lower emissions. Improvement of mechanical properties of steels can be achieved by chemical composition and manufacturing process. However, both factors have a significant impact on the resulting weldability of these materials. HSLA steels use new strength-enhancing methods based primarily on controlled cooling processes in rolling mills and microstructure management using micro-alloying of the steel. During the welding process, the material is heated very quickly following by fast cooling. This temperature cycle leads to a change of the microstructure and mechanical properties in the heat affected area (HAZ), mainly changes in structural phase composition, grain size, carbide dissolution, and so on. These changes consequently reflect in the mechanical properties, especially in hardness, ductility, toughness, yield and tensile strength. The greatest influence on these changes has the thermal input and the cooling time parameter $t_{8/5}$, which determines the resultant welded joint microstructure. The most critical area of the welding joint is, however, the heat affected area. The welding temperature cycle defines the sub-zones of HAZ. Depending on the distance from the heat source, there is a different thermal influence in each subzone. This leads to formation of different microstructures and mechanical properties of the particular area. HAZ can be divided into four main sub-zones. It is a coarse-grained heataffected zone (CGHAZ), a fine-grained heat-affected zone (FGHAZ), an inter-critical or partially transformed heataffected zone (ICHAZ) and a sub-critical or annealed zone (SCHAZ). The division of HAZ into individual sub-zones is shown in Figure 1. [1, 2, 8]. When high-strength steels are welded, the HAZ becomes “softer”. The term “softening of HAZ” is used for the subzone in HAZ, where the hardness is lower than the hardness of the base material. The microstructure of steels with tensile strength close to 900 MPa is usually composed of martensite or bainite, which is tempered under the transformation point A1 during production. Because during welding the material is exposed to temperatures above A_1, the HAZ microstructure will irreversibly change. In the following cooling of HAZ, it is not possible to achieve conditions as in the production of the base material [3, 5] causing softening mainly in the ICHAZ and SCHAZ sub-zones. Research has shown, that this sub-zone has lower mechanical properties and, as a consequence, fatigue crack initiate more rapidly in this area.

svega zavarljivost i sposobnost oblikovanja.

Smanjenje sopstvene težine na primer vozila, omogućava smanjenje potrošnje i emisije gasova. Poboljšanje mehaničkih osobina se može postići modifikacijom heijskog sastava i procesnih parametara u preradi. Sa druge strane, oba ova pristupa značajno utiču na zavarljivost.

U HSLA čelicima se čvrstoća povećava kombinacijom kontrolisanog hladjenja u valjaonici i prisustvom mikrolegirajućih elemenata u čeliku. U toku zavarivanja, materijal se prvo veoma brzo zagreva, a zatim i brzo hladi.

Ovaj termički ciklus dovodi do promena strukture, a time i mehaničkih osobina u ZUT, uglavnom usled faznih promena, promene veličin zrna, rastvaranja karbida i sl. Ove promene značajno utiču na mehaničke osobine, naročito tvrdoću, plastičnost, žilavost, granicu tečeenja i zateznu čvrstoću.

Najveći uticaj na ove promene imaju unos toplote i parametar $t_{8/5}$, odredjujući finalnu mikrostrukturu. Zato se zona uticaja toplote smatra kritičnim mestom u zavarenom spoju. Termički ciklus definiše podzone unutar ZUT-a.

U zavisnosti od rastojanja od izvora toplote, uticaj u svakoj od podzona je različit, što ima za posledicu nastanak različitih mikrostruktura i mehaničkih osobina u svakoj podzoni. ZUT se može podeliti u četiri glavne podzone: grubozrna zona uticaja toplote (CGHAZ), finozrna zona uticaja toplote (FGHAZ), interkritična zona uticaja toplote (ICHAZ) i podkritična zona uticaja toplote (SCHAZ). Podela ZUT na podzone je prikazana na slici 1 [1, 2, 8].

Zavarivanjem čelika visoke čvrstoće, ZUT omekšava. Termin „omekšavanja u ZUT-u“ se odnosi za podzonu u kojoj je tvrdoća smanjena u odnosu na tvrdoću osnovnog metala (OM).

Mikrostrukturu čelika čvrstoće preko 900MPa uobičajeno čini martenzit ili beinit, koji se u proizvodnji otpušta ispod temperature A_1.

Kako u toku zavarivanja temperatura u ZUT-u prelazi A_1 temperaturu, mikrostruktura će pretrpeti nepovratne promene.

Hladjenjem koje sledi, u ZUT nije moguće dobiti mikrostrukturu koja se dobija nakon proizvodnje [3,5], već dolazi do omekšavanja uglavnom u ICHAZ i SCHAZ podzonama.

Istraživanja su pokazala da ove podzone imaju niže mehaničke osobine, te se posledično u ovim područjima lakše inicira zamorna prslina.

It was also confirmed, that the width of the softened area is increasing due to the increasing heat input and the hardness decreases from the increasing cooling time $t_{8/5}$. [5].

Takodje je potvrdjeno da se širina omekšane zone povećava sa povećanjem unosa toplote i da tvrdoća opada sa produženjem vremena thadjenja $t_{8/5}$. [5].

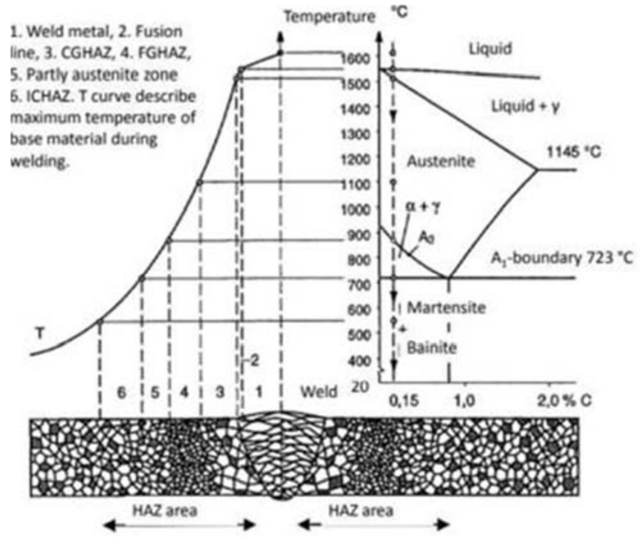

Figure 1. *Maximum temperature of material during welding and HAZ microstructure after welding of steel [2]*
Slika 1. *Maksimalna temperatura materijala tokom zavarivanja i mikrostrukture u ZUT posle zavarivanja čelika [2].*

The majority of the recent papers, regarding welding of the high strength steels (especially S960), investigate the effect of the processing parameters and technology on the resulting properties, but those studies mostly consider the quenched and tempered steels and sheets with thickness of 8 mm and greater. It is well known that the welding of the thin sheets can reveal some differences in the resulting properties of the welded joint when compared to the thick sheets [4, 6]. The aim of the research is to point out changes in the microstructure and mechanical properties of the butt welded joint, 3 mm thick S960MC steel, welded by the MAG method.

2. Experimental methods and materials

In this experiment, the S960MC steel was delivered according to EN 10149-2 standard [9]. The required chemical composition according to this standard and the chemical composition according to inspection certificate of investigated steel are shown in Table 1. The required mechanical properties according to EN 10149-2 standard and the mechanical properties according to inspection certificate of investigated steel are shown in Table 2. Sheets with dimensions of 150×300 mm and thickness of 3 mm were used for experimental welded joint. The weld was prepared as the square-groove butt welding joint and gap width was 1.5 mm. The welding was performed according to the proposed welding parameters listed in Table 3 with the MAG process.

Najveći deo savremenih saopštenja koji se odnose na zavarljivost čelika povišene čvrstoće (naročito S960), istražuje uticaj procesnih parametara i tehnologije zavarivanja na finalne osobine, uglavnom razmatrajući kaljene i otpuštene čelike u debljinama 8 mm i debljim. Poznato je da se pri zavarivanju tankih limova mogu pojaviti razlike u mehaničkim osobinama u odnosu na zavarene deblje limove [4,6]

Ciljovog rada je da ukaže na promene mikrostrukture i mehaničkih osobina sučeonih spojeva čelika S960 debljine 3 mm korišćenjem MAG postupka.

2. Eksperimentalni deo

U ovom radu je ispitan čelik S960 isporučen u skladu sa EN 10149-2 standardom [9]. U tabeli 1 su dati zahtevani hemijski sastav prema navedenom standardu i sastav ispitanog čelika. U tabeli 2 su date zahtevane mehaničke osobine prema navedenom standardu i mehaničke osobine ispitanog čelika.

Ploče dimenzija 150x300mm, debljine 3 mm su korišćene u eksperimentima zavarivanja. Ivice ploča su pripremljene u obliku I sučeonog spoja sa zazorom od 1,5 mm. Zavarivanje je izvedeno MAG postupkom, sa parametrima datim u tabeli 3.

The copper coated solid wire Carbofil 3NiMoCr (EN ISO 16834-A: G 89 5 M21 Mn4Ni2.,5CrMo) was used for welding. Chemical composition and mechanical properties of used welding wire are shown in Table 4. This wire belongs to the “undermatched” type of filler material, where yield strength of the weld metal is less than the yield strength of the base material.

Bakrom obložena žica Carbofil 3NiMoCr (EN ISO 16834-A G89 5 M21 Mn4Ni2,5CrMo) je korišćena za zavarivanje. Hemijski sastav i mehaničke osobine korišćene žice su date u tabeli 4. Ova žica pripada grupi dodatnih materijala niže čvrstoće (undermatched), kod kojih je tranica tečenja niža u odnosu na granicu tečenja osnovnog materijala.

Table 1. *Chemical composition of tested steel*
Tabela 1. *Hemijski sastav ispitanog čelika*

According to U skladu sa	Mechanical properties, thickness3mm Mehaničke osobine S960, debljina 3mm										
	C	Si	Mn	P	S	Al	Nb	V	Ti	Mo	B
EN10149-2*	0,120	0,60	2,20	0,025	0,010	0,015	0,09	0,20	0,250	1,000	0,005
Tested steel	0,087	0,18	1,11	0,009	0,001	0,0030	0,002	0,01	0,022	0,128	0,001
Maximum values of alloying elements except Al. Al_{tot} at a total is minimum value. The sum Nb+V+Ti max. 0,22% Maksimalni sadržaji legirajućih elemenata osim Al. Al_{tot} je minimalna vrednost. Zbir Nb+V+Ti maksimalno 0,22%											

Table 2. *Mechanical properties of tested steel*
Tabela 2. *Mechaničke osobine čelika*

According to U skladu sa	Mechanical properties, thickness 3 mm Mehaničke osobine S960, debljina 3 mm		
	$Rp_{0.2}$, MPa	Rm, MPa	A, %
EN10149-2*	Min. 960	980-1250	Min. 7
Tested steel Ispitani čelik	1031	1154	12
	1038	1147	11

Table 3. *Welding parameters*
Tabela 3. *Parametri zavarivanja*

Beads Prolaz	Weld Process Postupak	Filler Material Diameter, mm Dodatni materijal – poluprečnik, mm	Polarity Polaritet	Welding Current, A Struja zavarivanja, A	Welding Voltage, V Napon zavarivanja, V	Travel speed, cm/min Brzina zavarivanja, cm/min	Wire feeding rate, m/min Brzina dodavanja žice, m/min	Gas flow, l/min Protok gasa,l/min	Heat Input, kJ/cm Uneta toplota, kJ/cm
1	135	1	DC+	125-135	18-19	45-50	4,5	16	2,7
Schielding gas: M21, 82%Ar+18%CO, according to EN ISO 14175 standard [10] Zaštitni gas: M21, 82%Ar+18%CO, prema standardu EN ISO 14175 [10] Filler Material: G89 5 M21 Mn4Ni2,5CrMo according to EN ISO 16834-A standard [11] Dodatni materijal: G89 5 M21 Mn4Ni2,5CrMo prema standardu EN ISO 16834-A [11] Other parameters: without preheating, cooling on air, without Post Weld Heat Treatment Ostali parametri: bez predgrevanja, hladjenje na vazduhu, bez termičke obrade posle zavarivanja									

Table 4. *Chemical composition and mechanical properties of welding filler material*
Tabela 4. *Hemijski sastav i mehaničke osobine dodatnog materijala*

Designation of welding wire: Carbofil 3NiMoCr, manufacturer Oerlikon. Standard Designation of Welding Filler Material: EN ISO 16834-A G89 5 M21 Mn4Ni2,5CrMo Oznaka žice za zavarivanje: Carbofil 3NiMoCr, proizvodjač Oerlikon. Standardno označavanje dodatnog materijala za zavarivanje: EN ISO 16834-A G89 5 M21 Mn4Ni2,5CrMo													
Chemical composition of welding filler material, wt% Hemijski sastav dodatnog materijala, tež%													
	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Al	V	Ti	Zr
EN16834*	0,13	0,50 0,80	1,60 2,10	0,015	0,018	0,20 0,60	2,30 2,80	0,30 0,65	0,30	0,120	0,030	0,100	0,1000
Tested steel Ispitani čelik	0,11	0,66	1,77	0,009	0,007	0,41	2,43	0,46	0,17	0,007	0,007	0,069	0,0019
* The individual values in table are maximum values Pojedinačne vrednosti u tabeli su maksimalni sadržaji													
Mechanical properties of welding filler material, wt% / Mehaničke osobine dodatnog materijala, tež%													
EN16834*	Rp$_{0,2}$, MPa		≥ 890	R$_m$, MPa		940-1180		A, %	≥15	KCV, J		≥ 47/-50°C	
Tested steel Ispitani čelik			≥ 930			≥ 980			≥14			≥47/-50°C	

After the welding procedure, the specimens were cut in the transversal direction from the sheets at the minimal distance of 25 mm from the beginning of the welds. Three tests of weld joint were performed:

- macroscopis and mikroskopic evaluation,
- evaluation of microhardness,
- transverse tensile test.

The quality of the welding joint must be assessed objectively according to the further described criteria. For the evaluation of mechanical properties of the welded joint according to EN ISO 15614-1 standard [14] the following applies:

- the tensile strength of the welded joint must be equal to or above the minimum required tensile strength of the base material (Rm ZS ≥ 980 MPa),
- maximum welded joint hardness (for base material included in group 2.2 according to EN ISO 15608 standard [15]) shall be 380 HV without heat treatment after welding. For steels over R$_p$0,2 ≥ 890 MPa the critical value must be agreed.

In practice, the critical values are often reduced. For example for steel S960MC must be Rp0,2 ≥ 10MPa. The upper and lower limit is also prescribed for the hardness evaluation. For example, the hardness of welded joint of steel S960MC must be in range 260–450 HV (as welded).

3. Result and Discussion

3.1 Macrostructures and microstructures evaluation

The macro and microstructure evalution after the welding were characterized by the optical microscopy. Specimens were prepared by the standard procedure for preparation of metallographic specimens and etched by 1% Nital. The macrostructure of the welded joint (Figure 2) showed no cracks, pores and other internal defects.

Nakon zavarivanja, uzorci su isečeni u poprečnom pravcu, najmanje 25 mm od oba kraja spoja. Obavljene su tri vrste ispitivanja:

- odredjivanje makro i mikrostrukture
- merenje mikrotvrdoće
- poprečni test zatezanjem.

Kvalitet zavarenog spoja mora biti utvrdjen objektivno u skladu sa narednim kriterijumima. Za odredjivanje mehaničkih osobina zavarenog spoja u skladu sa EN ISO 15614-1 standardom [14] primenjuje se sledeće:

- granica tečenja zavarenog spoja mora biti jednaka ili viša od minimalno zahtevane granice tečenja osnovnog metala (Rm ZS ≥ 980MPa),
- maksimalna vrednost tvrdoće (za materijale koji spadaju u grupu 2.2 u skladu sa EN ISO 15608 standardom [15]) mora biti 380HV bez dodatne termičke obrade posle zavarivanja. Za čelike sa R$_p$0.2 ≥ 890MPa, kritična vrednost mora biti unapred usaglašena.

U praksi, kritične vrednosti su uobičajeno smanjene. Za merenje tvrdoće se takođe daje opseg najniže i najviše vrednosti. Na primer, tvrdoća u zavarenom spoju čelika S960MC mora biti u granicama 260-450 HV, u zavarenom stanju.

3. Rezultati i diskusija

3.1 Makrostruktura i mikrostruktura

Makrostruktura i mikrostruktura posle zavarivanja su posmatrane na svetlosnom mikroskopu. Uzorci su pripremljeni prema standardnoj proceduri za pripremu i nagriženi u nitalu 1%.

Reinforcement of the butt weld on the face and root side was within the limits of the standard. Transition of the weld metal into the base material was smooth with correct weld toe angle. The microstructure of the base metal is shown in the Figure 3a and consists of the mixture of tempered martensite and bainite. Microstructural observation shows significant changes in the HAZ of the examined weld. According to the microstructure observation throughout the HAZ, several structural different sub-zones were recorded. The phase transformations in the HAZ depend on the thermal exposure, to which individual parts of the HAZ were subjected and on the time of this thermal exposure. Closer to the weld metal and fusion zone, the area was exposed to higher temperatures, but also the cooling rate was higher. In the HAZ of the examined weld, the three main sub-zones were identified (naturally, transition areas were present between these clearly distinguished subzones). The similar behaviour was reported by authors [7, 13, 16, 17, 12]. In the direction from the weld metal to the base metal, the first observed zone was the coarse grain zone (CGHAZ) (Figure 3e). The CGHAZ is the area, which was heated high above the Ac_3 temperature, what resulted in the transformation of the base metal to austenite, which subsequently grew. Followed by the rapid cooling, the enlarged austenitic grains transformed back to coarse martensite. The second area in HAZ is the fine grain heat affected zone (FGHAZ) (Figure 3c). This area was heated slightly above the Ac_3 temperature, but for a very short holding time.

Makrostruktura zavarenog spoja, prikazana na slici 2, pokazuje da nema prisutnih pora, prslina ili drugih unutrašnjih grešaka. Nadvišenje spoja kako sa korene strane, tako i na licu je u okviru vrednosi dopuštenih standardom. Prelazak od metala šava u osnovni metal je bez diskontinuiteta sa pravilnim uglom nadvišenja. Mikrostruktura osnovnog metala je prikazana na slici 3a i sastoji se od beinita i otpuštenog martenzita. U ZUT-u se mogu videti brojne različite mikrostrukture i mogu se razdvojiti različite pod-zone. Fazne transformacije do kojih dolazi u ZUT-u zavise of temperature na koju je bio zagrejana svaka tačka u ZUT-u i vremena koje je provela na toj temperaturi. Što je tačka bliže liniji stapanja, područje je izloženo višoj temperaturi, ali je posledica i veća brzina hladjenja. U ZUT-u koji je ispitan u ovom radu su razdvojene tri glavne podzone (uz prelazna područja izmedju njih). Slično ponašanje je već saopštavano [7, 13, 16, 17,12].

U smeru od metala šava prema osnovnom metalu, prva zona koja se može uočiti je grubozrna zona (CGHAZ), slika 3e. Ovo je područje koje je zagrejano na temperature iznad A_3, čime je dobijen austenit u kome je došlo do porasta zrna. Pri brzom hladjenju, grubozrni austenit prelazi u martenzit koji takodje karakteriše veliko zrno.

Drugo područje u ZUT-u je finozrna zona (FGHAZ), slika 3c. Ovo je područje koje je bilo zagrejano neposredno iznad A_3 temperature i kratko boravilo na toj temperaturi.

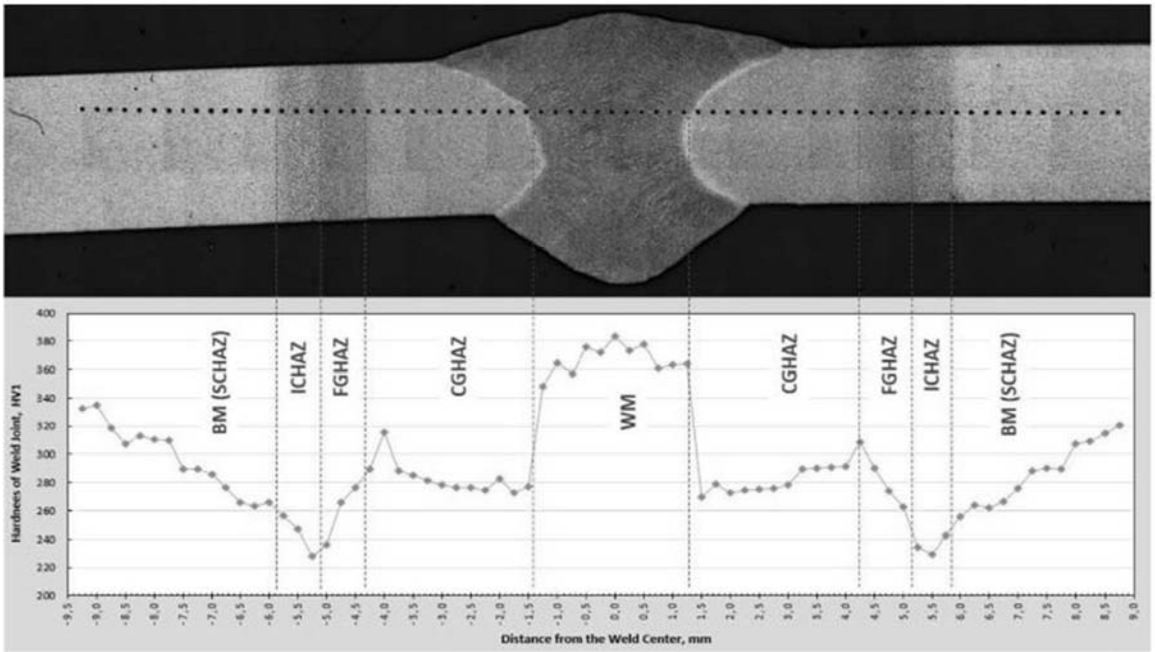

Figure 2. *Macrostructure of the S960MC welded joint and the microhardnes profile HV1 of sub-zones HAZ (BM – base material, WM – weld metal)*

Slika 2. *Makrostruktura zavarenig spoja čelika S960MC i raspodela mikrotvrdoće HV1 unutar podzona u ZUT (BM – osnovni metal, WM – metal šava)*

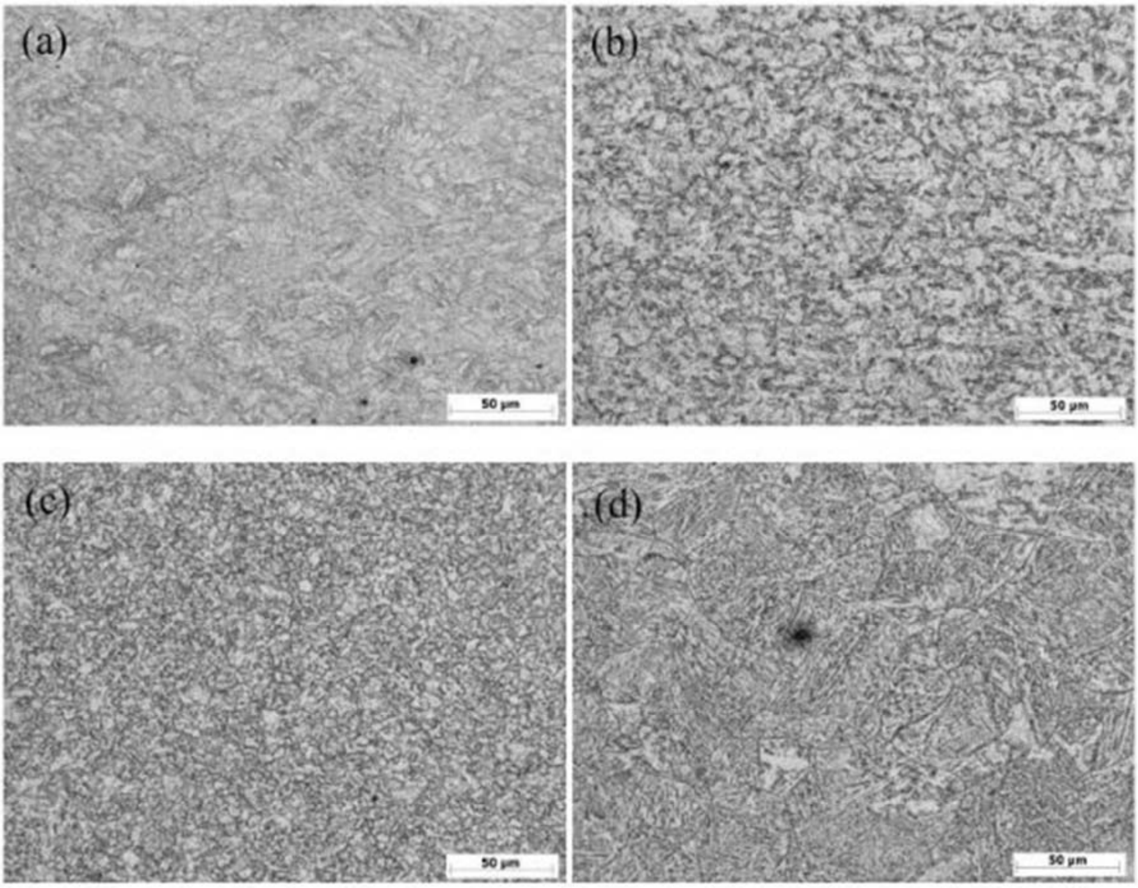

Figure 3. *Microstructure of the base material and sub-zones HAZ of the S960MC welded joint a) base material, b) ICHAZ, c) FGHAZ, d) CGHAZ*
Slika 3. *Mikrostruktura osnovnog metala i podzona ZUT-a u spoju čelika S960MC: (a) osnovni metal, (b) ICHAZ, (c) FGHAZ, (d) CGHAZ*

Exposure to heat in this zone caused the transformation of the base metal to austenite, but due to the relatively low temperature and very short duration of this exposure, followed by the rapid cooling, it resulted in the refinement of austenitic structure and its subsequent transformation to martensite. The last area of the HAZ is called the intercritical heat affected zone (ICHAZ) (Figure 3b). This area was exposed to temperatures in the range between Ac$_1$ and Ac$_3$ where the martensite is partially transformed to austenite. This exposure resulted in formation of the mixture of martensite and austenite, which transformed, after the rapid cooling, to martensite and ferrite, while the untransformed martensite was tempered. The resulting microstructure of this area is the mixture of martensite, ferrite and tempered martensite – similar to other studies [7, 16]. According to other authors, the ICHAZ is the weakest area in the welded quenched and tempered steels [18]. The width of the ICHAZ was approximately 750 μm. In addition, the base metal near the HAZ (SCCHAZ) was affected by the introduced heat, but heat exposure did not exceed the Ac1 temperature, so no phase transformation occurred, only a

Izlaganje toploti u ovoj zoni je dovelo do pojave austenita, ali zahvaljujući relativno niskoj temperaturi i kratkom vremenu izlaganja, austenitna zrna su smanjena. Brzo hladjenje ovakve strukture dovodi do pojave veoma finog martenzita. Poslednja oblast je sub zona interkritičnog ZUT-a (ICHAZ), slika 3b. Ova subzona je bila zagrejana u temperaturno područje izmedju A$_1$ i A$_3$ temperatura, tako da se polazni martenzit transformisao u mešavinu austenita i ferita. Brzim hladjenjem ove smeše se dobija martenzit i ferit, dok se deo martenzita koji nije prelazio u austenit dodatno se otpušta. Finalnu strukturu u ovom području čine martenzit, ferit i otpušteni martenzit, što je u saglasnosti sa rezultatima drugih autora [7, 16]. Prema nekim autorima ICHAZ je najslabije područje u kaljenim i otpuštenim čeliima [18]. Širina zone ICHAZ je procenjena na 750μm. Dodatno, osnovni metal u blizini ZUT (SCHAZ) je takodje zagrevan, ali zagrevanjem nije premašena temperatura A$_1$, tako da izostaju fazne transformacije, već samo otpuštanje martenzita, tempering of the martensite phase, which resulted in decrease of microhardness in that area.

3.2 Microhardness evaluation

Microhardness measurements were used for characterization of changes of the properties through the welds. The microhardness was measured in the line, from the base metal, through the HAZ, weld metal to the base metal on the other side. For all the microhardness measurements, the force F=9.8 N (HV1 method) was used, distance between indentation was 0,25 mm. The microhardness of the base material was 359 HV1 (average value with ten measurements in the center line). Microhardness profile (Figure 2) shows continual decrease of microhardness in the direction from the base metal to ICHAZ. This decrease is related to the tempering of martensite in the base metal structure. Decrease of strength related properties is common behavior for all the high strength steels (quenched tempered and TMCP steels), when they are heated in the range 450°C-Ac1 temperature, due to martensite tempering [19]. The lowest values of microhardness were obtained in the ICHAZ, where only 66% of the base metal hardness was recorded. The ICHAZs seems to be the most critical area. In FGHAZ, the microhardness started to increase and reached its maximum throughout the HAZ. In the area CGHAZ, a small decrease of microhardness was recorded in direction to the weld metal, what was related to the excessive grain growth in this zone. The Figure 4 shows detail of HAZ with the ICHAZ sub-zone and individual microhardness values, the minimum value 228HV1 is in ICHAZ. The average values of microhardnees of each HAZ sub-zone are shown in Table 5

što za posledicu ima sniženje tvrdoće u ovom području.

3.2 Mikrotvrdoća

Merenje mikrotvrdoće je korišćeno za praćenje promena osobina kroz ceo spoj. Mikrotvrdoćaje merena duž linije, od osnovnog metala, kroz ZUT, metal šava, sve do osnovnog metala sa suprotne strane. Korišćeno je opterećenje F=9,81N (HV1 method), sa korakom merenja 0,25mm. Mikrotvrdoća osnovnog metala je iznosula 359HV1 (srednja vrednost 10 merenja). Raspodela mikrotvrdoće je prikazana na slici 2, gde se vidi kontinuirano sniženje mikrotvrdoće, od osnovnog metala do ICHAZ. Ovo smanjenje je pripisano otpuštanju martenzita u osnovnom metalu. Smatra se da je smanjenje čvrstoće i sličnih osobina uobičajeno za sve čelike povišene čvrstoće (kaljene i otpuštene ili mikrolegirane) usled otpuštanja martenzita kada se zagrevaju u temperaturno područje 450°C-Ac1 [9]. Najmanje vrednosti mikrotvrdoće su zabeleženeu ICHAZ i bile su na nivou 66% mikrotvrdoće osnovnog metala. Zato ICHAZ izgleda kao najkritičnije područje. Prema finozrnoj podzoni ZUT, mikrotvrdoća se povećava i dostiže maksimalne vrednosti. Mikrotvrdoća u smeru ka metalu šava dalje blago opada, što se smatra posledicom porasta austenitnog zrna pre transformacije u grubozrnom ZUT-u (CGHAZ). Na slici 4 je prikazan deo ZUT koji pokriva interkritičnu podzonu (ICHAZ) i položaje merenja i vrednosti izmerene mikrotvrdoće, uključujuću minimalnu vrednost od 228HV1. Prosečne vrednosti tvrdoće u svakoj od podzona su date u tabeli 5.

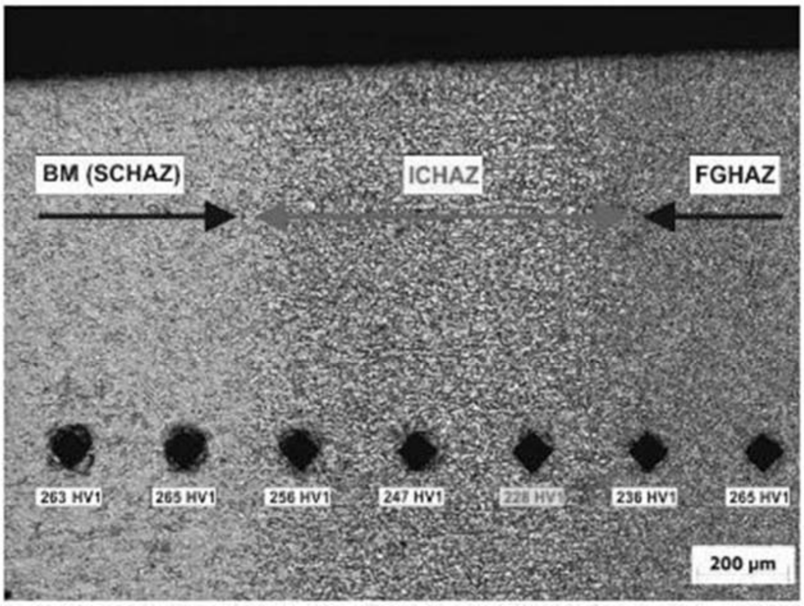

Figure 4. *Detail of HAZ with the ICHAZ sub-zone and individual microhardness values*
Slika 4. *Detalj untar ZUT-a sa ICHAZ subzonom. Date su pojedinačne vrednosti izmerene mikrotvrdoće*

Table 5. *Values of microhardness of the individual sub-zones in HAZ*
Tabela 5. *Vrednosti mikrotvrdoće u pojedinim pod-zonama u ZUT*

	Left of weld metal Levo od metala šava				Centre of weld Metal šava	Right of weld metal Desno od metala šava			
Sub zone of HAZ Podzone u ZUT-u	SCHAZ	ICSHZ	FGHAZ	CGHAZ	WM	CGHAZ	FGHAZ	ICSHAZ	SCHAZ
HV1	297	244	267	283	368	283	276	236	287

3.3 Tensile test

The tensile tests were carried out, according to EN ISO 6892-1 standard [20] to obtain the mechanical properties of the welded joint. Specimens for the tensile tests were prepared according to EN ISO 4136 standard [21]. The tensile test of the base material was made on two samples when the inspection certificate was issued. It achieves an average value of $R_{p0,2}$ = 1035MPa and R_m = 1151MPa. Results of the tensile tests of welded joint are shown in Table 6. The tensile tests show the significant reduction of the tensile strength and yield strength when compared to the original base material. The tensile strength was reduced to 85% of the base material value. The yield strength was reduced as well, and it reached 86% of the base material. Fracture of specimens, tested by the tensile tests, occurred approximately 6 mm from the weld center in all specimens, what corresponds to the microhardness measurements and appearance of the most softened zone in that area. Thus, it can be said that the fracture occurs in the narrow area of the ICHAZ. The Figure 5a shows the fracture profile and Figure 5b macro fracture surface of one part of the test specimen.

3.3 Ispitivanje zatezanjem

Testovi zatezanjem su izvedeni u skladu sa standardom EN ISO 6892-1 [20], kako bi se odredile mehničke osobine zavarenog spoja. Uzorci za ispitivanje su bili pripremljeni u skladu sa standardom EN ISO4136 [21]. U cilju provere, dva uzorka osnovnog materijala su ispitana. Dobijene su prosečne vrednosti od $R_{P0.2}$=1035MPa i R_m=1151MPa. Rezultati zateznih ispitivanja su dati u tabeli 6.

Rezultati ukazuju na značajno smanjenje zatezne čvrstoće i granice tečenja zavarenog spoja u odnosu na osnovni metal. Zatezna čvrstoća je snižena na 86% vrednosti zatezne čvrstoće osnovnog materijala. Granica tećenja je takodje snižena na 86% vrednosti granice tečenja osnovnog materijala. Mesto loma se nalazi na približno 6 mm od srednje ose spoja, što odgovara izmerenoj tvrdoći i prisustvu najmekše zone. Zato je zaključeno da je do loma došlo u interkritičnoj zoni ZUT (ICHAZ). Na slici 5a je prikazan profil preloma, a na slici 5b je prikazana makro površina preloma zatezne epruvete.

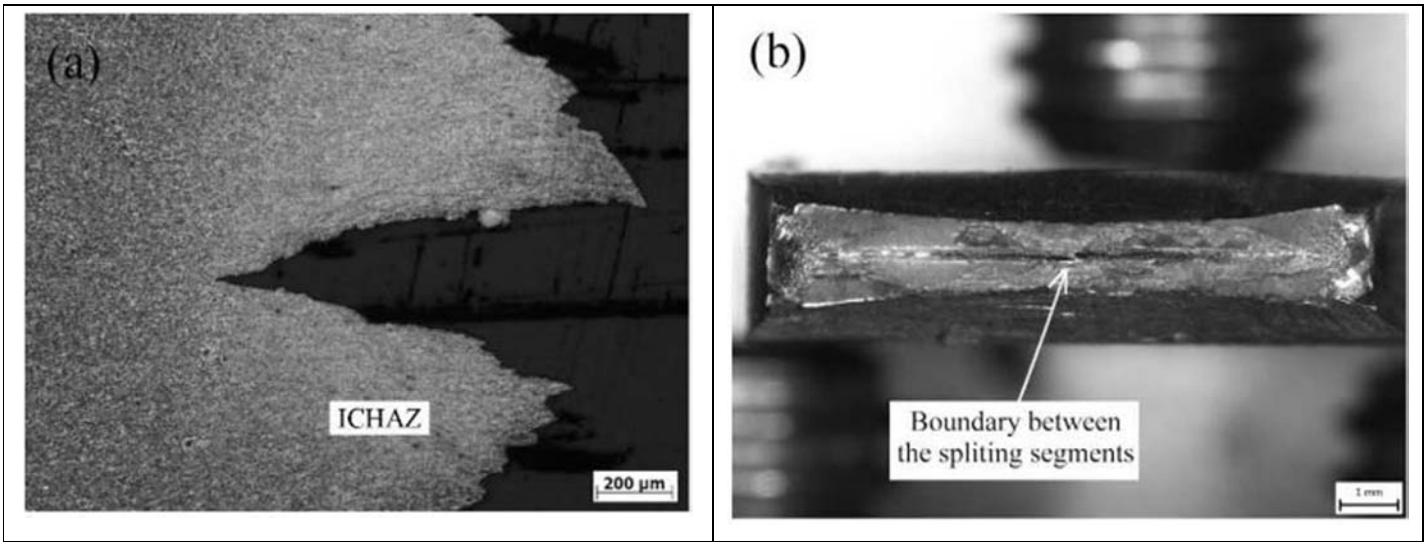

Figure 5. *Fracture profile (a) and macro fracture surface (b) of tensile test specimen after rupture*
Slika 5. *Prelom na epruveti nakon testa zatezanjem:(a) poprečna ravan preloma, (b) makro površina preloma*

The fracture is located in the ICHAZ area. This phenomenon is a result of changes in the ICHAZ microstructure, where the softening occurs in the narrow areas. Specimen splits into two segments, with the boundary between the segments coinciding with the mid-thickness position within the plate. Authors [7] speculated that this splitting is due to the specific rolling and fabrication process for the plate, which can lead to variation in the chemical composition in the through-thickness direction. As plastic deformation accumulates, a crack may first develop parallel to the rolling direction before creating the final fracture.

Lom se nalazi u ICHAZ podzoni. Ovaj fenomen je posledica promena u strukturi u ICHAZ, pošto dolazi do omekšavanja u uskoj podzoni. Uzorak se razdvaja na dva dela, praktično duž srednje linije. Ovo ponašanje je dovedeno u vezu sa tehnologijom valjanja i procesa izrade limova, koji mogu dovesti do lokalnih segregacija / varijacije hemijskog sastava po debljini ploče [7]. Usled akumulacije deformacije u toku valjanja, prskotina se može prvo javiti pralelno pravcu valjanja, pre završnog loma.

Table 6. *Mechanical properties of welded joint*
Tabela 6. *Mehaničke osobine zavarenog spoja*

Sample Uzorak	Mechanical properties Mehaničke osobine			Place of fracture Mesto loma
	$R_{p0.2}$, MPa	R_m, MPa	A, %	
1-1	794	826	5	Out of the weld Van zavarenog spoja
1-2	836	858	3	Out of the weld Van zavarenog spoja
Average value Prosečna vrednost	815	842	4	

4. Conclusions

Based on the metallographic examination and mechanical tests of the welded joints of steel S960MC the following conclusions can be formulated:

- The S960MC steels sheets of 3 mm thickness were successfully welded with the G 89 5 M21 Mn4Ni2.5CrMo filler metal without appearance of any cracks and weld imperfections.
- The microstructure observations revealed a few different zones in the HAZ. The sub-zones CGHAZ, FGHAZ, ICHAZ, SCHAZ are clearly identified.
- The microhardness measurement shows that the ICHAZ is the weakest area of the whole joint, with microhardness of only 66 % of the base material hardness.
- The hardness of the base material (at zone SCHAZ), still at 9 mm from the weld centre, does not reaches its primary value.
- The weld metal has approximately the same hardness (368 HV1) as the base material (359 HV1).
- The tensile tests show the significant reduction of mechanical properties. According to EN 10149-2 the tensile strength reached 85% of the base metal, yield strength reached 86% and elongation less than 65% of the base metal values. According to Inspection certificate the tensile strength reached 79% of the base metal, yield strength reached 73% and elongation less than 33% of the base metal values.

4. Zaključci

Na osnovu metlografske analize i ispitivanja mehaničkih osobina, mogu se formulisati sledeći zaključci:

- Limovi debljine 3 mm čelika S960 su uspešno zavareni korišćenjem G89 5 M21 Mn4Ni2,5CrMo dodatnog materijala, bez pojave prslina ili drugih zavarivačkih grešaka.
- Metalografsko ispitivanje je pokazalo nekoliko različitih jasno definisanih podzona u ZUT i to CGHAZ, FGHAZ, ICHAZ i SCHAZ.
- Merenje mikrotvrdoće je ukazalo da je najniža mikrotvrdoća u celom spoju u ICHAZ subzoni i to na nivou 66% mikrotvrdoće osnovnog metala.
- Tvrdoća izmerena u SCHAZ zoni, na 9 mm od centra spoja je još uvek niža od vrednosti osnovnog metala.
- Metal šava ima približno istu vrednost mikrotvrdoće (368 HV1) kao i osnovni metal (359 HV1).
- Rezultati zateznih ispitivanja ukazuju na značajno smanjenje mehaničkih osobina. U skladu sa standardom EN 10149-2, zatezna čvrstoća dostiže 85%, granica tečenja 86% a izduženje je manje od 65% vrednosti osnovnog metala. Prema izveštaju o ispitivanju zatezna čvrstoća je dostigla 79%, granica tečenja 73%, a istezanje manje od 33% vrednosti osnovnog materijala.

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References

[1] SSAB. 2019. A Stronger, Lighter, and More Sustainable World. [Online] 2019. [Datum: 10. Januar 2019.] https://www.ssab.com/.

[2] T. Pirinen, PhD. thesis, The Effects of Welding Heat Input on the Usability of High Strength steels in welded structures, Lappeenranta University of Technology, Lappeenranta, Finland (2013).

[3] Hochhauser, F., Ernst, W., Rauch, R. et al. Weld World, 56 (5– 6), 56-77 (2012)

[4] M. Jambor, R. Ulewicz, F. Nový, O. Bokůvka, L. Trško, M. Mičian, D. Harmaniak, Evolution of Microstructure in the Heat Affected Zone of S960MC GMAW Weld, Terotechnology 2017, Materials Research Proceedings, 5, 78-83 (2018)

[5] Lundin, C. D., Gill, T. P. S. a Qiao, C. Y. 1990. Heat affected zones in low carbon microalloyed steels. Recent trends in Welding Science and Technology Proceedings, 2nd International Conference, Gatlinburg (1990)

[6] Jambor, M., Novy, F., Mician, M., Trsko, L., Bokuvka, O., Pastorek, F., Harmaniak, D., Communications - Scientific Letters of the University of Zilina, 20 (4), 29-35, (2018)

[7] W. Guo et al., Materials and Design, 85, 534–548 (2015)

[8] J. Moravec, P. Rohan, METAL 2011: 20th Anniversary International Conference on Metallurgy and Materials, 803808 (2011)

[9] EN 10149-2 Hot rolled flat products made of high yield strength steels for cold forming - Part 2: Technical delivery conditions for thermomechanically rolled steels

[10] EN ISO 14175 Welding consumables. Gases and gas mixtures for fusion welding and allied processes

[11] EN ISO 16834-A Welding consumables - Wire electrodes, wires, rods and deposits for gas shielded arc welding of high strength steels - Classification

[12] T. Pała, I. Dzioba, Arch. Metall. Mater. 62 (4), 2081-2087 (2017)

[13] S. Błacha, M.S. Węglowski, S. Dymek, M. Kopyściański, Arch. Metall. Mater. 62 (2), 627-634 (2017)

[14] STN EN ISO 15614-1 Specification and qualification of welding procedures for metallic materials - Welding procedure test - Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys

[15] TNI CEN ISO/TR 15608 Welding - Guidelines for a metallic materials grouping system

[16] Guo, W., Li, L., Dong, S., Crowther, D., Thompson, A., Optics and Lasers in Engineering, 91, 1-15 (2017).

[17] Nowacki, J., Sajek, A., Matkowski, P., Archives of Civil and Mechanical Engineering, 16, 777-783 (2016)

[18] Sharma, V., Shahi, A. S., Journal of Materials Processing Technology, 253, 2-16, (2018)

[19] Gaspar, M., Balogh, A., Production Processes and Systems, 6, 9-24 (2013)

[20] EN ISO 6892-1 Metallic materials - Tensile testing - Part 1: Method of test at room temperature

[21] EN ISO 4136 Destructive tests on welds in metallic materials - Transverse tensile test