*J. Słania*, R. Krawczyk*, D. Masłoń***

# TECHNOLOGY OF WELDING JOINTS MIXED WITH DUPLEX STEEL

# TEHNOLOGIJA ZAVARIVANJA SPOJEVA MEŠANIH SA DUPLEKS ČELIKOM

**Originalni naučni rad / Original scientific paper**
**UDK / UDC: 669.14.018.8:620.193.4 ; 669.14.018.8:621.791.05**
**Rad primljen / Paper received:**
Avgust 2017.

**Adresa autora / Author's address:**
** Czestochowa Univers ity of Technology, 69 J.H. Dąbrowsk iego Str., 42-200 Częstochowa, Poland*
*** Fabryka Aparatur y i Urządzeń „FA MET " SA, 102C Oświęcimsk a Str., Opole, Poland*
*Corresponding author: jacek_slania@poczta.onet.p*

***Prevod izvornog rada na srpski jezik: Milica Antić,dipl.ing***

***Rad je u izvornom obliku objavljen u*** Arch. Metall. Mater., Vol. 61 (2016), No 1, p. 159–168DOI: 10.1515/amm-2016-0029

**Ključne reči:** zavarivanje, dupleks čelici, mešani spojevi

**Key words:** welding, duplex steel, mixed joints

Results of the examinations of sample plates of mixed joints with the duplex steel were discussed. Examinations were taken on the sample plates of mixed joints of sheet plates type P355NL1 and X2CrNiMoN22-5-3 welded by the flux-cored wire DW-329A by the Kobelco company of the following category T 22 9 3 NL RC/M3 in the gas shroud M21 (Ar+18%CO2) (plate no.1), and nickel covered electrodes E Ni 6082 by the Böhler company (plate no. 2). Results of the side bend test of welded joint, transverse tensile test, stretching of the weld metal, impact strength, micro and macroscopic metallographic examinations, and measurements of the delta ferrite content were presented.

Diskutovano je o rezultatima ispitivanja uzoraka ploča mešanih spojeva sa dupleks čelikom. Ispitivanja su sprovedena na pločastim uzorcima mešanih spojeva od limova tipa P355NL1 i X2CrNiMoN22-5-3 zavarenih punjenom žicom DV-329A kompanije Kobelco iz sledeće kategorije T 22 9 3 NL RC / M3 u zaštiti gasne mešavine M21 (Ar + 18% CO2) (ploča br. 1) i obloženom elektrodom od nikla E Ni 6082 kompanije Bohler (ploča broj 2). Prikazani su rezultati ispitivanja bočnog savijanja zavarenog spoja, poprečnog zatezanja, istezanja metala šava, udarne žilavosti, mikro i makroskopskih metalografskih pregleda i merenja sadržaja delta ferita.

## 1. Introduction

Duplex steel owes its two-phase structure a set of mechanical properties connected with ductility and plasticity as well as a high resistance to different types of corrosion. Thismaterial allows to obtain advantages from joining austenite and ferrite phases. Carefully chosen chemical composition guarantees better properties to much more expensive highalloyed austenite steel [1-7].

Presented examinations in the article were taken on the sample plates of mixed joints of sheet metal type P355NL1 and X2CrNiMoN22-5-3 welded by the flux-cored wire DW-329A produced by the Kobelco company of a following category T 22 9 3 NL RC/M3 in the gas shroud M21 (Ar+18%CO2) (plate no. 1), and nickel coated electrodes E Ni 6082 by the Böhler company (plate no. 2).

Above experiment was done to prove the properties of a joint made by the filler material of a duplex steel structure, and a high-nickel material, as well as specifying an influence of a thermal treatment on the changes of the duplex steel structure

## 1. Uvod

Dupleks čelik zahvaljujući svojoj dvofaznoj strukturi ima podešenost mehaničkih osobina vezanih za duktilnost i plastičnost, kao i visoku otpornost na različite vrste korozije. Ovaj materijal omogućava dobijanje prednosti spajanja austenitnih i feritnih faza. Pažljivo odabrani hemijski sastav garantuje bolje osobine od mnogo skupljih visoko-legiranih austenitnih čelika [1-7]. Predstavljena ispitivaja u članku su uzeti sa pločastih uzoraka mešanih spojeva od limova tipa P355NL1 i X2CrNiMoN22-5-3 zavarenih punjenom žicom DV-329A kompanije Kobelco sledeće kategorije T 22 9 3 NL RC / M3 u mešavini gasova M21 (Ar + 18% CO2) (ploča broj 1) i niklenom obloženom elektrodom E Ni 6082 kompanije Bohler (ploča broj 2).

Gore pomenuti eksperiment je izveden radi dokazivanja osobina spoja sa dodatnim materijalom strukture dupleks čelika i materijala sa visokim sadržajem nikla, kao i utvrdivanje uticaja termičkog tretmana na promene strukture dupleks čelika.

## 2. Properties, chemical composition of materials. Schaeffler's diagram

Differences of properties between P355NL1 steel, and corrosion resistant X2CrNiMoN22-5-3 duplex steel are givn in Table 1.

## 2. Osobine, hemijski sastav materijala, Šeflerov dijagram

Razlike osobina između čelika P355NL1 i korziono otpornog čelika X2CrNiMoN22-5-3.date su u tabeli 1.

| Type | | Re, MPa | Rm, MPa | A, % | HB | KV, J (-40°C) |
|---|---|---|---|---|---|---|
| P355NL1 | Min | 395 | 533 | 32.5 | 175 | 101 |
| | Max | 400 | 552 | 33.0 | 183 | 114 |
| X2CrNiMo N22-5-3 | Min | 470 | 739 | 31.6 | 223 | 229 |
| | Max | 472 | 747 | 34.9 | 223 | 240 |

***Table 1.*** *Comparison of mechanical properties of P355NL 1 steel and X2CrNiMoN22-5-3 steel [14]*
***Tabela 1.*** *Upoređenje mehaničkih osobina čelika P355NL i X2CrNiMoN22-5-3[14]*

On the base of a chemical composition of both metal sheets and used filler materials, expected structures of the welds' materials made during processes were specified. The Schaeffler's diagram was used to illustrate it. (Fig. 1)

Na bazi hemijskog sastava obe metalne ploče i korišćenih dodatnih materijala, određene su očekivane strukture materijala zavarenih spojeva napravljenih tokom procesa  Dijagram Schaeffler-a je korišćen za ilustraciju. (sl. 1).

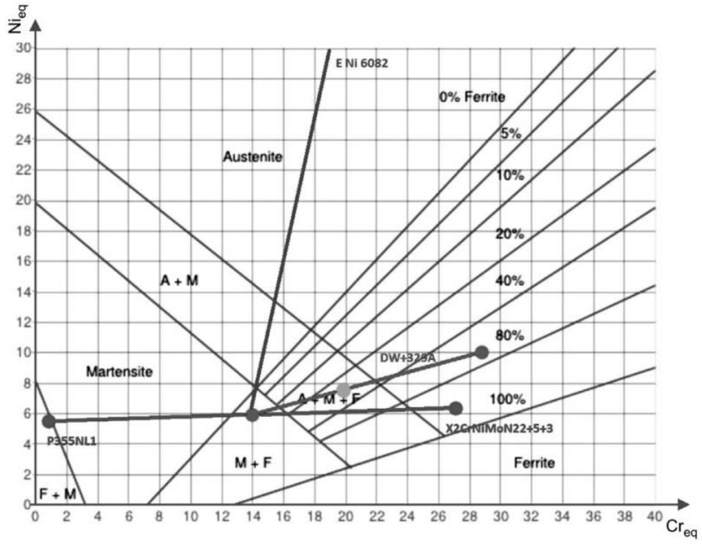



***Fig. 1*** *The Schaeffler's diagram [17]*
***Sl. 1*** *Dijagram Schaeffler-a [17]*

After calculating an equivalent of chromium and nickel (formula 1, 2) and applying the results to the diagram, following data was obtained:
an austenite-ferrite-martensite mixed structure with an approximate value of ferrite 10% by using a flux-cored duplex wire.
a diagram does not cover in its range material of such high content of nickel (clearly shows a plain austenite structure) by using nickel covered electrodes

Nakon izračunavanja ekvivalenta hroma i nikla (formula 1, 2) i primene rezultata na dijagramu, dobijeni su sledeći podaci:
mešovita struktura austenit-ferit-martenzit sa približnom vrednošću ferita od 10% primenom dupleks punjene žice
dijagram ne pokriva u njegovom opsegu materijale sa tako visokim sadržajem nikla (jasno pokazuje jednostavnu strukturu austenita) korišćenjem niklovih obloženih elektroda

$$Creq = Cr+Mo+1,5Si+0,5Nb \quad (1)$$

$$Nieq = Ni+30C+0,5Mn \quad (2)$$

| C | Si | Mn | P | S | Cr | Ni | Mo | N | Co |
|---|---|---|---|---|---|---|---|---|---|
| 0.026 | 0.45 | 1.42 | 0.029 | 0.001 | 22.26 | 5.11 | 3.12 | 0.1690 | 0.07 |

***Table 2** Chemical composition of X2CrNiMoN22-5-3 metal sheet [14]*
***Tabela 2.** Hemijski sastav ploče od čelika X2CrNiMoN22-5-3[14]*

| C | Si | Mn | P | S | Al | Cr | Ni | Mo | Cu |
|---|---|---|---|---|---|---|---|---|---|
| 0.170 | 0.380 | 1.190 | 0.007 | 0.0029 | 0.033 | 0.180 | 0.014 | 0.004 | 0.160 |
| **V** | **Nb** | **Ti** | **B** | **N** | | | | | |
| 0.006 | 0.008 | 0.013 | 0.0003 | 0.0068 | | | | | |

***Table 3.** Chemical composition of P355NL 1 metal sheet [4]*
***Tabela 3.**Hemijski sastav ploče od čelika P355NL 1[4]*

| C | Si | Mn | P | S | Cu | Ni | Cr | Mo | N |
|---|---|---|---|---|---|---|---|---|---|
| 0.025 | 0.74 | 0.93 | 0.015 | 0.002 | 0.08 | 9.23 | 23.21 | 3.38 | 0.16 |

***Table 4.** Chemical composition of the flux-cored wire DW-329A – Kobelco [12]*
***Tabela 4.** Hemijski sastav punjene žice DW-329A – Kobelco [12]*

| C | Si | Mn | P | S | Nb | Cr | Ni | Mo | Cu |
|---|---|---|---|---|---|---|---|---|---|
| 0.024 | 0.40 | 5.16 | 0.006 | 0.005 | 2.22 | 18.83 | 69.70 | 1.0 | 0.02 |
| Ti | Fe | | | | | | | | |
| 0.081 | 2.70 | | | | | | | | |

***Table 5.** Chemical composition of the ThermanitNicro 82 coated electrode– Böhler [3]*
***Tabela 5.** Hemijski sastav obložene elektrode ThermanitNicro 82 – Böhler [3]*

It is necessary to point that the Schaeffler's diagram relates to the constant cooling conditions of the weld, thus a real result may considerably differ. Above differences result from the dynamics of a welding process, and particularly an influence of heat which is difficult to predict, and the foremost conditions of cooling the weld [8-11].

## 3. Technology of welding

Welding sample plates was made in the downhand position PA. An initial preheating was not applied, instead, an interpass temperature was kept on the level not higher than 150°C.
An order of applying beads is presented in the picture 2, while the real parameters obtained during the process of welding are included in the table 6.

Neophodno je ukazati na to da se dijagram Schaeffler-a odnosi na konstantne uslove hlađenja šava, tako da se pravi rezultat može znatno razlikovati. Gore pomenute razlike su rezultat dinamike procesa zavarivanja, a posebno uticaja toplote što se teško predviđa, kao i najvažniji uslovi za hlađenje šava [8-11].

## 3. Tehnologija zavarivanja

Ploče za uzorke za zavarivanje izrađene su u položaju PA. Početno predgrevanje nije primenjeno, umesto toga, međuslojna temperatura je održavana na nivou koji nije veći od 150°C.
Na slici 2 je prikazan redosled nanošenja zavara, dok su stvarni parametri dobijeni tokom procesa zavarivanja dati u tabeli 6.

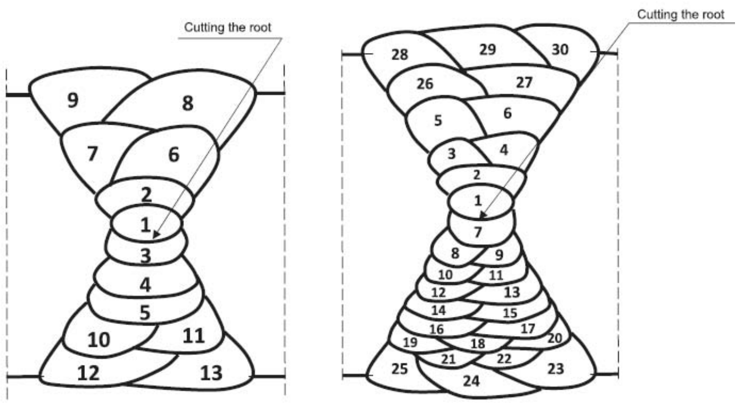



***Fig. 2.** An order of applying beads*
***Sl. 2.** Redosled polaganja zavara*

Used parameters allowed to obtain a proper amount of inserted heat (linear energy ranges from 0,3 to 1,7 kJ/mm),does not exceed recommended values (maximum value of a linear energy is 2,5 kJ/mm).

Korišćeni parametri dozvoljavaju postizanje odgovarajuće količine unete toplote (linearna energija se kreće od 0,3 do 1,7 kJ/mm), ne prelazi preporučene vrednosti (maksimalna vrednost linearne energije 2,5 kJ/mm).

| PLATE NO. 1 | | | | PLATE NO. 2 | | | |
|---|---|---|---|---|---|---|---|
| No. of bead | Current intensity A | Voltage V | Speed of welding cm/min | No. of bead | Current intensity A | Voltage V | Speed of welding cm/min |
| 1 | 215 | 30.7 | 32.7 | 1 | 91 - 94 | 23.5 – 26.0 | 11,1 |
| 2 - 7 | 235 - 270 | 31.2 – 32.3 | 21.8 – 40.0 | 2 - 7 | 109 - 120 | 23.2 – 27.0 | 14,2 |
| 8 - 9 | 240 - 275 | 32.3 | 24.9 – 29.1 | 8 - 18 | 119 - 131 | 21.5 – 27.3 | 20,0 |
| 10 – 11 | 230 - 275 | 32.3 | 33.8 – 46.2 | 19 - 20 | 112 - 115 | 22.5 – 24.5 | 24,0 |
| 12 - 13 | 250 - 280 | 32.3 | 32.7 – 33.6 | 20 - 26 | 109 - 125 | 23.0 – 26.5 | 21,4 |
| Linear energyofwelding. kJ/cm | | | 7.7 – 17-2 | Linear energyofwelding. kJ/cm | | | 2,8 – 12,3 |

***Table 6.*** *Real parameters obtained during a welding process*
***Tabela 6.*** *Realni parametri postignuti tokom procesa zavarivanja*
*Legenda: plate No- lim br. ; No of bead-broj zavara; current intensity-jačina struje; voltage-napon; speed of welding-brzina zavarivanja; linear energy oof welding-linijska energija pri zavarivanju*

## 4. Thermal treatment after welding

After welding a thermal treatment – stress relief annealing was applied (table 7) in order to delete welding stress. Then, non-destructive and destructive testing were done, and their results are presented later in the article.

## 4. Termička obrada posle zavarivanja

Termička obrada posle zavarivanja - žarenje za smanjenje napona (tabela 7) je primenjena kako bi se uklonili naponi nastali zavarivanjem. Zatim su obavljena ispitivanja bez i sa rzaranjem, a rezultati su predstavljeni kasnije u članku.

| **Type of treatment Vrsta obrade** | Stress relief annealing Žarenje za smanjenje napona | | |
|---|---|---|---|
| Material Materijal | P355NL1 + X2CrNiMoN22-5-3 | | |
| No. Br. | Actions Aktivnosti | Value Vrednost | [unit] jedinica |
| 1 | Place in the furnace in the maximum temperature Staviti u peć na maksimalnoj temperaturi | 300 | [°C] |
| 2 | Heat gradually to the temperature Postepeno zagrevanje na temperaturu | 570-590 | [°C] |
| 3 | Maximum speed of heating Maksimalna brzina zagrevanja | 100 | [°C/hour.] [°C/h] |
| 4 | Time of annealing Vreme žarenja | 30 | [min] |
| 5 | Cool in the furnace up to the temperature Hladiti u peći do temperature | 350 | [°C] |
| 6 | Maximum speed of cooling Maksimalna brzina hlađenja | 100 | [°C/hour.] [°C/h] |
| 7 | Afterwards, cool in the mild air Nakon toga, hlađenje na mirnom vazduhu | Yes da | - |

***Table 7.*** *Parameters of a thermal treatment after welding*
***Tabela 7.*** *Parametri termičke obrade posle zavarivanja*

## 5. Non-destructive testing.

### VT – visual testing

The first non-destructive testing, including 100% of the length of the examined welded joint is a visual testing, which is done according to the PN-EN ISO 17637 standard. During examination there were not any of disqualifying discrepancies specified in the PN-EN ISO 5817 standard.

## 5. Isptivanje bez razaranja

### VT-vizuelna kontrola

Prvo ispitivanje bez razaranja koje se obavlja, obuhvata 100% dužine ispitanog zavarenog spoja, predstavlja vizuelna kontrola, koja se vrši prema standardu PN-EN ISO 17637. Tokom ispitivanja nije bilo nijednog nedozvoljenog odstupanja od navedenih u standardu PN-EN ISO 5817.

**PT – penetration testing**
There was a penetration testing done according to the EN ISO 571-1 standard after visual testing. Mr. Chemie GMBH products were used. Examination included 100% of the welded joint, there were not any discrepancies.

**RT – radiographic testing**
The only volume examination which was taken was a radiographic testing according to the PN-ENISO 1435 standard. The whole area of the joint during examination together with the base material was taken into account, except 20 mm scraps on both sides.SMART 300HP ANDREX lamp was used, as well as X-ray film IX100 by the Fuji Film
Radiographic images did not reveal any welding discrepancies.

**6. Collecting and preparing samples to destructive testing.**
A way of collecting samples according to the PN-EN ISO 15614-1 is depicted in the picture 3.

**PT-ispitivanje penetrantima**
Nakon vizuelne kontrole obavljeno je ispitivanje penetrantima prema standardu EN ISO 571-1. Korišćeni su proizvodi kompanije Chemie GmbH. Ispitivanjem je obuhvaćeno 100% zavarenog spoja i nije bilo nikakvih odstupanja.

**RT-radiograafsko ispitivanje**
Jedino zapreminsko ispitivanje koje je izvršeno je radiografsko ispitivanje prema standardu PN-EN ISO 1435. Obuhvaćena je čitava površina spoja zajedno sa osnovnim materijalom, izuzev 20 mm otpatka sa obe strane. Korišćen je uređaj SMART 300HP ANDREKS, kao i rendgenski IKS100 film Fuji.
Radiografske slike nisu pokazale odstupanja u zavarivanju.

**6. Prikupljanje i priprema uzoraka za ispitivanje sa razaranjem**
Način grupisanja uzoraka prema PN-EN ISO 15614-1 prikazan je na slici 3.

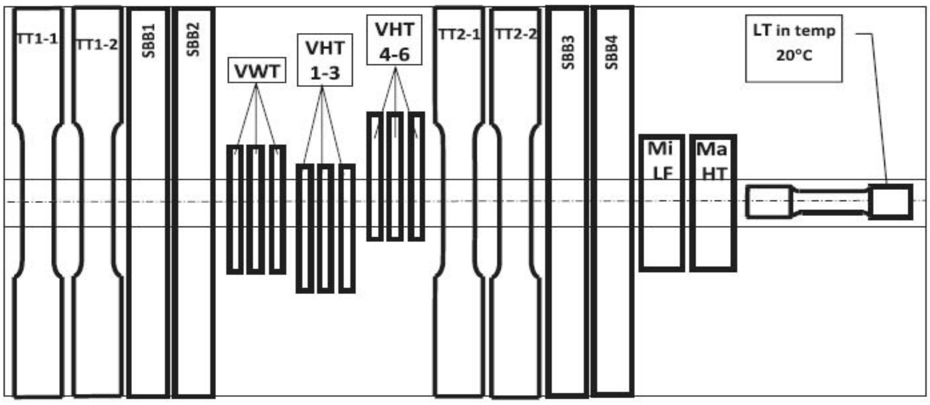



***Fig. 3.*** *Places of collecting samples from the sample plates. TT– tension-torsion, SBB – surface band bending, Mi – micro, Ma – macro, VWT, VHT – notch impact value, HT – hardness testing, LF – ferrite number , LT – tension of weld metal [15,22]*

***Sl. 3.*** *Mesta za grupisanje epruveta iz uzoraka ploča. TT-zatezanje-uvijanje, SBB- savijanje preko površine, Mi-mikro, Ma-makro, VWT, VHT- vrednost udarne žilavosti, HT- ispitivanje tvrdoće, LF- feritni broj, LT-zatezanje metala šava*

Whereas the methods of preparation, a scheme of taken examinations, and their results are presented underneath. All the examinations were taken in exactly the same conditions in case of both sample plates.

**7. Side bend test**

The test was done according to the PN-EN ISO 5173 standard on four lateral samples (fig. 4). A bending mandrel of 40 mm diameter was used. A traditional machine ZD40 used to stretch of a maximum power 400 kN was used [28].

Metode pripreme, šema preduzetih ispitivanja i njihovi rezultati dati su ispod. Sva ispitivanja su sprovedena pod istim uslovima u slučaju oba uzorka ploča.

**7. Ispitivanje bočnim savijanjem**

Ispitivanje je urađeno prema standardu PN-EN ISO 5173 na četiri bočna uzorka (slika 4). Korišćen je trn za savijanje prečnika 40 mm. Korišćena je tradicionalna mašina ZD40 za zatezanje maksimalne snage 400 kN [28].

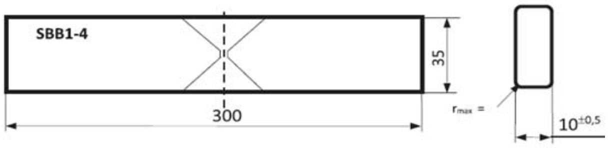
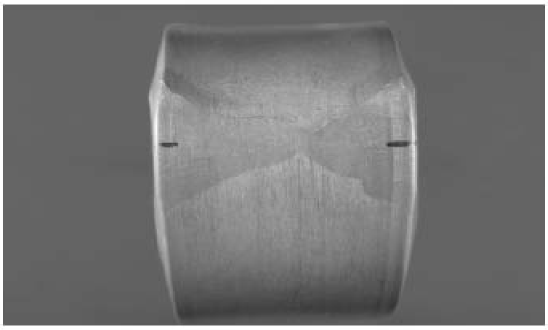


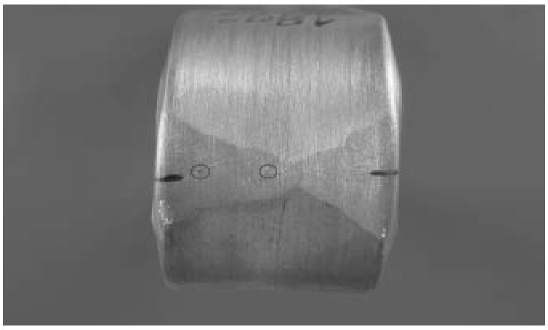

***Fig. 4.*** *A way of preparing samples to the side bend [18]*
***Sl. 4*** *Način pripreme uzoraka za bočno savijanje [18]*

Pictures of the samples after side bend are presented in the picture 5.

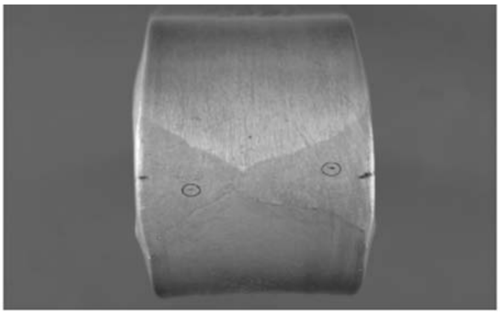
Slike uzoraka nakon bočnog savijanja prikazane su na slici 5.



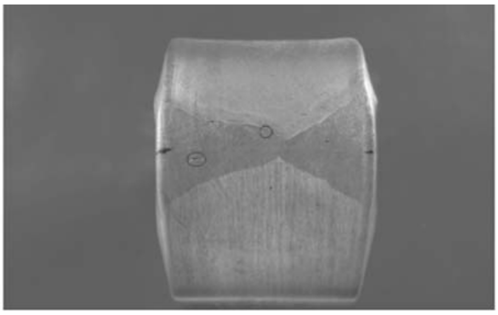
*SBB1 – Plate 1 – 136*



*SBB1 - Plate 2 – 111*

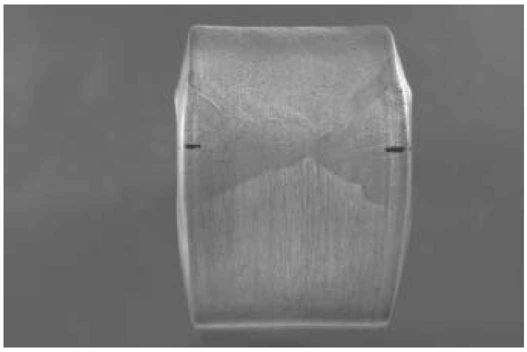


*SBB2 – Plate 1 – 136*

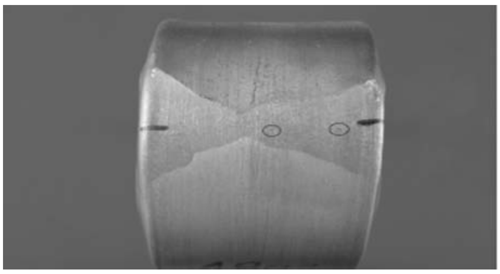


*SBB2 – Plate 2 – 111*

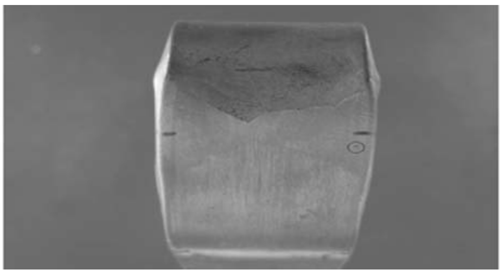
*SBB3 – Plate 1 – 136*



*SBB3 – Plate 2 – 111*



*SBB 4 – Plate 1 – 136*



*SBB 4– Plate 2 – 111*

***Fig. 5*** *Pictures of the samples after side bend*
***Sl. 5*** *Slike uzoraka posle bočnog savijanja*

Bending tests did not reveal any discrepancies in the base materials, welds and heat-affected zones. In case of both sample plates there appeared only slight cracks, which do not disqualify the joint. A result of an examination was positive (table 8, Fig. 5)

Testovi savijanja nisu otkrili nikakva odstupanja u osnovnim materijalima, zavarima i zonama uticaja toplote. U slučaju obe ispitne epruvete uzoraka pojavile su se neznatne prsline, koje ne diskvalifikuju spoj. Rezultat pregleda bio je pozitivan (tabela 8, slika 5)

***Fig. 6.*** *A phenomena of non-axial deformation of bent samples*
***Sl. 6*** *Pojava neaaksijalne deformacije savijenih uzoraka*

It is vital to point that PN-EN ISO 15614-1 standard allows to use 2 tests of bending longitudinal samples instead of 4 tests of side bend in case of mixed joints. It is done toavoid a problem of non-axial deformation of samples during examination, which is caused by too high difference of a resistance and plasticity of both materials. It was observed in the above experiment (Fig. 6). Above test was done in order to examine the joint in difficult technological conditions, therefore more risky 4 side bends were made [15, 18, 22].

Važno je ukazati na to da standard PN-EN ISO 15614-1 dozvoljava korišćenje 2 ispitivanja podužnim savijanjem umesto 4 ispitivaja bočnim savianjem u slučaju mešovitih zavarenih spojeva. To je i učinjeno da bi se izbegao problem neaaksijalne deformacije uzoraka tokom ispitivanja, što je uzrokovano previsokom razlikom otpornosti i plastičnosti oba materijala. To je uočeno u gore navedenom eksperimentu (slika 6). Prethodno ispitivanje je obavljeno kako bi se ispitao spoj u teškim tehnološkim uslovima, zbog čega je urađeno rizičnije savijanje sa 4 strane. [15, 18, 22].

## 8. Transverse tensile test

Transverse tensile test was done on four samples prepared according to the picture 7 in the room temperature in accordance with the PN-EN ISO 4136 standard. Sizes of the samples were fixed to the possibilities of the tensile testing machine of 400kN power. Taking into account a high tensile strength of the duplex steel, it was necessary to take two samples from the joint. A minimum criteria for the joint was equal to 470MPa [23].

## 8. Ispitivanje poprečnim zatezanjem

Ispitivanje poprečnim zatezanjem obavljeno je na četiri uzorka pripremljena prema slici 7 na sobnoj temperaturi u skladu sa standardom PN-EN ISO 4136. Veličine uzoraka bile su fiksirane na mogućnosti mašine za ispitivanje zatezanjem snage 400 kN. Uzimajući u obzir visoku zateznu čvrstoću dupleks čelika, bilo je potrebno uzeti dva uzorka iz spoja. Minimalni kriterijumi za spoj su bili jednaki 470MPa [23].

| Sample | An angle of bend, ° | Plate 1 (136) | Plate 2 (111) |
|---|---|---|---|
| SBB1 | 180 | Lack of cracks | Openings l1=0.2mm. l2=0.8 mm |
| SBB2 | 180 | Openings l1=1.2mm. l2=0.4mm | Openings l1=1.7mm. l2=0.5 mm |
| SBB3 | 180 | Openings l1=0.7mm. l2=1.2mm | Lack of cracks |
| SBB4 | 180 | Openings l1=1.5mm. d=0.5mm | Opening l1=1.3mm |

***Table 8*** *Results of the side bend tests*
***Tabela 8.*** *Rezultati ispitivanja bočnim savijanjem*

*Legenda: sample-uzorak; an angle of bend- ugao savijanja; plate-lim; lack of cracks-bez prslina; opening- otvaranje*

| Sample | Plate 1 - 136 | | Plate 2 - 111 | |
|---|---|---|---|---|
| | Rm, MPa | Breaking place | Rm, MPa | Breaking place |
| TT1-1 | 536 | P355NL1 material | 557 | P355NL1 material |
| TT1-2 | 525 | P355NL1 material | 558 | P355NL1 material |
| TT2-1 | 520 | P355NL1 material | 559 | P355NL1 material |
| TT2-2 | 524 | P355NL1 material | 546 | P355NL1 material |

***Table 9*** *Results of the tension tests*
***Tabela 9.*** *Rezultati ispitivanja zatezanjem*

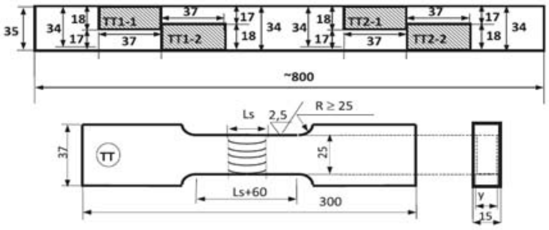
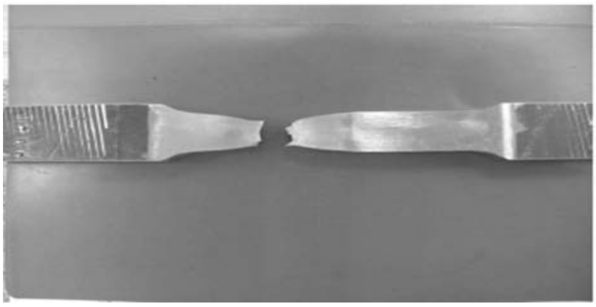


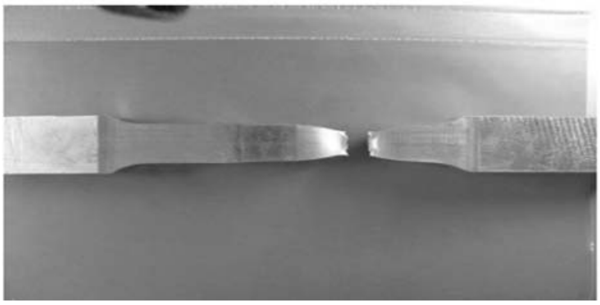

***Fig. 7.*** *A way of taking and preparing samples for tension [23]*
***Sl. 7.*** *Način uzimanja i pripreme uzoraka za zatezanje [23]*

Pictures of the samples after transverse tensile are presented in the picture 8.

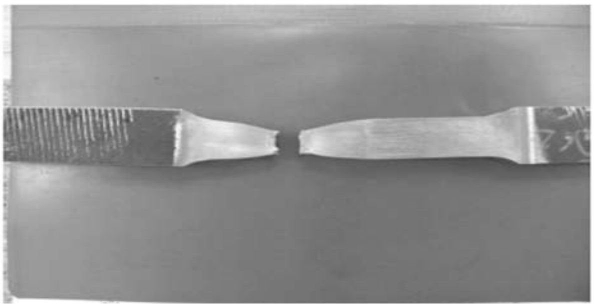
Slike uzoraka nakon poprečnog zatezanja prikazane su na slici 8.



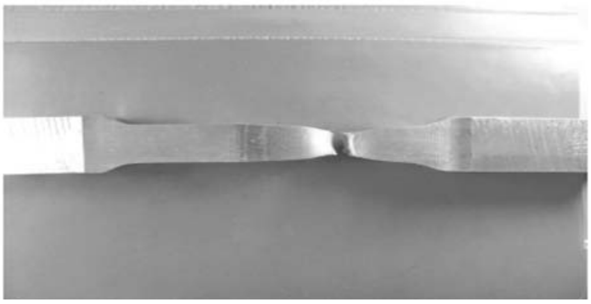
*TT1 – 1 – Plate 1 – 136*



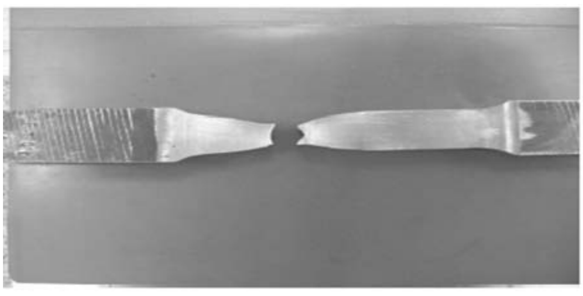
*TT1 – 1 – Plate 2 – 111*



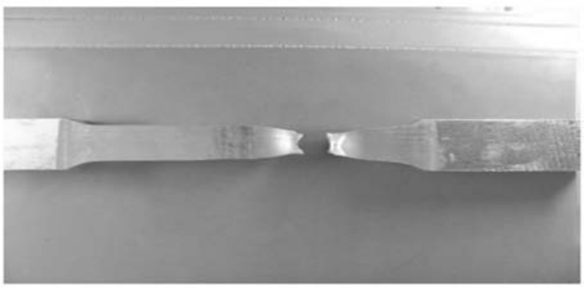
*TT1 – 2 – Plate 1 – 136*



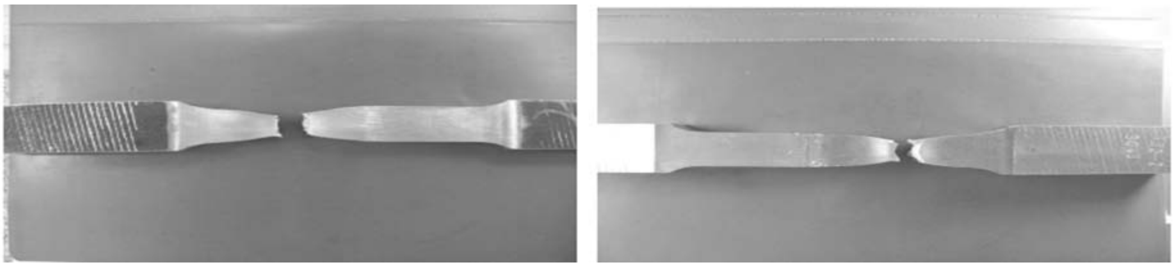
*TT1 – 2 – Plate 2 – 111*



*TT2 – 1 – Plate 1 – 136*



*TT2 – 1 – Plate 2 – 111*



*TT2 – 2 – Plate 1 – 136* *TT2 – 2 – Plate 2 – 111*

***Fig. 8.*** *Pictures of the samples after transverse tensile*
***Sl. 8.*** *Slike uzoraka posle poprečnog zatezanja*

Tension tests proved that duplex steel is characterised by the greater tensile strength than the P355NL1 steel – samples were broken in the structural steel (fig. 8). An examination has finished positively, because a minimal resistance of the joint was obtained (table 9).

Ispitivanja zatezanjem su dokazala da se dupleks čelik odlikuje većom zateznom čvrstoćom od čelika P355NL1 - uzorci su se polomili na delu konstrukcionog čelika (slika 8). Ispitivanje se završilo pozitivno, jer je postignuta minimalna otpornost spoja (tabela 9).

## 9. Weld metal tensile test

Weld metal tensile test was done according to the PN-EN ISO 876 standard in order to measure tensile strength of the same weld. A way of preparing a sample presents picture 9 [13].

## 9. Ispitivanje zatezanjem metala šava

Ispitivanje zatezanjem metala šava je izvedeno u skladu sa standardom PN-EN ISO 876 kako bi se izmerila zatezna čvrstoća istog šava. Način pripreme uzorka predstavljen je na slici 9 [13].

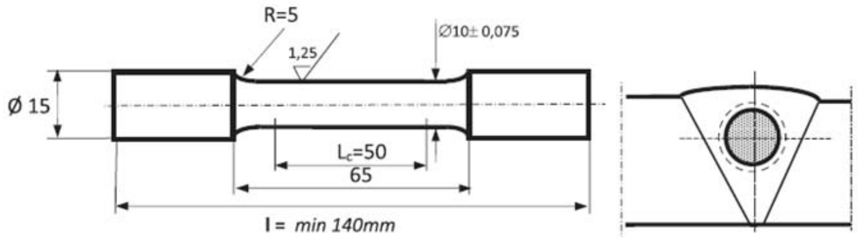


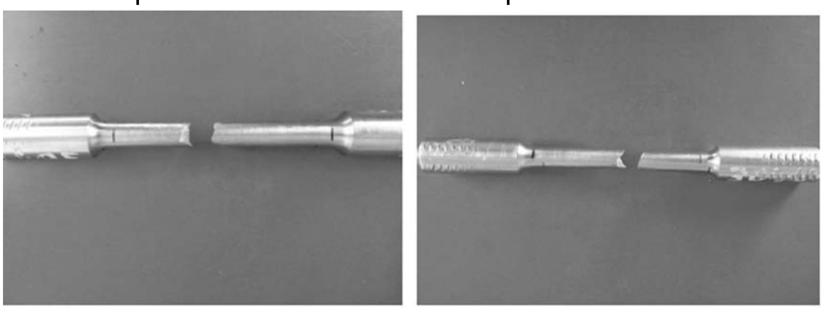

***Fig. 9.*** *A way of taking and preparing a sample to stretch the weld metal. [26]*
***Sl. 9.*** *Način uzimanja i pripreme uzoraka za istezanje metala šava [26]*

| Sample | Re, MPa | Rm, MPa | Elongation, % | Result of the examination |
|---|---|---|---|---|
| LT1-1- Plate 1 - 136 | 384 | 513 | 27.8 | Positive |
| LT1-1- Plate 2 - 111 | 416 | 675 | 44.4 | Positive |

***Table 10*** *Weld metal tensile tests' results*
***Tabela 10.*** *Rezultati sipitivanja zatezanjem metla šava*

Pictures of the samples after tensile testing of the weld metal are presented in the picture 10.

Slike uzoraka nakon ispitivanja zatezanjem metala šava prikazane su na slici 10.



LT – 1 – Plate 1 – 136 LT – 1 – Plate 2 – 111

**Fig. 10** Pictures of the samples after tension of the weld metal
**Sl. 10.** Slike uzoraka posle zatezanja metala šava

Except of measuring tensile strength of the weld,there was also a measurement of elongation A5, and the limit of plasticity. An examination was taken in the room temperature. Following criteria were taken into account: Re ≥ 315MPa, A ≥ 21%, Rm ≥ 470MPa (table 10) [26]. Higher resistance and plasticity values were obtained in case of the plate no. 2, which is the result of using nickel based electrodes.

Osim merenja zatezne čvrstoće šava, takođe je mereno izduženje A5 i granica plastičnosti. Ispitivanje je izvršeno na sobnoj temperaturi. U obzir su uzeti sledeći kriterijumi: Re ≥ 315MPa, A ≥ 21%, Rm ≥ 470MPa (tabela 10) [26]. Dobijene su veće otpornosti i plastičnosti u slučaju ploče br. 2, što je rezultat korišćenja elektroda na bazi nikla.

## 10. Impact strength test

Due to the mixed connection, except of a standard threeset samples taken from the weld and three from heat-affected zones, an additional set was used from the heat-affected zone of the second material. Recommendations from PN-EN ISO 9016 and PN-EN ISO 148-1 standards were used. Pictures 11 and 12 depict a way of taking each set. An examination was = 300 J weight [24, 25]
Pictures of the samples after an impact strength test are presented in the picture 13.

## 10. Ispitivanje energije udara

Zbog mešovitog spoja, izuzev standardnih šesnaest uzoraka uzetih iz šava i tri iz zona pod uticajem toplote, korišćen je dodatni set iz zona uticaja toplote drugog materijala. Korišćene su preporuke standarda PN-EN ISO 9016 i PN-EN ISO 148-1. Slike 11 i 12 prikazuju način uzimanja svakog seta. Ispitivanje je obavljeno uz = 300 J opseg. [24, 25]
Slike uzoraka nakon ispitivanja energije udara su prikazane na slici 13.

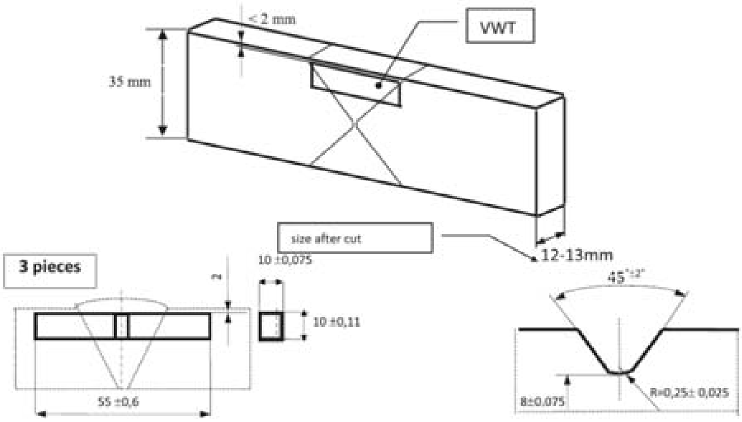



***Fig. 11.*** *A way of preparing samples taken from the weld to the impact strength tests [14]*
***Sl. 11.*** *Način pripreme uzoraka uzetih iz metala šava za ispitivanje udarom [14]*

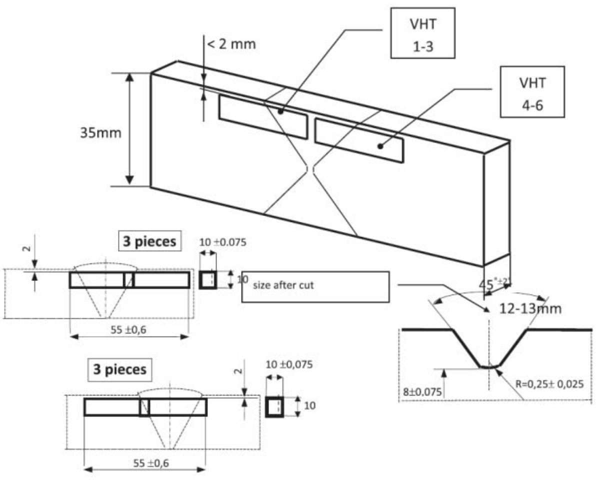
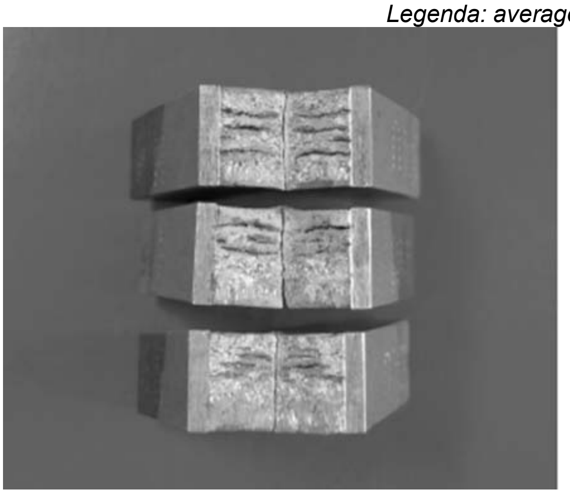



***Fig. 12.*** *A way of preparing samples taken from the heat-affected zones to the impact strength tests [14]*
***Sl. 12.*** *Način pripreme uzoraka uzetih iz zona uticaja toplote za ispitivanje udarom [14]*

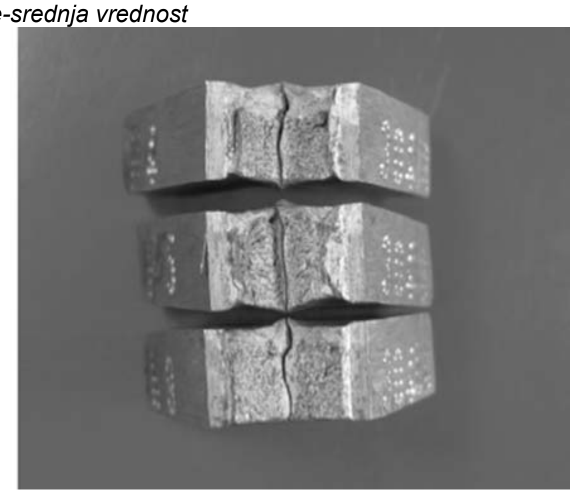
| Plate | Sample | 1, J | 2, J | 3, J | Average, J |
|---|---|---|---|---|---|
| 1 – 136 | VWT1/2 – P355NL1 | 88 | 26 | 26 | 47 |
| | VHT1/2 – weld | 14 | 5 | 6 | 8 |
| | VHT1/2 - X2CrNiMoN22-5-3 | 33 | 36 | 18 | 29 |
| 2 – 111 | VWT1/2 – P355NL1 | 140 | 130 | 138 | 136 |
| | VHT1/2 – weld | 128 | 128 | 133 | 130 |
| | VHT1/2 - X2CrNiMoN22-5-3 | 75 | 110 | 59 | 81 |

***Table 11*** *Results of the impact strength tests*
***Tabela 11.*** *Rezultati ispitivanja udarom*

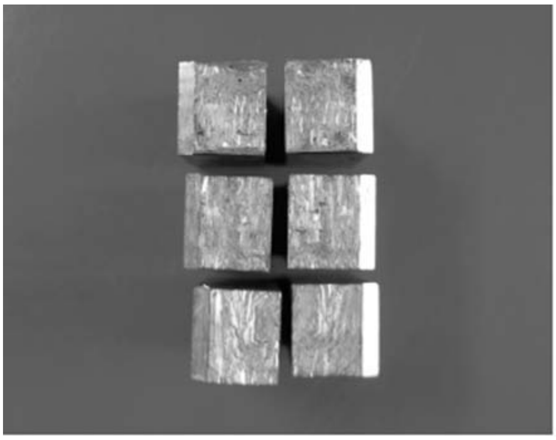
*Legenda: average-srednja vrednost*



*VHT1/2 P355NL1 – Plate 1 – 136*

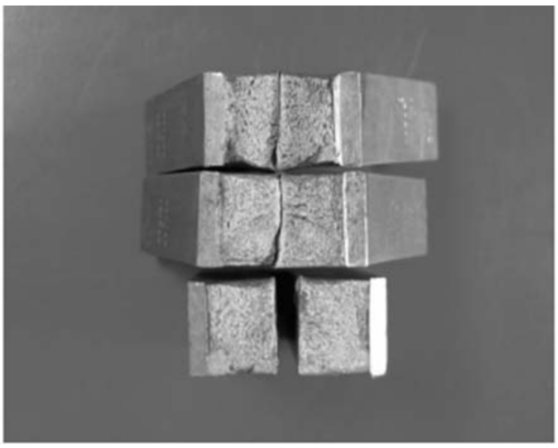


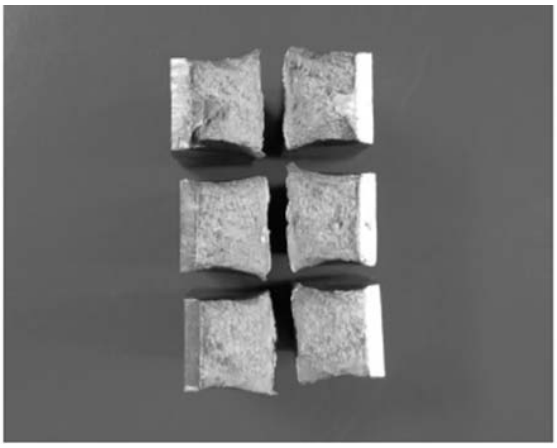
*VHT1/2 P355NL1 – Plate 2 – 111*



*VWT0/2 weld – Plate 1 - 136*

*VWT0/2 weld – Plate 2 – 111*





*VHT1/2 X2CrNiMoN22-5-3 – Plate 1 – 136 VHT1/2 X2CrNiMoN22-5-3 – Plate 2 – 111*

***Fig. 13.*** *Pictures of samples after an impact strength test*
***Sl. 13.*** *Slike uzoraka posle ispitivanja udarom*

Impact strength tests have finished negatively in case of the plate no. 1. A required value of breaking operation equals to 27 J was not obtained both for P355NI1 material, and also 40 J for the duplex steel (table 11). It is caused by an increase of embrittlement activated by the carbon diffusion from the carbon steel into the weld during a thermal treatment, and an occurrence of the brittle sigma phase.

In case of using nickel based filler material (plate no. 2) much higher breaking operation values were obtained.

Elements included in the chemical composition of used electrodes mostly nickel, niobium and titanium, which are stabilizers, stopped carbon diffusion. Moreover, they caused appearance of carbides, which increase embrittlement and decrease resistance of the material to corrosion. Pictures prove that samples taken from the nickel welded joint (plate no. 2) broke in a plastic way, while the fracture of samples from the plate no. 1 is evidently brittle.

Ispitivanje udarom negativno je završeno u slučaju ploče br. 1. Potrebna vrednost jednaka 27 J nije dobijena ni za materijal P355NI1, niti 40 J za dupleks čelik (tabela 11). To je uzrokovano povećanjem krtosti aktivirane difuzijom ugljenika od ugljeničnog čelika u šav pri termičkoj obradi i pojavom krte sigma faze.

U slučaju korišćenja dodatnog materijala na bazi nikla (ploča broj 2) dobijene su mnogo veće vrednosti.

Elementi sadržani u sastavu upotrebljenih elektroda uglavnom nikl, niobijum i titan, koji su stabilizatori, zaustavili su difuziju ugljenika. Štaviše, oni su izazvali pojavu karbida, čime se povećava krtkost i smanjuje otpornost materijala na koroziju. Slike pokazuju da su uzorci uzeti iz niklom zavarenog spoja (ploča broj 2) lomili plastično, dok je prelom uzoraka sa ploče br. 1 očigledno krt.

## 11.Macroscopic examination

Macroscopic examination was taken according to PN-EN 1321 standard on a previously taken and etched metallographic specimen (fig. 14). Adler's solution was used to etch. [20]

## 11. Makroskopsko ispitivanje

Makroskopsko ispitivanje je izvedeno u skladu sa standardom PN-EN 1321 na prethodno uzetom i obrađenom metalografskom uzorku (slika 14). Za nagrizanje je korišćen Adlerov rastvor [20]

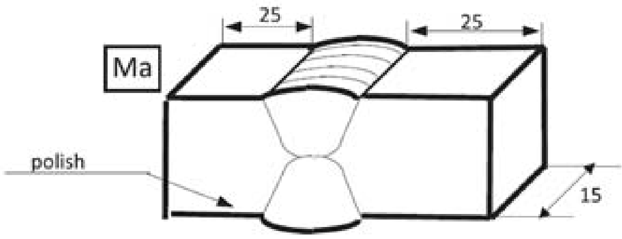



***Fig. 14.*** *A way of preparing a metallographic specimen [10]*
***Sl. 14.*** *Način pripreme metalografske eperuvete [10]*

Macroscopic pictures of plates are presented in the picture 15.

Makroskopske slike ploča su prikazane na slici 15.

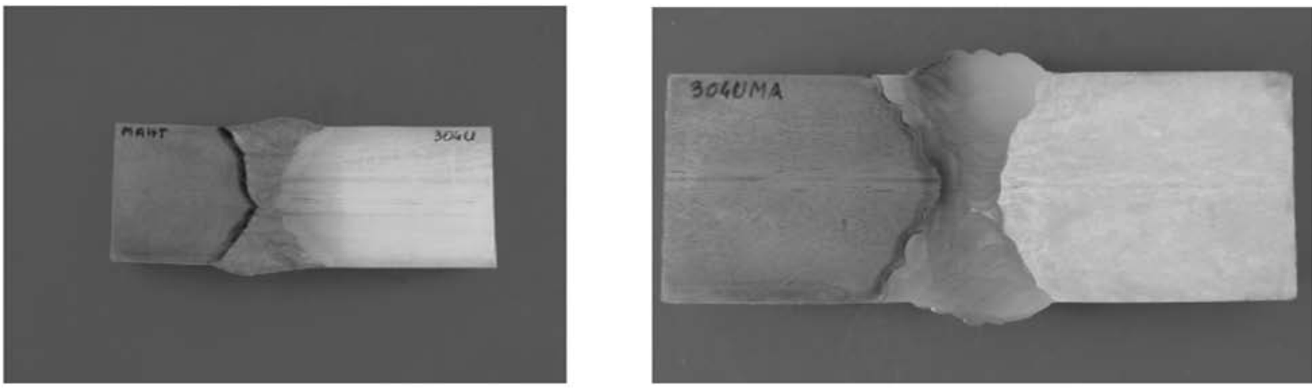


*Plate no. 1* *Plate no. 2*

***Fig. 15.*** *Macroscopic pictures of plates*
***Sl. 15***. *Makrostrukture na limovima*

Macroscopic examination did not reveal any of unaccepted discrepancies in the section of examined plates (fig. 15)

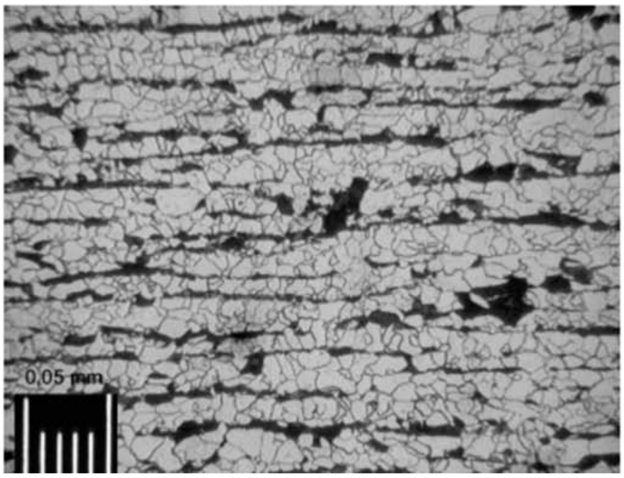
Makroskopski pregled nije otkrio nijedno od neprihvatljivih odstupanja u delu ispitanih ploča (slika 15).

**12. Microscopic examination**

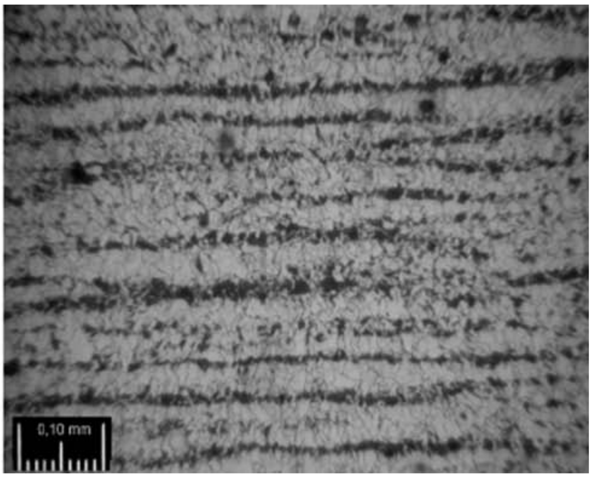
Microscopic images were taken on the metallographic specimen etched by the agent consisting of nital and Mi20Fe (fig. 16). Zoom 200:1 was used. An examination was taken according to the PN-EN 1321 standard [20]

**12. Ispitivanje mikrostrukture**

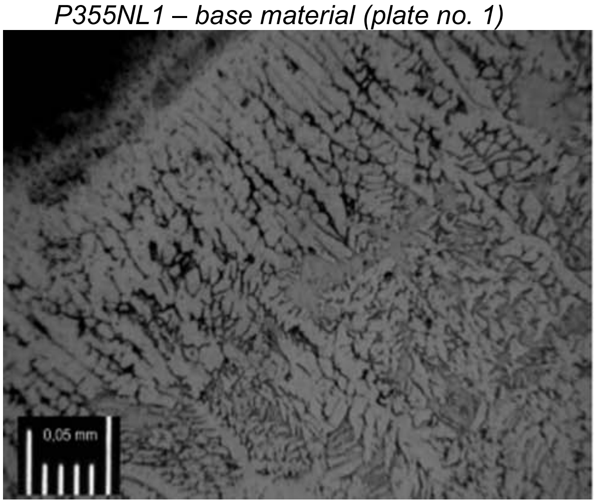
Mikroskopske slike su uzete na metalografskom uzorku koji je nagrižen agensom koji se sastoji od nitala i Mi20Fe (slika 16). Uvećanje je 200: 1. Ispitivanje je izvedeno prema standardu PN-EN 1321 [20]



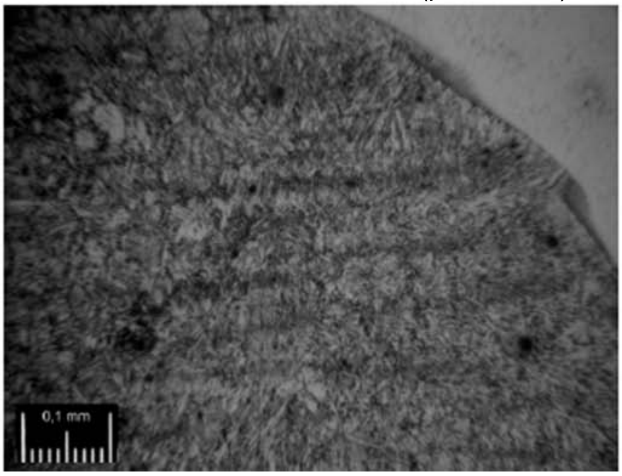

*P355NL1 – base material (plate no. 1)*



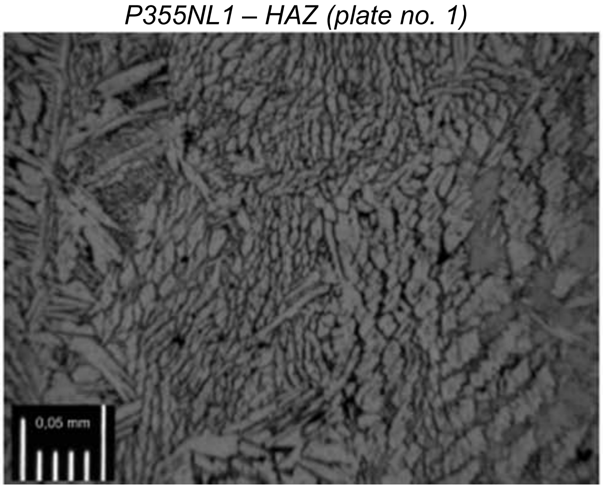

*P355NL1 – base material(plate no. 2)*



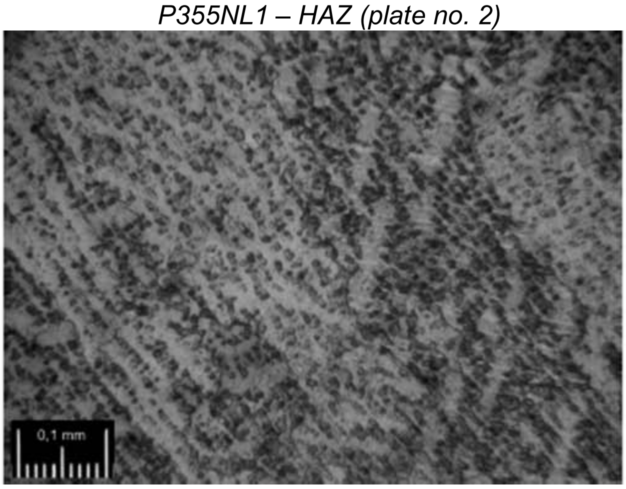

*P355NL1 – HAZ (plate no. 1)*



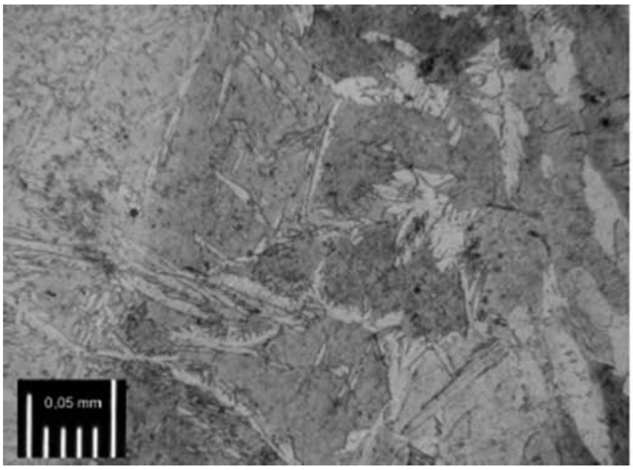

*P355NL1 – HAZ (plate no. 2)*



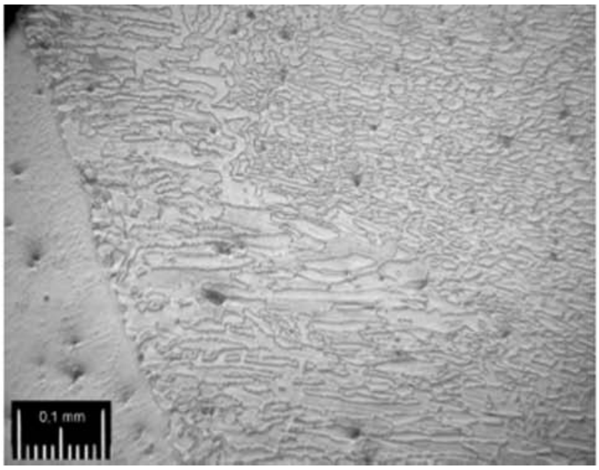

*weld (plate no. 1)*



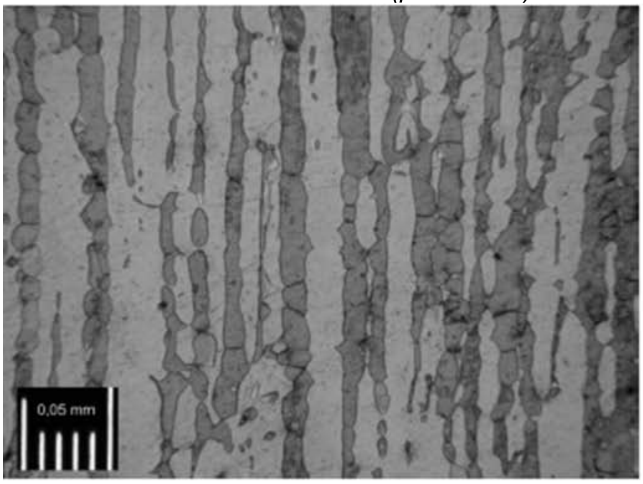

*weld (plate no. 2)*



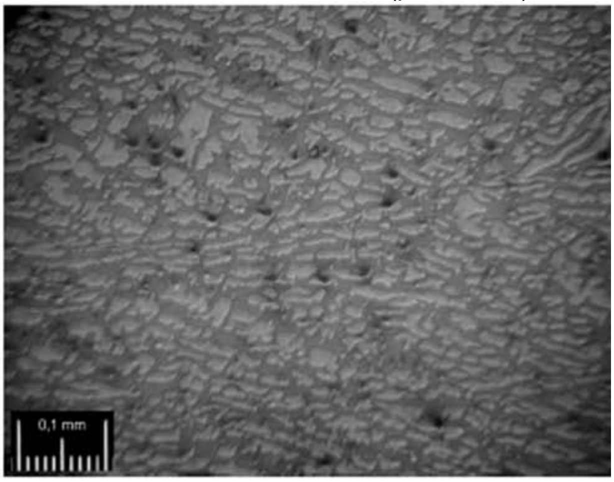

*X2CrNiMoN22-5-3 – HAZ (plate no. 1)*




*X2CrNiMoN22-5-3 – HAZ(plate no. 2)*




*X2CrNiMoN22-5-3 –( plate no. 1)*




*X2CrNiMoN22-5-3(plate no. 2)*

*Legenda: plate no-lim br.; HAZ-ZUT; weld-metal šava*

***Fig. 16.*** *Microscopic pictures of plates*

***Sl. 16.*** *Mikrostrukture limova*

A structure of a heat-affected zone on the side of the duplex steel in case of the plate no. 1 includes about 40-50% ferrite. The weld indicates a ferrite-austenite structure with a required share of ferrite i.e. 30-70% Microscopic examination in case of the plate no. 2 does not reveal any microcracks or other discrepancies. It was stated that the base material on the side of the carbon steel has a ferrite-pearlite structure, and on the side of the duplex steel has a ferrite-austenite structure with a ferrite content of about 45%. The weld is characterised by the ferrite-austenite structure of grown austenite grains with a ferrite content not exceeding a value of 85% near the weld line (fig. 16).

**13. Hardness test**

Hardness test by the Vickers method was done on the metallographic specimen, previously used in the macroscopic examination. Hardness test was done according to the PN-EN ISO 9015-1 standard along specified measurement lines (fig.17). Vickers testing device was used 430 SVD with the load of HV10 [19].

Struktura zone uticaja toplote na strani dupleks čelika u slučaju ploče br. 1 sastoji se od oko 40-50% ferita. Metal šava pokazuje strukturu ferita-austenita sa potrebnim udelom ferita tj. 30-70%
Mikroskopski pregled u slučaju ploče br. 2 ne otkriva nijednu mikroprslinu ili druga odstupanja. Ustanovljeno je da osnovni materijal na strani ugljeničnog čelika ima feritno-perlitnu strukturu, a na strani dupleks čelika ima feritno-austenitnu strukturu sa sadržajem ferita od oko 45%. Šav karakteriše feritno-austenitna struktura sa krupnim austenitnim zrnima i sadržajem ferita koji ne prelazi vrednost 85% u blizini linije stapanja (slika 16).

**13. Ispitivanje tvrdoće**

Ispitivanje tvrdoće po Vikersovoj metodi obavljeno je na metalografskom uzorku, ranije korišćenom za makroskopski pregled. Ispitivanje tvrdoće je obavljeno prema standardu PN-EN ISO 9015-1 duž određenih mernih linija (slika 17). Korišćeni uređaj je Vikers 430 SVD sa opterećenjem HV10 [19].

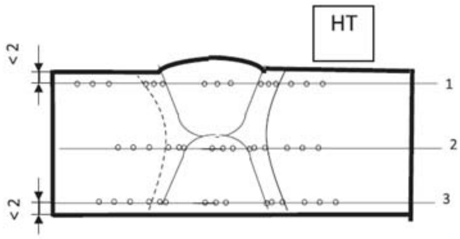



***Fig. 17.*** *A way of doing a hardness test [19]*
***Sl. 17.*** *Način merenja tvrdoće*

| nr | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 158 | 151 | 160 | 173 | 193 | 219 | 276 | 290 | 290 | 266 | 258 | 258 | 251 | 245 | 243 |
| 2 | 150 | 146 | 146 | 202 | 212 | 206 | 272 | 262 | 304 | 279 | 279 | 279 | 243 | 245 | 240 |
| 3 | 139 | 138 | 140 | 177 | 199 | 206 | 274 | 281 | 287 | 276 | 276 | 274 | 240 | 233 | 242 |

***Table 12*** *Results of hardness tests of the plate 1 – method 136*
***Tabela 12.****Rezultati ispitivanja tvrdoće na limu 1- postupak 136*

| Nr | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 149 | 153 | 151 | 202 | 224 | 249 | 187 | 172 | 177 | 258 | 240 | 237 | 227 | 235 | 228 |
| 2 | 150 | 149 | 153 | 183 | 186 | 201 | 197 | 209 | 199 | 279 | 266 | 260 | 227 | 230 | 228 |
| 3 | 149 | 149 | 146 | 183 | 202 | 235 | 191 | 193 | 173 | 251 | 225 | 233 | 233 | 238 | 235 |

***Table 13*** *Results of hardness tests of the plate 2 – method 111*
***Tabela 13.*** *Rezultati ispitivanja tvrdoće na limu 2- postupak 111*

Results of the hardness tests are depicted in the picture 18

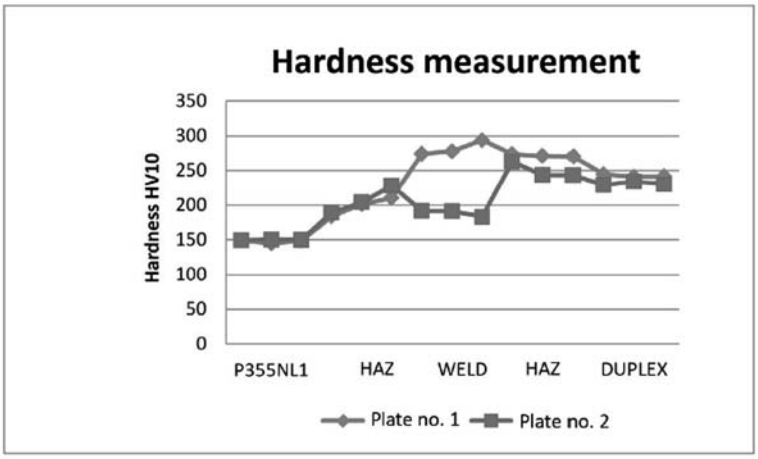



***Fig. 18.*** *Results of the hardness measurement*
***Sl. 18.*** *Rezultati merenja tvrdoće*

In case of the plate no. 1, the lowest hardness was stated inside the P355NL1 metal sheet, its value is much higher in the duplex steel, and definitely the highest in the weld (table 12, 13). Hardness of both base materials plate no. 2 is very close to the measurement of the plate no. 1, whereas in case of the weld much lower hardness was observed in the joint made by the nickel based electrodes. It is caused by the high plastic properties of mentioned electrodes.

It is vital to point that according to the PN-EN ISO 15614- 1 standard hardness test is not done for the

Rezultati ispitivanja tvrdoće prikazani su na slici 18

U slučaju ploče br. 1, najmanja tvrdoća je na limu P355NL1, njegova vrednost je mnogo viša u dupleks čeliku i definitivno najviša u metalu šava (tabela 12, 13). Tvrdoća oba osnovna materijala na ploči br. 2 je veoma blizu merenju ploče br. 1, dok je u slučaju metala šava u spoju sa elektrodom na bazi nikla, zabeležena znatno niža tvrdoća. To je uzrokovano visokim plastičnim svojstvima pomenutih elektroda.

Važno je naglasiti da se prema standardu PN-EN ISO 15614- 1 standardno ispitivanje tvrdoće se ne

materials from the group 10 including duplex steel. In case of above sample plates
an examination was taken only to do an experiment [15].

## 14. Examining a content of delta ferrite

Examining a content of delta ferrite was taken according to the PN-EN ISO 8249 standard by the Fischer MP 30E-S Feritscope (fig. 19) on the previously used for an examination a metallographic specimen. Measurements refer an area of the weld, the duplex steel, and the black steel [21].

In case of both sample plates a content of delta ferrite in the structural steel ranges from 96 to 100%. There was a considerable decrease of ferrite share (plate no. 1) in the duplex steel from the joint welded by the flux-cored wire in comparison to plate no. 2. The weld made by the duplex wire is characterized by the dual microstructure. A device cannot measure a content of delta ferrite in the nickel weld due to insufficient sensitivity of the feritscope. Thus, it can be stated that a share of delta ferrite does not exceed 0,1%.

radi na materijalima grupe 10, uključujući i dupleks čelik. U slučaju gore navedenih uzoraka,
Ispitivanje je preduzeto samo radi eksperimenta [15].

## 14. Ispitivanje sadržaja delta ferita

Ispitivanje sadržaja delta ferita obavljeno je u skladu sa standardom PN-EN ISO 8249 uređajem Fischer MP 30E-S Feritscope (slika 19) na prethodno korišćenom metalografskom uzorku. Merenja obuhvataju površinu metsala šava, dupleks čelik i crni čelik [21].

U slučaju oba uzorka, sadržaj delta ferita u konstrukcijskom čeliku se kreće od 96 do 100%. Postojalo je značajno smanjenje feritnog udela (ploča broj 1) u dupleks čeliku iz spoja zavarenog punjenom žicom u odnosu na ploču br. 2. Šav dobijen žicom od dupleks čelika, karakteriše dvojna mikrostruktura. Uređaj ne može izmeriti sadržaj delta ferita u šavu od nikla zbog nedovoljne osjetljivosti feritskopa. Stoga se može konstatovati da udeo delta ferita ne prelazi 0,1%


***Fig. 19.*** *The Fisher MP 30E-S Feritscope*
***Sl. 19.*** *Fisher MP 30E-S Feritscope*

| No. | Zone | 1, % | 2, % | 3, % | 4, % | 5, % | Average % |
|---|---|---|---|---|---|---|---|
| 1 | Weld | 43.0 | 39.0 | 48.0 | 50.0 | 40.0 | 44.00 |
| 2 | X2CrNiMoN22-5-3 | 26.0 | 33.0 | 32.0 | 26.0 | 27.0 | 28.80 |
| 3 | P355NL1 | 95.0 | 96.0 | 99.0 | 95.0 | 97.0 | 96.40 |

***Table 14*** *Results of examining a content of delta ferrite – plate 1 – method 136*
***Tabela 14.*** *Rezultati ispitivanja sadražaja delta ferita –lim 1- postupak 136*

| No. | Zone | 1. % | 2. % | 3. % | 4. % | 5. % | Average % |
|---|---|---|---|---|---|---|---|
| 1 | Weld | Out of range of the device (sensitivity 0.1%) | | | | | |
| 2 | X2CrNiMoN22-5-3 | 45.0 | 44.8 | 45.6 | 45.6 | 44.3 | 45.06 |
| 3 | P355NL1 | 98.9 | 100.0 | 99.2 | 98.3 | 97.7 | 98.80 |

***Table 15*** *Results of examining a content of delta ferrite – plate 2 – method 111*
***Tabela 15.*** *Rezultati ispitivanja sadražaja delta ferita –lim2- postupak 111*

## 15. Summary and conclusions

A part of examinations taken on the samples from the plate no. 1 (welded by the flux-cored wire) has finished negatively. Impact strength tests showed too low breaking operation,while examining a content of ferrite, and the macroscopic examinations revealed a lack of a required share of the α structure in the weld. It is a result of an appearance the brittle sigma phase connected with the carbon diffusion caused by the thermal treatment of the weld.
All the examinations taken on the plate no. 2 have finished positively. Despite a thermal treatment after welding there was not any increase of embrittlement. The weld metal based on nickel, and the foremost stabilizing elements, which are included in the content of electrodes, kept carbon diffusion, and therefore the joint obtained high plastic and resistance properties.
Welding different types of joints of the duplex steel with a low-alloyed steel does not make any troubles. Difficulties appear during a thermal treatment. A proper solution is a use of materials based on nickel, and particularly a precise choice of parameters, which do not allow to overheat the joint.

## 15. Rezime i zaključak

Deo ispitivanja na uzorcima sa ploče br. 1 (zavarena punjenom žicom) završena je negativno. Ispitivanja udarom su pokazale su suviše niske vrednosti energije, dok su ispitivanje sadržaja ferita i makroskopski pregledi pokazali nedostatak potrebnog udela α strukture u metalu šava. To je rezultat prisustva krte sigma faze koja je povezana sa difuzijom ugljenika izazvanom termičkom obradom zavarenog spoja.
Sva ispitivanja obavljena na ploči br. 2 su pozitivno završeni. Uprkos termičkoj obradi nakon zavarivanja, nije bilo povećanja krtosti. Metal šava na bazi nikla i najzastupljeniji elementi za stabilizaciju, koji su sadržani u elektrodi, održali su difuziju ugljenika, a samim tim i zavareni spoj dobija visoke osobine plastičnosti i otpornosti.
Zavarivanje različitih vrsta spojeva dupleks čelika sa nisko legiranim čelikom ne čini nikakve probleme. Teškoće se javljaju tokom termičke obrade. Pravilno rešenje je korišćenje materijala baziranih na niklu, a naročito precizan izbor parametara, koji ne dozvoljavaju pregrevanje zavarenog spoja.

## References
## Literatura

[1] J. Nowacki, Stal dupleks i jej spawalność, Warszawa 2009.
[2] A. Lisiecki, Welding of titanium alloy by Disk laser. Proc. Of SPIE 8703, Laser Technology 2012: Applications of Lasers, 87030T (January 22, 2013), DOI : 10.1117/12.2013431.
[3] T. Węgrzyn, J. Mirosławski, A. Silva, D. Pinto, M. Miros, Oxide inclusions in steel welds of car body, Materials Science Forum 636-637, 2010.
[4] A. Lisiecki, Diode laser welding of high yield steel. Proc. Of SPIE 8703, Laser Technology 2012: Applications of Lasers, 87030S (January 22, 2013), DOI : 10.1117/12.2013429.
[5] T. Węgrzyn, Mathematical Equations of the Influence of Molybdenum and Nitrogen in Welds. Conference of International Society of Offshore and Polar Engineers ISOPE´2002, Kita Kyushu, Japan 2002, Copyright by International Society of Offshore and Polar Engineers 4, ISBN 1-880653-58-3, Cupertino – California – USA 2002.
[6] T. Węgrzyn, The Classification of Metal Weld Deposits in Terms of the Amount of Oxygen, Proceedings of the Conference of International Society of Offshore and Polar Engineers ISOPE'99, Brest, France 1999, International Society of Offshore and Polar Engineers 4, 212-216,Cupertino – California, USA 1999.
[7] T. Wegrzyn, J. Piwnik, D. Hadrys, Oxygen in steel WMD after welding with micro-jet cooling, Archives of Metallurgy and Materials 58, 4, 1067-1070 ( 2013).
[8] Ł. Konieczny, R. Burdzik, T. Figlus, The possibility to control and adjust the suspensions of vehicles, J. Mikulski (Ed.): Activities of Transport Telematics, pp. 378-383, TST 2013, CCIS 395.
[9] T. Wegrzyn, J. Piwnik, J. Łazarz, D. Hadrys,Main micro-jet cooling gases for steel welding ,Archives of Metallurgy and Materials 58, 2, 556-559 (2013).
[10] R. Burdzik, Identification of structure and directional distribution of vibration transferred to car-body from road roughness, submitted to Journal of Vibroengineering 16(1),324-333 (2014).
[11] K. Lukaszkowicz, A. Kriz, J. Sondor, Structure and adhesion of thin coatings deposited by PVD technology on the X6CrNiMoTi17-12-2 and X40 CrMoV5-1 steel substrates, Archives of Materials Science and Engineering 51 40-47 (2011).
[12] Metrode – katalog produktów.
[13] Böhler – katalog produktów.

[14] Atesty blach.
[15] PN-EN ISO 15614-1:2008 – Specyfikacja i kwalifikowanie technologii spawania metali – Badanie technologii spawania – Część 1: Spawanie łukowe i gazowe stali oraz spawanie łukowe niklu i stopów niklu.
[16] PN-EN ISO 15609-1:2007 – Specyfikacja i kwalifikowanie technologii spawania metali – Instrukcja technologiczna spawania – Część 1: Spawanie łukowe.
[17] PN-EN ISO 17633:2010 – Materiały dodatkowe do spawania – Druty elektrodowe proszkowe i pręty do spawania łukowego w osłonie gazu i bez osłony gazu elektrodą metalową stali nierdzewnych i żaroodpornych – Klasyfikacja.
[18] PN-EN ISO 5173:2010 – Badania niszczące spoin w materiałach metalowych – Badanie na zginanie.
[19] PN-EN ISO 9015-1:2011 – Badania niszczące złączy spawanych metali – Badanie twardości – Część 1: Badanie twardości złączy spawanych łukowo.
[20] PN-EN 1321:2000 – Spawalnictwo – Badania niszczące metalowych złączy spawanych – Badania makroskopowe i mikroskopowe złączy spawanych
[21] PN-EN ISO 8249:2005 – Spawanie – Określanie liczby ferrytu (FN) w stopiwie nierdzewnych chromowo-niklowych stali austenitycznych i ferrytyczno-austenitycznych dupleks.
[22] PN-EN 13445-4:2009 – Nieogrzewane płomieniem zbiorniki ciśnieniowe – Część 4: Wytwarzanie.
[23] PN-EN ISO 4136:2011 – Badania niszczące złączy spawanych metali – Próba rozciągania próbek poprzecznych.
[24] PN-EN ISO 9016:2011 – Badania niszczące złączy spawanych metali – Badanie udarności – Usytuowanie próbek, kierunek karbu i badanie.
[25] PN-EN ISO 148-1:2010 – Metale – Próba udarności sposobem Charpy'ego – Część 1: Metoda badania.
[26] PN-EN 876:1999 – Spawalnictwo – Badania niszczące spawanych złączy metali – Próba rozciągania próbek wzdłużnych ze spoin złączy spawanych.
[27] www.e-spawalnik.pl.