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

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.

Keywords: S960MC, heat affected zone, sub-zones in HAZ, heat input, mechanical properties

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...
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 $t_{95}$, 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 heat-affected zone (FGHAZ), a fine-grained heat-affected zone (CGHAZ), an intercritical or partially transformed heat-affected 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 $A_1$ 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. svenga zavarljivost i sposobnost oblikovanja. Smanjenje sopstvene težine na primer vozila, omogućava smanjenje potrošnje 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 valjaonic i prisustvom mikrolegirajućih elemenata u čeliku. U toku zavarivanja, materijal se prvo veoma brzo zagrea; 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 žila, rastvaranja karbida i sl. Ove promene značajno utiču na mehaničke osobine, naročito tvrdoću, plastičnost, žilavost, granicu tečenja i zateznu čvrstoću. Najveći uticaj na ove promene imaju unos toplote i parametar $t_{95}$ određujući finalnu mikrostrukturu. Zato se zona uticaja toplote smatra kritičnim mjestom u zavarenom spoju. Termički ciklus definiše podzone unutar ZUT-a. U zavisnosti od rastojanja od izvora toplote, uticaj u svakoj od podzone je različit, što ima za posledicu nastanak različitih mikrostrukturnih i mehaničkih osobina u svakoj podzoni. ZUT se može podeliti u četiri glavne podzone: grubozrna zona uticaja toplote (CGHAZ), finoizrima zona uticaja toplote (FGHAZ), interkritična zona uticaja toplote (ICHAZ) i podkritična zona uticaja toplote (SCHAZ). Podела 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 podzona u kojoj je tvrdoća smanjena u odnosu na tvrdoću osnovnog metala (OM).

Mikrostrukturu čelika čvrstoće preko 900MPa ubičajeno čini martensit 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 pretrepti 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 prслиna.
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].

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 150x300 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.

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].

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 u mehaničkim osobinama sučeonih 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 ispitanih čelika. U tabeli 2 su date zahtevane mehaničke osobine prema navedenom standardu i mehaničke osobine ispitanih 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 dati 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.

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

| According to U skladu sa | Mechanical properties, thickness 3 mm | Mehaničke osobine S960, debljina 3 mm |
|--------------------------|--------------------------------------|-------------------------------------|
|                          | 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. Mehaničke osobine čelika

| According to U skladu sa | Mechanical properties, thickness 3 mm | Mehaničke osobine S960, debljina 3 mm |
|--------------------------|--------------------------------------|-------------------------------------|
|                          | $R_{p0.2}$, MPa | $R_m$, MPa | A, % |
| EN10149-2*               | Min. 960 | 980-1250 | Min. 7 |
| Tested steel             | 1031     | 1154    | 12 |
| Ispitani čelik           | 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 toplo, kJ/cm |
|--------------|-----------------------|---------------------------------------------------------------|-----------------|------------------------------------------|----------------------------------------|-----------------------------------------|---------------------------------------------|---------------------------------|---------------------------------|
| 1            | 135                   | 1 DC+                                                        | 125-135         | 18-19                                    | 45-50                                  | 4,5                                     | 16                           | 2,7                            |

Shielding 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

| Chemical composition of welding filler material, wt% |
|----------------------------------------------------|
| C | Si | Mn | P | S | Cr | Ni | Mo | Cu | Al | V | Ti | Zr |
|---|----|----|---|---|----|----|----|----|----|----|----|----|
| EN16834* | 0.13 | 0.50 | 0.80 | 2.10 | 0.015 | 0.20 | 2.30 | 0.30 | 0.30 | 0.120 | 0.030 | 0.100 | 0.100 |
| Tested steel | 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

| Mechanical properties of welding filler material, wt% / Mehaničke osobine dodatnog materijala, tež% |
|-----------------------------------------------------------------------------------------------|
| Rp₀,₂, MPa | Rₘ, MPa | A, % | KCV, J | ≥ 47/-50°C |
| EN16834* | ≥ 900 | 940-1180 | ≥ 15 | | |
| Tested steel | ≥ 930 | ≥ 980 | ≥ 14 | | |

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:

- macroscopic and miroskopick 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 Rₚ₀,₂ ≥ 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).

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

- određivanje makro i mikrostrukture
- merenje mikrotvrdosti
- poprečni test zatezanjem.

Kvalitet zavarenog spoja mora biti utvrđen objektivno u skladu sa narednim kriterijumima. Za određivanje 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 Rₚ₀,₂ ≥ 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. Result and Discussion

3.1 Macrostructures and microstructures evaluation

The macro and microstructure evaluation 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.
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 \( A_c^3 \) 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 \( A_c^3 \) temperature, but for a very short holding time.

**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 zavarenog spoja čelika S960MC i raspodela mikrotvrdoće HV1 unutar podzona u ZUT (BM – osnovni metal, WM – metal šava)
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 $A_1$ and $A_3$ 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 $A_1$ temperature, so no phase transformation occurred, only a
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°CvAc1 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. ICHAZ 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 microhardnesses of each HAZ sub-zone are shown in Table 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
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 $R_{p0.2} = 1035$ MPa and $R_m = 1151$ MPa. 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.

| Sub zone of HAZ | SCHAZ | ICHAZ | FGHAZ | CGHAZ | WM | CGHAZ | FGHAZ | ICHAZ | SCHAZ |
|-----------------|-------|-------|-------|-------|----|-------|-------|-------|-------|
| HV1             | 297   | 244   | 267   | 283   | 368| 283   | 276   | 236   | 287   |

3.3 Ispitivanje zatezanjem
Testovi zatezanjem su izvedeni u skladu sa standardom EN ISO 6892-1 [20], kako bi se odredile mehaničke osobine zavarenog spoja. Uzorci za ispitivanje su bili pripremljeni u skladu sa standardom EN ISO 4136 [21]. U cilju provere, dva uzorka osnovnog materijala su ispitana. Dobijene su prosečne vrednosti od $R_{p0.2}=1035$ MPa i $R_m=1151$ MPa. 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 smanjena na 86% vrednosti zatezne čvrstoće osnovnog materijala. Granica tečenja je takodje smanjena 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.
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.

Table 6. Mechanical properties of welded joint

| Sample | Mechanical properties | Place of fracture |
|--------|-----------------------|-------------------|
|        | R_p0.2, MPa | R_m, MPa | A, %     |
| 1-1    | 794           | 826       | 5        |
| 1-2    | 836           | 858       | 3        |
| Average value | 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.
Acknowledgements
The authors gratefully acknowledge the contribution of the Education Grant Agency of the Slovak Republic under the grant no. 009ŽU-4/2019. Next the research was supported by the Slovak Research and Development Agency under the contract no. APVV-16-0276 and APVV-16-0300 and next by the ITMS 26210120017 Project of “Centre for research and development in the field of the electron-beam and progressive arc technologies of welding, cladding and surface-finishing”.

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., Nový, 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. Pala, I. Dzioba, Arch. Metall. Mater. 62 (4), 2081-2087 (2017).
[13] S. Blacha, M.S. Węgierski, 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.