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ANALYSIS OF MECHANICAL AND STRUCTURAL PROPERTIES OF MICRO ALLOYED STEEL WELDED JOINTS DEPENDING ON QUALITY OF CORED WIRE

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Original scientific paper

The aim of this study was to master new quality cored wires made of steel strips and the cores filled with metal powders and low molecular hydrophobic compounds. For experimental research, the specimens were made of micro alloyed steel type NIOMOL 490K intended for making welded structures subjected to dynamic loads and effects of low temperature. Welding of test specimens was done using the MAG method in CO_2 shielding with two new quality cored wires. The testing included the determination of mechanical properties of the base metal (BM) and the weld metal (WM), which apart from having sufficient strength must also have good toughness. The microstructures of BM, WM and heat affected zone (HAZ) were analysed, due to possible formation of a heterogeneous microstructure, which can reduce toughness. Results of testing of welded joints should define a new quality of cored wires in view of welding-technological characteristics. The results indicate that the new quality cored wires can produce good mechanical-structural properties of welded joints.

Keywords: *cored wire, mechanical properties of welded joints, micro alloyed steel welding, microstructure*

Analiza mehaničkih i strukturnih svojstava zavarenih spojeva mikrolegiranog čelika u ovisnosti o kvaliteti punjenih žica

Izvorni znanstveni članak

Cilj istraživanja bio je homologizirati punjene žice izrađene od uske čelične trake i jezgra ispunjenog metalnim prahovima i niskomolekularnim hidrofobnim spojevima bolje kvalitete. Za ispitivanje su izrađene epruvete od mikrolegiranog čelika NIOMOL 490K, namijenjenog za izradu zavarenih konstrukcija izloženih dinamičkom opterećenju i djelovanju niske temperature. Zavarivanje epruveta je urađeno u zaštiti CO_2 postupkom (MAG) s dvije različite kvalitete niklom punjene žice. Izvršeno je ispitivanje mehaničkih svojstava osnovnog materijala (OM) i metala šava (MŠ), koji pored dovoljne čvrstoće mora imati i dobru žilavost. Također su izvršena i metalografska ispitivanja OM, MŠ i zone utjecaja topline (ZUT), zbog heterogenosti mikrostrukture koja može smanjiti žilavost. Rezultati ispitivanja zavarenih spojeva izvedenih s ovim kvalitetnim punjenim žicama trebaju definirati novi proizvod u pogledu zavarivačko-tehnoloških karakteristika. Dobiveni rezultati ukazuju da se novom kvalitetom punjenih žica mogu dobiti dobra mehaničko-strukturna svojstva zavarenih spojeva.

Ključne riječi: *mehanička svojstva zavarenog spoja, mikrostruktura, punjena žica, zavarivanje mikrolegiranog čelika*

1 Introduction

Worldwide there is a growing trend of use of fine grained structural steels, which are used in all areas of technology where a high efficiency of usage of tensile strength is required, i.e. ratio R_e/R_m is as high as possible. Fine grained structural steels have low carbon content and are micro alloyed with alloying elements in small quantities, to increase the yield stress from 400 to 1000 MPa. With this class of steel the symbol R_e points out that the yield stress, i.e. plastic limit, is the main property for characterization of these materials; its minimum value is expressed in MPa and contained in the primary marker of steel [1, 2]. For micro alloyed fine grain structural steels, often used alloying elements are aluminium, niobium, vanadium and titanium, which in the reaction with nitrogen and carbon form nitrides, carbides or carbonitrides preventing the growth of crystal grains in the austenite region. This allows getting crystal grains size 6 or smaller in delivery condition or after welding. Aluminium from 0,020 % to 0,050 % binds nitrogen into finely distributed nitrides, decreasing in grain size, increasing yield strength and providing resistance to brittle fracture. Adding aluminium secures that the steel is resistant to aging and insensitive to stress corrosion. The addition of Nb, V or Ti either alone or in combinations of two or three elements also binds nitrogen into nitrides and with carbon forms carbides which provide finely spaced non-metal inclusions. Niobium already forms carbonitrides at quantities of 0,005 % to 0,010 % and significantly increases the yield stress, but toughness deteriorates, so its effect must be coordinated with the correct choice of thermo mechanical treatment. Vanadium is added in the amount of 0,05 ÷ 0,15 % and has the same effect as Nb. Vanadium has a stronger effect on decreasing the grain size due to faster and easier production of VN and VCN than AlN. The joint effect of adding V + Nb significantly increases the yield stress and with the proper selection of thermo mechanical treatment does not reduce toughness. Similar effects are present when adding Nb and Ti together. Yield stress increases significantly in the normalized condition, and additional release further weakens the effect due to agglomeration of carbonitrides. Properties of fine grained structural steels are set by the standard EN 10025. Fine grained structural steels are used in the area of lower temperatures to –60 °C. The chosen fine grained micro alloyed steel designed for welded structures is NIOMOL 490K with a minimal yield stress of R_e = 490 MPa. The structure of the micro alloyed steel of high strength, obtained by the process of thermo-mechanical treatment is fine-grained ferrite-pearlite [3 ÷ 5]. Micro alloyed steel's resistance to brittle fracture is checked by impact examination, by determining of impact energy consumption using Charpy KV standard specimens. For sheets and strips, the testing is done in transversal direction with respect to the rolling direction, while for profiles and rods it is done in longitudinal direction. For some steels for lower temperatures checking of impact energy in a normalized and aged condition at room temperature is requested [4].

Choice of filler for welding fine grained structural steels is based on chemical composition and mechanical -

structural characteristics of the base metal (BM), welding process and projected requirements for the properties of welded joints [3, 4, 6 ÷ 10]. The most important alloying chemical elements in the filler for welding fine grained structural steels are Ni and Mo which have a significant impact on the quality of the weld metal (WM). Nickel favours the formation of needle-acicular ferrite; it increases the resistance of the weld metal to brittle fracture, so it is a regular alloying element of WM of fine grained micro alloyed steels. Addition of nickel over 1,5 %, significantly increases yield stress due to shifts in the transformation of γ to α. Molybdenum in the filler decreases the temperature of transformation of α to γ, reduces grain size in the primary structure of WM, increases the amount of acicular ferrite and removes the upper bainite, retaining the thin plates of primary ferrite in the weld metal base. Molybdenum in the filler significantly increases the yield stress with favourable toughness.

Mechanical properties and microstructure of welded joints are of crucial importance for safety and reliability in operation mode [11 ÷ 14]. Welded joint properties of micro alloyed steels, such as impact toughness and tensile strength are closely related to chemical composition, rate of solidification and recrystallization and microstructure [3, 5, 6]. Welding parameters such as current strength, voltage and welding speed define the heat input during welding [4]. The heat-affected zone (HAZ), heated from 1050 °C to 1150 °C, has a high influence on the welded joint properties. Width of the HAZ depends on the welding parameters, while the changes of these parameters alter the specific heat input. When welding fine grained steels in particular, the amount of heat introduced should be taken into account; too much heat induces coarse grain formation and decrease in toughness [15, 16]. In the heat affected zone, dissolution occurs of carbide, nitride, carbonitride, as well as austenite grain growth. The microstructure of HAZ has a ferrite-pearlite structure and rarely a bainite structure which depends on the thermal welding cycle [3, 4]. The thermal cycle of welding results in heterogeneity of the mechanical and metallurgical properties in the heat affected zone and weld metal [17, 18]. The overall and local inequality of the material strength and the presence of errors directly affect the load carrying capacity of the weld metal and fracture toughness. Under the influence of repeated thermal cycles, in the narrow region of the HAZ, areas of reduced toughness appear along the fusion line. There are a large number of different factors that influence the toughness of the HAZ of micro alloyed steels [4, 19 ÷ 21]. In the multipass weld metal, the thermal cycle of the subsequent passing affects the previously created weld metal layer and the HAZ, which multiplies the diversity of micro structural areas. Some of them have the character of local brittle areas (LBA) and can influence the toughness of the welded joint as a whole. They are often places of emergence and spreading of a brittle fracture [22 ÷ 24]. The microstructure of weld metal of fine grain steel joints can be made up of three modifications of ferrite. These are needle ferrite (acicular ferrite), polygonal ferrite (primary ferrite) and Widmanstatten ferrite, which occur due to different mechanisms of transformation and differently affect the strength and toughness of the welded joint. By outer appearance, the tiny grains of needle ferrite are separated by high carbon boundaries. Such a structure of needle ferrite provides maximum resistance to crack development [4, 19].

In this paper, the results of experimental research of the effects of content of nickel and molybdenum in cored wires on the mechanical properties and microstructure of welded joints of micro alloyed steel NIOMOL 490K are presented. The main objective of this study was to master new qualities of cored wires marked FW Ni2Mo and FW Ni1Mo made of narrow steel strips and metal powder and low molecular hydrophobic compounds filled cores. Welding of samples was done using the MAG welding process. Mechanical properties of the BM and WM were examined and metallographic tests of the BM, WM and HAZ were done. The obtained results indicate that the new quality cored wires can give good mechanical - structural properties of welded joints at room temperature.

2 Materials and experimental details

For the experimental welding, two types of quality cored wire were used, marking FW Ni2Mo (2,30 to 2,70 % Ni and 0,26 ÷ 0,3 % Mo) and marking FW Ni1Mo (0,706 ÷ 1,00 % Ni and 0,36 ÷ 0,4 % Mo) with a 3,8 mm diameter and a steel NIOMOL 490K as the base metal. In Fig. 1, the samples of cored wire are shown.

Figure 1 Cored wire FW Ni2Mo and FW Ni1Mo

Properties of micro alloyed steel NIOMOL 490K are set by the standard SRPS EN 10025. This type of steel is micro alloyed with molybdenum; it has yield stress of at least 490 MPa and toughness of 24 ÷ 34 J at a low temperature of –60 °C. The chemical composition of the steel is given in Tab. 1, and its mechanical properties are shown in Tab. 2.

Table 1 Chemical composition of NIOMOL 490K /wt.%

C	Si	Mn	P	S	Al	Cr
0,10	0,41	0,57	0,008	0,002	0,042	0,53

Table 2 Mechanical properties of NIOMOL 490K

Direction	Yield strength	Ultimate strength	Elongation at fracture	Impact energy
	$R_{p0,2}$ / MPa	R_m / MPa	A / %	ISO-V / J
L-T	576	694	28,1	242, 248, 263
T-L	571	699	22,8	245, 248, 255

L – longitudinal direction, T – transverse direction

Preparation of edges of experimental 12 mm thick plates of micro alloyed steel NIOMOL 490K was done at an angle of 60º (for the MAG welding process in CO_2 shielding), Fig. 2.

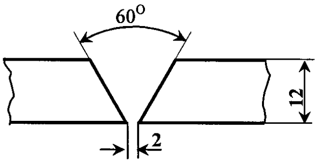


Figure 2 Preparation of edges of the experimental plates

The welding parameters of micro alloyed steel were selected beforehand for their optimization. Welding of test samples was done using the MAG process with a combination of gases Ar/CO_2 at a ratio 80/20 with cored wires FW Ni2Mo and FW Ni1Mo. Welding parameters are given in Tab. 3.

Table 3 Welding parameters

Welding process	Voltage / V	Current / A	Welding rate / cm/mm	Heat input / kJ/cm
MAG	28	310	32	16 ÷ 18

In Fig. 3, a welded plate (thickness 12 mm), from which the test specimens were cut, is shown.

Figure 3 Welded plate

In Fig. 4, a sketch of cutting of specimens from welded plates for testing of BM and welded joints is shown. The following specimens were cut from the plates: K - break test specimen, S - bending test specimen, T - toughness test specimen at +20 °C and M - specimens for metallographic testing of BM, WM and HAZ.

Spectrochemical analysis of the weld metal chemical composition was performed using the OES method on the ARL 2460 apparatus.

Yield stress, tensile strength and elongation of weld metal were tested on flat specimens with parallel and concave sides, on the AMSLER brake testing machine according to the standards SRPS EN 895 and SRPS EN 10002-1/1.

Resistibility of the base metal, weld metal and heat affected zone to brittle fracture was verified by examining impact at room temperature while determining impact energy consumption KV (J), using 10 × 10 × 55 mm Charpy type specimens with the ISO-V notch to the SRPS EN 875 and SRPS EN 10045-1 standards.

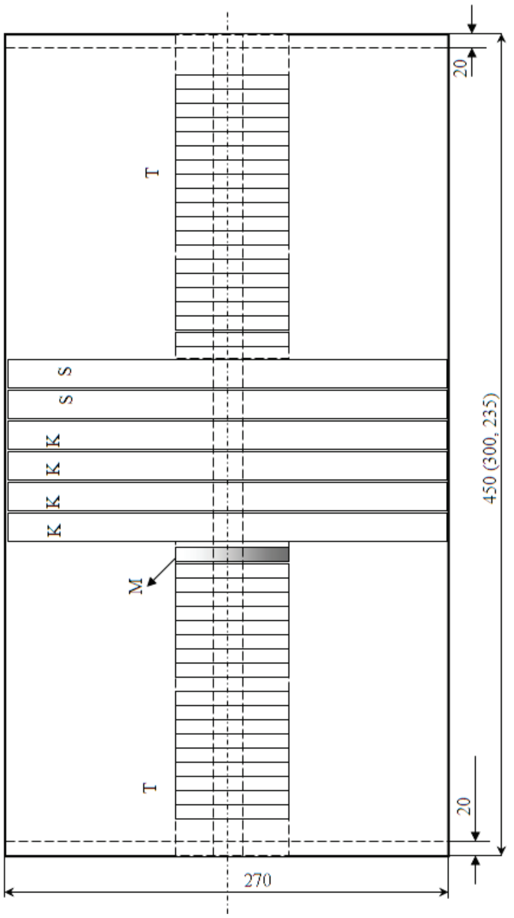


Figure 4 Sketch of cutting specimens for mechanical testing of base metal and welded joints

Examination of the base metal and welded joints microstructure was carried out under a light microscope according to SRPS EN1321 standard. Etching of samples was performed in 3 % nital. The structure of the base metal, weld metal and heat affected zone was examined.

3 Results and discussion

Tab. 4 contains the chemical composition of weld metal of welded samples No. 1 with cored wire FW Ni2Mo (2,30 ÷ 2,70 % Ni and 0,2 ÷ 0,3 % Mo) and samples No. 2 with cored wire FW Ni1Mo (0,70 ÷ 1,00 % Ni and 0,3 ÷ 0,4 % Mo). Control of the composition of the weld metal was done so the connection of the content of Ni and Mo and microstructure of welded joints could be made. Examination of the chemical composition confirmed that the content of elements Ni and Mo in the weld metal was within the set limits of cored wire quality.

The values of yield stress, tensile strength and elongation of weld metal are shown in Tab. 5. Ni content of over 1,5 % in the weld metal in sample No. 1 influenced increase in the value of yield stress and tensile strength compared to sample No. 2 with lower Ni content. Higher content of Ni favoured formation of a higher share of needle - acicular ferrite in the weld metal base in sample No. 1. These values were confirmed by metallographic examination of samples under a light microscope.

Table 4 Chemical composition of weld metal

Spec.	Chemical composition / wt. %										
	C	Si	Mn	S	Cr	P	Cu	Ni	Mo	Ti	Al
No. 1	0,07	0,27	1,120	0,012	0,022	0,012	0,52	2,598	0,233	0,020	0,016
No. 2	0,07	0,26	1,047	0,013	0,022	0,012	0,55	1,192	0,326	0,023	0,015

Table 5 Yield stress, tensile strength and elongation of weld metal

Spec.	Test specimen type	Dimens. of test specimens $a \times b$ / mm	Yield stress $R_{p0,2}$ / MPa	Tensile strength R_m / MPa	Elongation at fracture A / %	Break point
No. 1	With parallel sides	12 × 20	540	670	>24	BM - HAZ
No. 2	With parallel sides	12 × 20	520	630	>24	HAZ
No. 1	With sunk sides	12 × 24	570	700	>22	/
No. 2	With sunk sides	12 × 24	564	690	>22	/

The structure of the weld metal for both samples was dendrite pearlite - ferrite with acicular ferrite. Mo content of 0,2 ÷ 0,3 % in the weld metal of both samples further influenced fragmentation of the primary structure of the weld metal. Molybdenum with Ni in both samples positively influenced the formation of acicular ferrite. At the same time, they eliminated the formation of upper bainite in the weld metal, which increased the yield stress of the weld metal while achieving favourable toughness.

The values of consumed impact energy for the base metal, weld metal and heat affected zone are shown in Tab. 6. Based on the fracture properties of the weld metal and heat affected zone, it transpires that the fracture toughness of the heat affected zone is greater than the fracture toughness of the weld metal. The fracture in the heat affected zone shows a tough property at +20 °C. The measured values are consistent with the microstructure which was examined by light microscopy. The fine-grained heat affected zone with a ferrite-pearlite structure and spheroidized pearlite influenced greater impact energy consumption and increased toughness.

Impact energy consumption in all the samples is quite uniform, indicating that the weld metal and heat-affected zone have no local brittle zones. The highest toughness values were achieved in the weld metal and heat affected zone with cored wire IHIS FW Ni2Mo (2,30 ÷ 2,70 % Ni and 0,2 ÷ 0,3 % Mo). The increased nickel content has favourably affected the increase in toughness. Fracture properties of the weld metal and heat affected zone show that the tested weld metal is completely reliable at +20 °C.

Table 6 Impact energy of the weld metal

Spec.	Position of notch	Impact energy kV/J at +20 °C		
		1	2	3
1	WM	198	218	208
1	HAZ	280	246	260
2	WM	159	173	184
2	HAZ	249	225	234
BM	BM	291	304	291

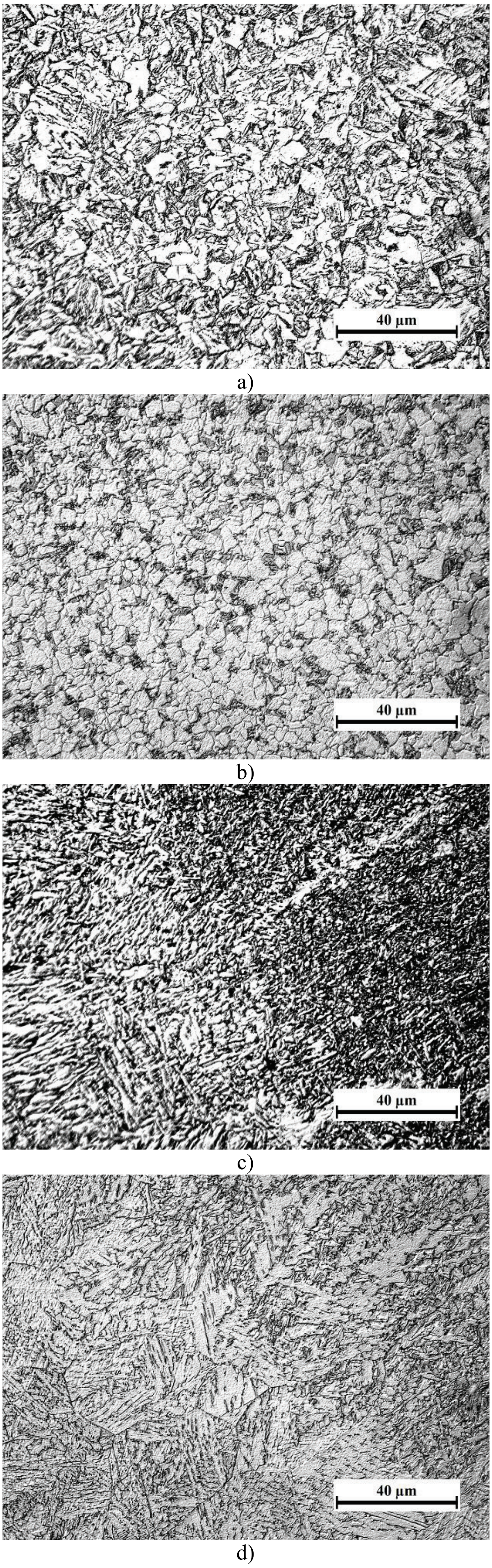
Fig. 5 shows the microstructure of the welded joint of sample No. 2, which is identical to the microstructure of the welded joint of sample No. 1. The micrographs shown relate to: a) BM, b) HAZ, c) HAZ fusion line, d) transitional zone between the HAZ and WM and e) WM. The microstructure of the base metal is a homogeneous fine-grained ferrite - pearlite, which is characteristic of the micro alloyed steel NIOMOL 490K of high strength. Fig. 5a clearly shows a delicate fine-grained structure of the base metal. In the heat affected zone microstructure is fine grained, ferrite - pearlite with spheroidized pearlite, which corresponds to the normalized structure of the heat affected zone. Fig. 5b clearly shows a delicate structure with fine-grained spheroidized pearlite in the HAZ.

The thermal cycle of welding has been optimized so that above temperature A_3 (1050 ÷ 1150 °C) there was no intensive growth of primary austenite grains. The optimal cooling rate influenced forming of a ferrite-pearlite structure. Also, in the heat affected zone there was no brittle phase bainite. Along the fusion line and the HAZ, grain growth and presence of bainite were not detected, Fig. 5c. The microstructure of the fusion line and transitional zone between the HAZ and the WM is fine-grained.

The transitional zone between the heat affected zone and weld metal is shown in Fig. 5d. The structure of the weld metal is of dendrite pearlite - ferrite with acicular ferrite, Fig. 5e. Acicular ferrite is a type of ferrite characterized by needle-shaped crystals. Three-dimensional shaped grains have a thin lens like form. This microstructure has an advantage over other microstructures, which increase toughness. Needle ferrite is formed in the interior of the austenite grains with the direct formation of germs from the inclusions, which resulted in the formation of randomly oriented short ferrite needles in the form of a woven mesh. This natural interweaving of ferrite needles, along with its fine grain size of 0,5 ÷ 5 μm, provides maximum resistance to cracking. Alloying elements Ni and Mo from cored wires were favourable for the formation of needle-acicular ferrite in the weld metal. Molybdenum influenced fragmentation of the primary structure of the weld metal and combined with Ni increased the amount of acicular ferrite. The presence of these elements prevented the formation of upper bainite in the weld metal, while retaining the primary ferrite in the weld metal base. This resulted in increased yield stress with favourable toughness.

4 Conclusion

This paper presents an analysis of the influence of Ni and Mo in cored wires FW Ni2Mo (2,30 ÷ 2,70 % Ni and 0,2 ÷ 0,3 % Mo) and FW Ni1Mo (0,70 ÷ 1,00 % Ni and 0,3 ÷ 0,4 % Mo) on the mechanical properties and microstructure of welded joints of micro alloyed steel NIOMOL 490K. The analysis led to the following conclusions:



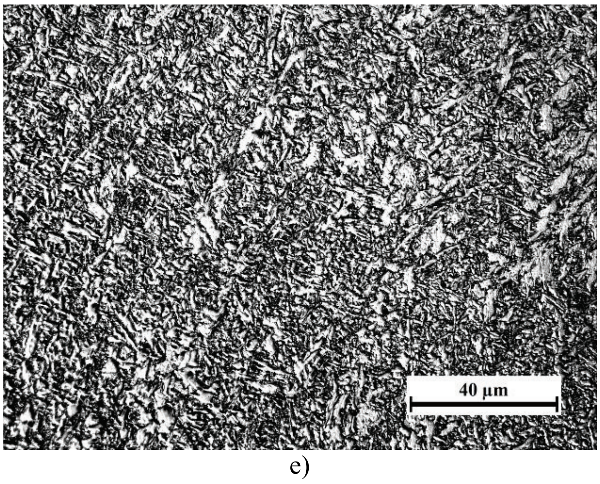


Figure 5 Microstructure of welded joint of weld sample No. 2: a) BM; b) HAZ; c) HAZ - fusion line; d) the transition zone between HAZ and WM, and e) WM.

Testing of the chemical composition of weld metal has confirmed that the contents of Ni and Mo were in the set limits of the new quality cored wire.

Ni content of over 1,5 % in the weld metal influenced increase in yield stress and tensile strength. Mo content of 0,2 ÷ 0,3 % in the weld metal further influenced fragmentation of the primary structure of the weld metal, which increased yield stress of the weld metal while obtaining favourable toughness.

Fracture toughness of the heat affected zone is higher than the fracture toughness of the weld metal. Fracture in the heat affected zone showed toughness properties at +20 °C. The amounts of consumed impact energy were in accordance with the microstructure. The fine-grained heat affected zone with ferrite-pearlite structure and spheroidized pearlite caused greater impact energy consumption and increase in toughness. The impact energy consumed for all samples was quite uniform, indicating that in the WM and HAZ there were no local brittle zones (LBZ) present. The highest toughness values were achieved in WM and HAZ with cored wire FW Ni2Mo. The increased nickel content favourably affected the increase in toughness. Fracture properties of the weld metal and heat affected zone show that the tested welded joint is completely safe in working mode at +20 °C.

The microstructure of the base metal is a homogeneous fine-grained ferrite - pearlite, which is characteristic of micro alloyed steel NIOMOL 490K. The microstructure of the HAZ is fine-grained ferrite - pearlite with spheroidized pearlite, which corresponds to the normalized structure. None of the tested samples showed presents of a brittle bainite phase in the HAZ. Along the fusion line and the HAZ no grain growth or presence of bainite were observed. The microstructure at the location of the fusion line and the transitional zone between the HAZ and weld metal is fine-grained. The structure of the WM is dendrite pearlite ferrite with acicular ferrite. Alloying elements Ni and Mo were favourable for the formation of needle-acicular ferrite in the weld metal. Molybdenum influenced fragmentation of the primary structure of the weld metal and with Ni increased the amount of acicular ferrite. The presence of these elements prevented the formation of upper bainite in the WM, while retaining the primary ferrite in the weld metal base. This resulted in the increase of yield stress with favourable toughness of the welded joint.

By using cored wire FW Ni2Mo for welding micro alloyed steel NIOMOL 490K, a good combination of mechanical properties and microstructure was achieved. The obtained results confirmed that with the new quality of cored wires good mechanical - structural properties of welded joints of fine-grained micro alloyed steel NIOMOL 490K can be achieved.

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