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Koceľova 15
815 94 Bratislava
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e-mail: zvaranie@centrum.sk
web: www.szswelding.sk

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  [1] Research Center, University of Žilina, Univerzitna 1, 010 26 Žilina, Slovakia
  [2] Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, 34000 Kragujevac, Serbia

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Možnosť nahradenia nízkouhlíkových konštrukčných ocelí vysokopevnostnými oceľami na výrobu zváraných konštrukcií v priemysle ťažkých strojov

Possibility of replacing low-carbon construction steels with high strength steels for producing the welded structures in heavy machinery industry

Prof. Ing. Ružica R. NIKOLIĆ[1), Res. Assoc. Ing. Djordje IVKOVIĆ[2), Assist. Prof. Ing. Dušan ARSIĆ[2), Prof. Ing. Vukić LAZIĆ[2), Ing. Martina JACKOVÁ[1)

Organizácia / Organization:
[1) Research Center, University of Žilina, Univerzitna 1, 010 26 Žilina, Slovakia
[2) Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, 34000 Kragujevac, Serbia

Tel.: +421 / 948 610 520 (Ružica R. Nikolić) **E-mail:** ruzica.nikolic@uniza.sk
ruzicarnikolic@yahoo.com

Abstrakt:

Moderné trendy výskumu a vývoja nových výrobkov sa zameriavajú na úsporu materiálov prostredníctvom znižovania hmotnosti rôznych častí, preto sa vysokopevnostné ocele (VPO) používajú častejšie ako bežné nízkouhlíkové konštrukčné ocele. Je dobre známe, že vysoká pevnosť HSS poskytuje možnosť výroby dielov s menšími rozmermi a prierezmi. To často vedie k zníženiu hmotnosti dielov a celých konštrukcií. Tu sú prezentované výsledky pokusu o nahradenie bežne používanej nízkouhlíkovej konštrukčnej ocele S235JR, ktorá má dobrú zvariteľnosť, vysokopevnostnou oceľou, v priemysle ťažkých strojov. Hlavným cieľom je zníženie hmotnosti pri zachovaní primeranej nosnosti a spoľahlivosti konštrukcií. Analyzovala sa konštrukčná oceľ P460NL1, výhody a nevýhody použitia HSS, zložitosť výberu vhodnej metódy zvárania, prídavných materiálov a technológie zvárania. Po skúšobnom zváraní na vzorkách sa vykonalo experimentálne overenie dôležitých mechanických a mikroštruktúrnych vlastností použitej náhradnej ocele.

Abstract:

Modern trends of research and development of new products are focused on saving materials through mass reduction of various parts, so the high strength steels (HSS) are used more often than the conventional low-carbon structural steels. It is well known that the HSS's high strength is providing the possibility for parts to be produced with smaller dimensions and cross-sections. This often results in the weight decrease of parts and whole structures. Here are presented results on an attempt to replace commonly used, low-carbon, structural steel S235JR, which has good weldability, with high strength steel, in industry of heavy machinery. The main objective is weight reduction while keeping the adequate load carrying capacity and reliability of structures. The structural steel P460NL1 was analyzed, as well as advantages and disadvantages of HSS application, complexity of selecting the adequate welding method, filler materials and welding technology. After the trial welding on samples, experimental verifying of important mechanical and microstructural properties was conducted of the applied replacement steel.

An analysis of the possibility to replace the low carbon construction steel S235JR with the high-strength steel P460NL1, is presented in this paper, i.e., all the advantages and disadvantages of using this HSS and selection of adequate welding technology, were considered.

2. Properties of the high strength steel

Steel P460NL1 is a fine-grained steel intended for the production of bottles and pipes under pressure. Due to its high strength, it belongs to the category of high-strength steels.
The chemical composition of this steel is shown in Tab. 1, and its mechanical properties in Tab. 2, [1-3].

Tab. 1 Chemical composition of the high strength steel P460NL1

C	Mn	Si	P_{max}	S_{max}	Cr_{max}	Ni	Al	Cu_{max}
0.20	1.52	0.41	0.008	0.001	0.13	0.47	0.02	0.18
Ti_{max}	Mo_{max}	Nb_{max}	V	Sn_{max}	As_{max}	Sb_{max}	Co_{max}	
0.0029	0.02	0.002	0.111	0.014	0.009	0.001	0.001	

Tab. 2 Mechanical properties of the high strength steel P460NL1

R_m, MPa	R_{eH}, MPa	A_5, %	Z, %	$KCV_{-40°C}$, J	$KCV_{-30°C}$, J	HV
725	473	19.2	38.0	32-35	42-45	207-210

3. Weldability assessment of the high strength steel

Selecting the most favorable welding technology is a complex technical and technological problem, which requires collecting and using a large amount of information and data for the base metal (BM) to be welded. That allows getting a broader picture of its behavior in different conditions. In addition to the chemical composition in the specific case, it is necessary to know whether it possesses the ability to form welded joints, i.e., its weldability. Further, the proneness of the steel in question to appearance of the cold cracks must be checked, as well. One of the most important tasks is selecting the appropriate filler metal (FM) for each base metal used. That selection depends on the type and grade of a particular steel, as well as on which properties of the welded joints are the most important in a certain structure, whether that is the weld's strength, or hardness or resistance to corrosion, or cracks.

The weldability of steel materials can be investigated in different ways, and in this paper, results are presented of the steels' weldability assessment obtained by applying computational/empirical expressions, [4-7].

The assessment of weldability according to the Chemically Equivalent carbon (CE) criterion is performed according to appropriate formulas that differ depending on the class of the steel being welded. Those formulas use the steel's chemical composition, i.e., the elements' shares, expressed in percents.

For evaluation of the steel P460NL1 weldability, the equivalent carbon (CE) is calculated according to expression (1), [4]. The limit value of CE for this type of steels is 0.35.

$$CE = C + \frac{Mn}{10} + \frac{V}{3} + 3 \cdot Ni\,. \qquad (1)$$

The CE value obtained for this steel was 0.392, which is bigger than the limit value of 0.35, what implies that this steel is conditionally weldable and that the preheating is necessary for successful welding.

For estimates of the steel's proneness to appearance of the cold cracks one uses the formulas that also use the shares of elements in the chemical composition of the material. However, the additional factors must be considered, those being influence of the material's thickness and the amount of the diffused hydrogen, which could enter the welded joint from the filler metal, [4-6].

The formulas used are the following:

$$P_{hp} = P_{CM} + \frac{K}{40000} + 0.015 \cdot \log\frac{H}{2.77} \quad \text{for } K \leq 1300 \tag{2}$$

and

$$P_{hp} = P_{CM} + \frac{K}{40000} + 0.075 \cdot \log\frac{H}{2.77} \quad \text{for } K > 1300, \tag{3}$$

with

$$P_{CM} = C + \frac{Si}{30} + \frac{Mn + Cu + Cr}{20} + \frac{Ni}{60} + \frac{Mo + V}{15} + 5 \cdot B\,, \tag{4}$$

where K is the stiffness intensity, calculated as a function of material's thickness s, mm, i.e., $K = 69 \cdot s\,, N/mm$; H is the content of the diffused hydrogen in ml per 100 g of the weld metal (WM). The limit value of P_{hp} is 0.24, which implies that if $P_{hp} \geq 0.24$ the steel in question is prone to formation of the cold cracks. Since the calculated value for the P460NL1 steel is 0.357, it means that it is prone to formation of cold cracks. Thus, heat treatment is necessary for obtaining healthy, crack-free welds.

The preheating temperature T_p is calculated according to empirical formulas or materials manufacturers' recommendations, [4-7]. For steel P460NL1 the preheating temperature is calculated according to the formula proposed by [4]:

$$T_p = 1600 \cdot P_{hp} - 308\ , \ ^\circ C. \tag{2}$$

The calculated value is 263.2 °C, so the adopted value was T_p = 265 °C.

4. Selecting the optimal welding technology

For the high-strength steel considered, it is necessary to select/define the most favorable, i.e., the optimal welding technology, [8]. The starting point is the choice of the welding procedure and appropriate additional materials (filler metals), and in the previous part it was established that due to the tendency of these steels to appear cold cracks, it is necessary to apply supplementary measures for its successful welding. For the considered steel, appropriate additional material was first selected, after which the test welding was performed.

The test welding of P460NL1 steel was performed using the MMAW procedure with preheating of the welded parts to 265 °C to prevent the appearance of cold cracks. The Galeb 70 electrode was used as a filler metal and the thickness of the welded samples was 20 mm, (Slovenian Steel Group, d. d., Jesenice, Slovenia), [9]. Tabs. 3, 4 and 5 present the chemical composition of the electrode, its mechanical properties and the welding parameters, respectively.

Tab. 3 Chemical composition of the electrode Galeb 70

Chemical composition, %				
C	Si	Mn	Ni	Mo
0.1	0.9	1.5	0.7	0.2

Tab. 4 Mechanical properties of the electrode Galeb 70

R_m, MPa	R_{eH}, MPa	A_5, %	KV, J
640-710	520-600	22-26	125-155

Tab. 5 Welding parameters for application of the electrode Galeb 70

s, mm	D_c, mm	J, A	U, V	v, mm/s	q, J/mm
20	2.5-3.25	90-130	23-25	1.46-3.8	695.8-1780.8

5. Experimental sample welding and test

The welding of the test samples was carried out using the previously described procedures. The objective was to find out how would the welding influence the original material characteristics of the selected HSS, i.e., would it still be possible to use it as a substitute for the low carbon steel S235JR, [14, 15].

The test samples of P460NL1 steel were welded with preheating of parts to 265 °C, due to the tendency for cold cracks appearance in the heat-affected zone. After the welding, appropriate samples were prepared for testing the tensile strength and impact toughness. For the tensile testing of steel P460NL1, prismatic samples with flat sides were prepared from welded plates, which were used to check the properties of the base material and the welded joint, Fig. 1.

Standard V-notch samples were used for impact toughness testing of the base metals, as well as of the welded joint with the V-notch on the weld's face. Six samples were prepared for the tensile test, three from the base metal and three from the welded plates, [16], Fig. 2. The results of the tensile test are shown in Fig. 3 in the form of a histogram.

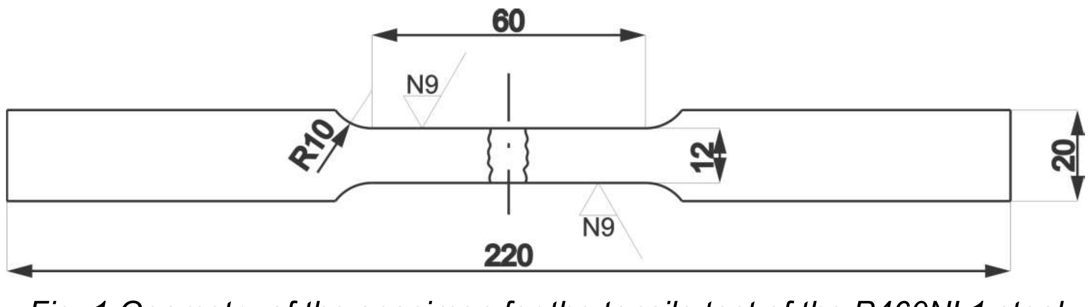


Fig. 1 Geometry of the specimen for the tensile test of the P460NL1 steel

The obtained results of the tension test show that the applied welding technology is suitable for the real parts welding because the yield stress and tensile strength values are close to or higher than the values obtained for the base metal.

a) *b)*

Fig. 2 Real appearance of the specimen for the tensile test: BM a); welded joint b)

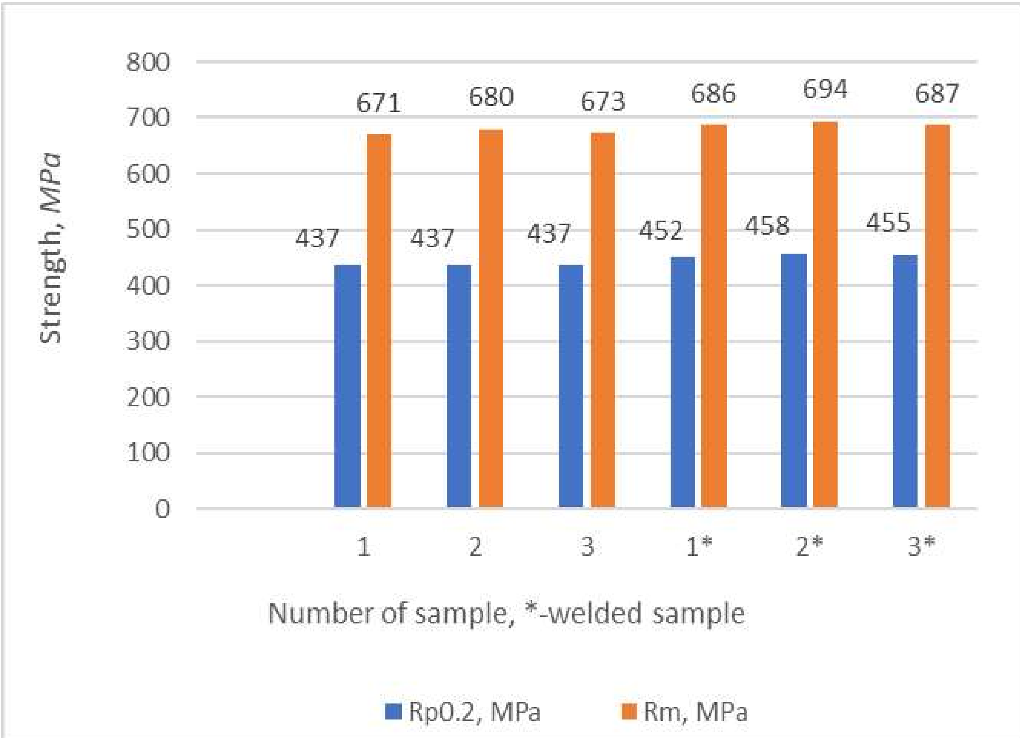


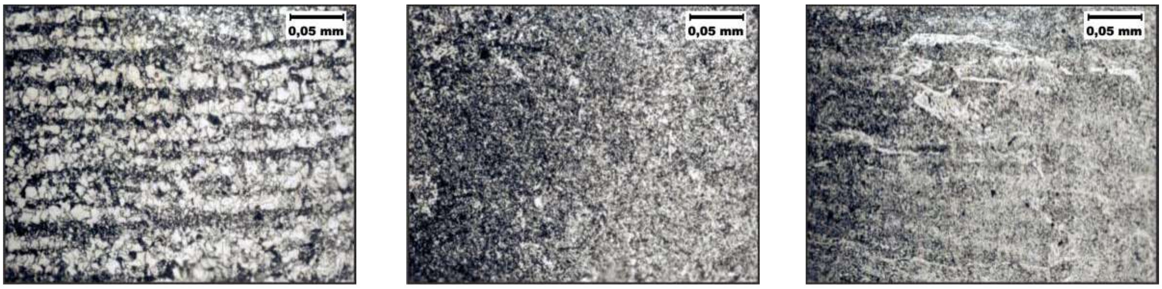
Fig. 3 Histogram display of the tensile test results

The results of the impact toughness test, [17], are shown in Tab. 6 and they also indicate that the applied technology can be applied for the welding real parts because the toughness of the parts obtained is significantly higher than the toughness of BM.

Tab. 6 Impact toughness test results for the P460NL1 steel

Notch	Base metal			Middel of the weld		
Sketch						
No	1	2	3	1	2	3
KV_2, 10^{-4} *J/mm*^{2}	129	94	120	228	195	246

Metallographic tests were also performed for the welded plates made of P460NL1 steel. A fine-grained ferrite-pearlite structure was observed in the base metal (BM), a finely distributed ferrite-perlite structure in the HAZ, and a Widmanstetten structure with the presence of interphase structures was shown in the weld metal (Fig. 4).



a) b) c)

Fig. 4 View of the microstructure of the P460NL1 steel: BM a); HAZ b); WM c)

The hardness measurement results, [18], show slightly higher values, however the obtained values are certainly less than 350 HV, which shows that the martensite formation did not occur (Fig. 5).

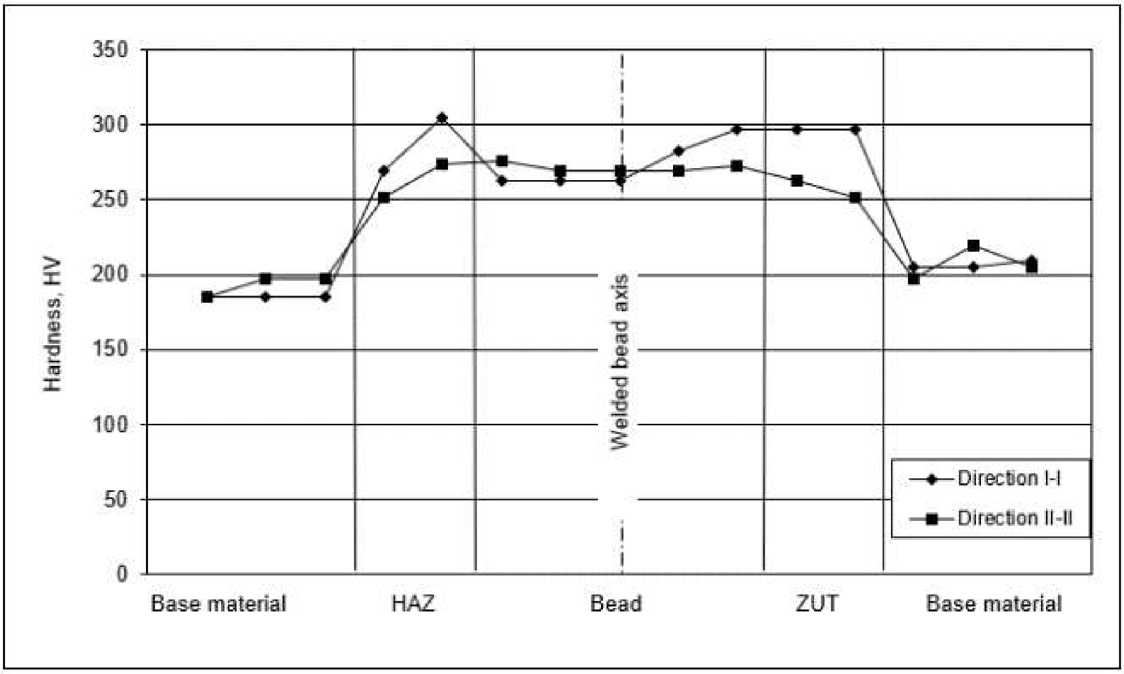


Fig. 5 Hardness distribution in the welded joint of the P460NL1 steel

6. Effect of replacing low carbon structural steel by HSS

The dimensions of the cross-sections of the parts are calculated by applying appropriate formulas in which the yield stress is most often a variable, and a relation can be established between the yield stress and the cross-section size of a part. The lower yield stress of a material would require the larger cross-section of the part in order for it to withstand the given load, and vice versa, the higher the yield stress, for the same load, the smaller the cross-section of a part. Considering that steel materials have the same density, parts of the same length with an increase in cross-sectional dimensions would have larger mass. Therefore, it can be concluded that the mass of a structure and the yield stress of the material are inversely proportional. The possibility of reducing the mass of a welded structure is further shown on a theoretical example.

A typical representative of the low-carbon structural steels is S235JR, [1]. This steel is widely used in mechanical engineering, especially for production of the welded structures. The main reason for this is its good weldability (due to low C content), satisfactory mechanical properties (R_m = 360-500 MPa, $R_{p0.2}$ = 235 MPa), as well as its low price compared to other structural steels. This steel is also applied for producing the parts of the chassis of railway wagon.

By using the steel, the yield stress value of which is different from the value of the used steel, the dimensions and mass of the parts would be different. It is clear that the use of a stronger material results in a lower mass of parts, and the yield stress ratio of the original and new material can be used as an indicator of potential reduction.

Let the complex welded construction of a railway wagon chassis be made of S235JR steel, the yield stress of which is 235 MPa, then let its mass be marked as 1, i.e., 100 %. The relationship between the yield stress of steel P460NL1 and S235JR and of steel is $Rp_{0.2}^{P460NL1}/Rp_{0.2}^{S235JR}$ = 2.01. This means that with the use of P460NL1, the expected mass of a structure is 2.01 times smaller, i.e., it would be 49.75 % of the mass of a structure that would be obtained from the S235JR steel.

It should be emphasized that the obtained result is only a theoretical indicator; some parts, despite the greater strength of the material, must have certain prescribed dimensions, to achieve the appropriate stiffness of a structure. However, this result shows the potential benefits that can be realized by using this HSS. By reducing the mass, energy efficiency increases, fuel consumption decreases and the amount of useful load on a structure can be increased.

7. Conclusions

The global trend in industry is to decrease the weight of structures, to reduce the fuel consumption, CO_2 emissions, etc. One of the approaches to reduce the mass of a structure is to replace classic carbon structural steels with steels of increased strength (HSSs). Since those steels are characterized by the high strength values, which are the result of complex thermo-mechanical procedures in ironworks, a great care must be taken when choosing the most favorable welding technology, due to the possibility of deterioration of the HSS's' properties due to the heat introduced by welding. In this work, the use of the high strength steel P460NL1 was considered as a replacement for the low carbon S235JR steel. The computational check of weldability has indicated that the P460NL1 steel is prone to the appearance of cold cracks. To avoid their occurrence, the successful welding of this steels was made possible with application of supplementary measure – the heat treatment (preheating to 265 °C). However, such a measure requires a significant economic expenditure, so when choosing materials, it is necessary to consider whether these costs are justified in relation to the potential benefits provided by their use.

For the welding of the considered steel, additional materials, welding parameters, as well as additional measures for welding of a steel prone to cold cracks, are proposed. The technology so defined was applied to the test welds. From them, the samples were prepared for tensile testing, impact toughness testing, metallographic tests and measurement (distribution) of hardness in the welded joint. The results of those tests indicate that the proposed technology is adequate and that it can be used to weld the real parts in practice.

Finally, a theoretical example has shown the potentials for reducing the mass of a structure, previously made of S235JR steel, by using the HSS P460NL1. It shows that the mass of such a structure would be reduced 2.01 times. This result is theoretical only, since the limitations, regarding the reduction of the dimensions of the parts, still exist. Thus, the minimum dimensions are set for individual parts, first of all, to prevent excessive reduction of stiffness of a structure as a whole.

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