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UDC: 621.311.21 : 621.181.004

Effect of Enhanced Mechanical Properties of Weld Metal and Heat Affected Zone on the Strength of the Welded Joint

ABSTRACT

Selection of steel, dimensions and fabrication technology for the welded structure are all parts of the design process, because they are in close connection with the function of the structural whole under certain conditions of exploitation for the predicted service life. Quality of welded joints in the process of production of the welded structure is being defined by properties that the structure has to possess in order to fulfill certain requirements, which is being accomplished by the selection of the adequate welding procedure and welding parameters, implementation of inspection programs for all technological operations, as well as by performing mechanical and technological tests in order to determine the magnitude of strength and deformation of base material and welded joints. Constituent parts of a welded joint are base material, heat affected zone and weld metal. Heat affected zone of structural steels is being characterized by the fusion zone, overheating zone, zone of complete normalization and zone of incomplete normalization.

In this paper the effect of change in hardness of weld metal and heat-affected zone on mechanical properties of welded joints when base material is quenched and tempered steel C45 (DIN EN 10083) is being considered. Test results showed that the application of welded structures made of quenched and tempered steels with hardness HV10 > 400 and tensile strength UTS > 600 MPa is useful only when the stress concentration is low ($\alpha_s \leq 2$) and when there are no residual stresses due to welding.

Keywords: quenched and tempered steel, mechanical properties, hardeness of the welded joint, heat affected zone

UTICAJ POVIŠENIH MEHANIČKIH SVOJSTAVA METALA ŠAVA I ZONE UTICAJA TOPLOTE NA ČVRSTOĆU ZAVARENOG SPOJA

REZIME

Izbor čelika, dimenzija i tehnologije izrade zavarene konstrukcije je deo procesa konstruisanja, jer je u uskoj vezi sa funkcijom konstrukcijske celine u određenim uslovima eksploatacije za predviđeni vek trajanja. Kvalitet zavarenih spojeva u procesu izrade zavarene konstrukcije definiše se karakteristikama koje konstrukcija mora posedovati da bi zadovoljila određene zahteve, što se postiže izborom odgovarajućeg postupka i parametara zavarivanja, sprovođenjem programa kontrole svih tehnoloških operacija u njihovoj izradi i mehaničkim i tehnološkim ispitivanjima čvrstoće i deformacija osnovnog materijala i zavarenih spojeva. Konstitutivni delovi zavarenih spojeve su osnovni materijal, zona uticaja toplote i metal šava. Zonu uticaja toplote konstrukcijskih čelika karakterišu zona stapanja, zona pregrevanja, zona potpune i zona nepotpune normalizacije.

U radu je razmotren uticaj promene tvrdoće metala šava i zone uticaja toplote na mehanička svojstva zavarenih spojeva čelika za poboljšanje Č.1530 (C45 prema DIN EN 10083). Rezultati ispitivanja su pokazali da primena zavarenih konstrukcija od čelika za poboljšanje sa tvrdoćom HV10 > 400 i zateznom čvrstoćom većom od 600 MPa je svrsishodna samo za konstrukcije sa niskom koncentracijom napona ($\alpha_s \leq 2$) i kada nema zaostalih napona usled zavarivanja.

Ključne reči: čelik za poboljšanje, mehaničke osobine, tvrdoća zavarenog spoja, zona uticaja toplpte

1. INTRODUCTION

Safety of welded structures depends on the simultaneous influence of technological, metallurgical, structural and exploitational factors, or in other words on the welding procedure and shape of welded joints, stress concentration and heterogeneity of structural and mechanical properties of constituent parts of welded joints (base material, heat affected zone, weld metal). Increase or decrease of endurance of welded joints under exploitation conditions, apart from the presence of stress concentrators and residual stresses that occur due to welding, is also being affected by the heterogeneity of mechanical properties of base material, heat affected zone and weld metal, as well as by the width of heat affected zone and weld metal, *figure 1*.

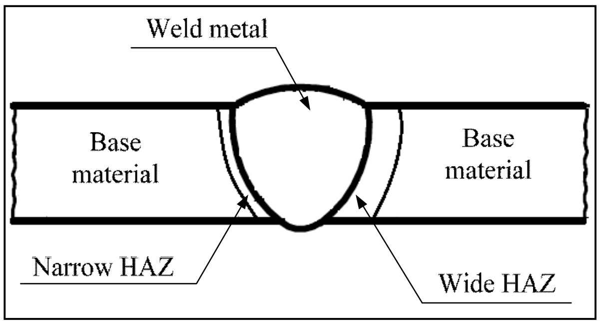


Figure 1. - *Appearance of a welded joint*

Structure and mechanical properties of individual constituent parts of welded joints depend on the welding regime and chemical composition of base and filler material. With the increase of the cooling rate within the subcritical temperature range, strength and yield stress for weld metal and heat affected zone grow and, depending on the chemical composition of steel, are 1.5 – 2 times larger than for base material [1].

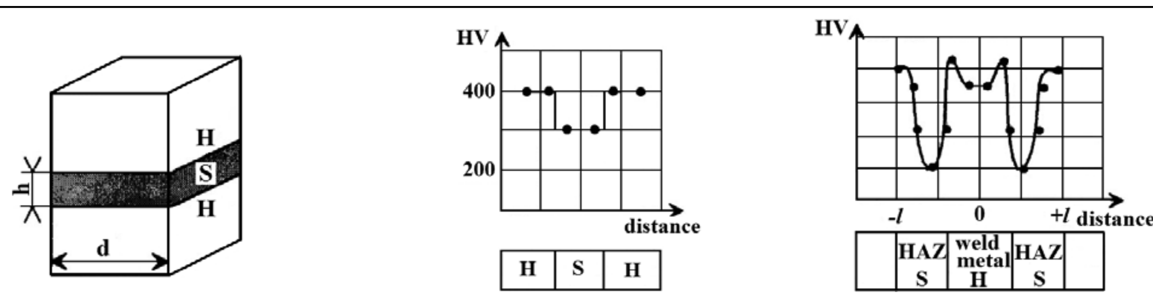
Numerous researches have been carried out around the world in order to determine the effect of various welding procedures on mechanical properties of quenched and tempered steels. Researches regarding the effect of laser welding parameters on geometry, mechanical properties and structure of weld metal and heat affected zone, showed that large increase of hardness in the area of the welded joint does not necessarily affect the mechanical properties in a negative way [2]. Experimental researches regarding the friction welding of steel C45 (DIN EN 10083) and tests that were carried out in order to determine the mechanical properties of weld metal and heat affected zone enabled the defining of optimum welding parameters for this procedure [3]. Predictions of temperature fields for quenched and tempered steels subjected to the effect of double elliptical heat sources were considered by Goldak and his associates, through the use of modelling and finite element method [4], while analyses of microstructures contributed in defining of geometry coefficient of a welded joint [5,6].

2. EFFECT OF THE WELDING THERMAL CYCLE ON MECHANICAL NONHOMOGENEITY OF THE WELDED JOINT

The presence of non-homogeneous zones is characteristic for welded joints. There are soft layers – zones with lower hardness value than that of the base material and hard layers - zones with higher hardness value than that of the base material. Those layers could exist in weld metal, diffusion zone, which is located in near proximity of the fusion zone, and in the heat affected zone, especially for thermally or thermomechanically hardened metals. Causes of occurrence of these non-homogeneous layers are diffusion of alloying elements from weld metal into base material, larger amount of hardened material in weld metal, near the fusion line, and presence of a thermal gradient.

Examples of distribution of hardness, measured transversely on macro strips of two samples, are presented in *figure 2*. When the martensite steel sample, prone to softening aging, is concerned, soft layer is located in weld metal, figure 2b. As far as the other sample, taken from thermally hardened steel, is concerned, soft layer is located in the heat affected zone. As can be seen in figures 2b and 2c, hardness sharply changes from a minimum value, caused by structural and technological properties of a welded joint, to a maximum value characteristic for base material.

Relative thickness of the soft layer κ is being obtained through the use of the following equation [1]:



a) Positions of soft and hard layer

b) Hardness values for soft and hard layer

c) Hardness distribution for the welded joint

Figure 2. - *Distribution of hardness, measured transversely on the macro strip of the welded joint*

$$\kappa = \frac{h}{d} \qquad (1)$$

where: h – width of the soft layer, mm
d – thickness or diameter of the sample, mm.

Static endurance of welded joints (σ) with variable mechanical properties of the soft or hard layer, subjected to pure shear or to tension, is being obtained as follows [7]:

– pure shea

$$\sigma_{SS} = 2 \cdot R_{SS} \cdot k_{\kappa}$$
$$\sigma_{SH} = 2 \cdot R_{SH} \cdot k_{\kappa} \qquad (2)$$

– tension

$$\sigma_{TS} = R_{TS} \cdot k_C$$
$$\sigma_{TH} = R_{TH} \cdot k_C \qquad (3)$$

where: R_{TS} – yield stress of the soft layer,
R_{TH} – yield stress of the hard layer,
k_C – coefficient of mechanical non-homogeneity (coefficient of contact strengthening).

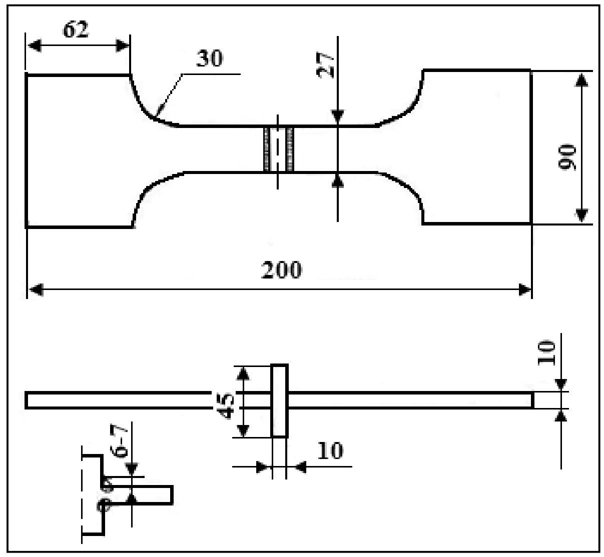


Figure 4. - *Specimen for hardness testing*

3. EXPERIMENTAL TESTS

Steel C45 is hardly weldable due to a large amount of carbon (C_E > 0.45). It is necessary to perform preheating of sheets before welding in order to create a reliable welded joint. Nevertheless, welding was performed without preheating, in order to avoid the effect of heat treatment on hardness values.

Analysis of parameters that greatly influence the selection of the welding procedure (weldability of the material, energetic possibilities of welding procedures, geometrical complexity, economic indicators) enabled the determination of the most adequate procedure

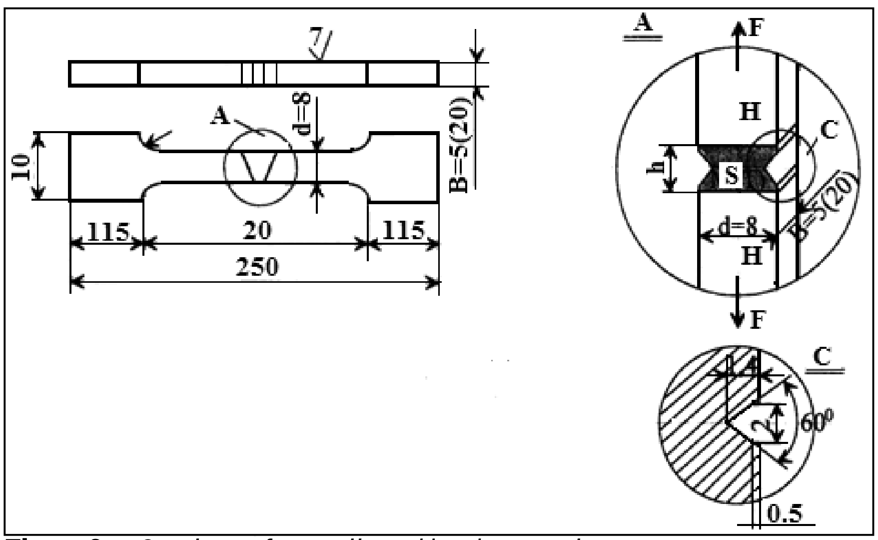
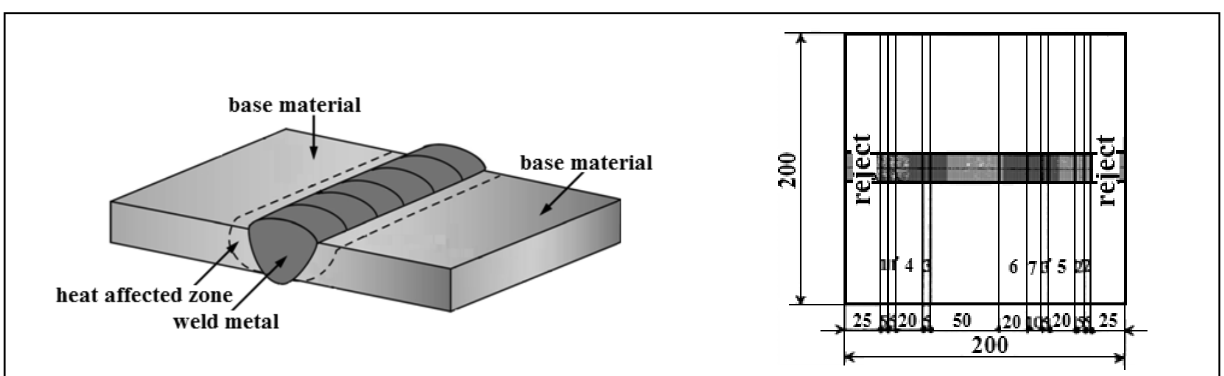


Figure 3. - *Specimens for tensile and hardness testing*



a) Plate with the butt joint from which the samples were taken
b) Sample dimensions

Figure 5. - *Plate with the butt joint and dimensions of samples from which the specimens were taken, depending on type of testing*

Table 1. - *Tensile strength results for specimens with a notch in the soft and hard layer*

Specimens	Groove in the soft layer	1	2	3	Mean value
	Groove in the hard layer	1'	2'	3'	
Tensile strength for the axisymmetrical deformation d>B	Soft layer, UTS [MPa]	550	540	542	544
	Hard layer, UTS [MPa]	670	675	680	675
Tensile strength of the soft layer for plannar deformation d<<B, UTS [MPa]		650	590	620	620

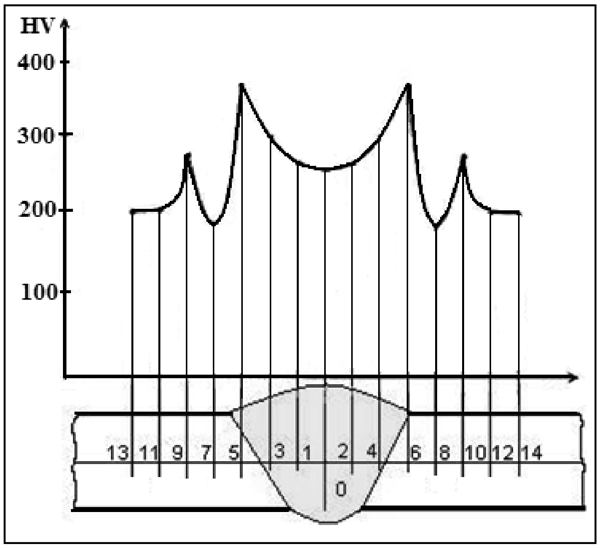


Figure 6. - *Hardness distribution diagram for the butt weld*

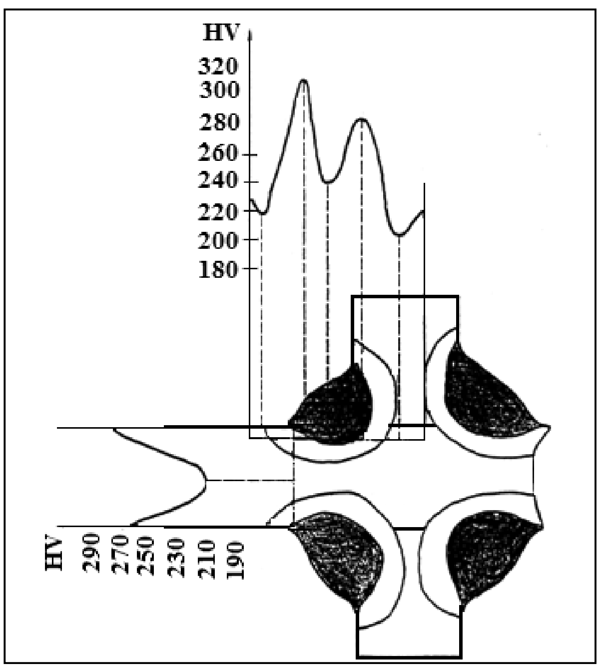


Figure 7. - *Hardness distribution diagram for the fillet weld*

– 111 and filler material - E 51 5B 262 (electrode diameter d_e = 3.25 mm*), with welding parameters* I = 130A, U = 25V, direct current (=), polarity (+), idle voltage of 70 V in all welding positions, except when welding vertically downwards.

Tensile and hardness testing have been performed on 250 x 10 x 5 (20) mm specimens with a butt weld, *figure 3*, while the hardness testing has been performed on 200 x 90 x 10 mm specimen with a cruciform welded joint, *figure 4*. Plate with the butt joint and dimensions of samples which were used for the fabrication of specimens, depending on the type of testing, are presented in *figure 5*. Tensile tests were performed on butt welds in case when d > B – axisymmetric deformation and when d << B – plannar deformation, figure 3. Plate with the butt weld and dimensions of samples from which the specimens were taken, depending on type of testing, are presented in *figure 5*. On specimens taken from samples 1, 2 and 3 grooves with stress concentration $\alpha_s \leq 2$ have been machined in the soft layer, while on specimens taken from samples 1',2',3' grooves were machined in the hard layer (width of specimens is 5 mm), according to figure 3 (details A and C). Notches have been machined in the soft layer of specimens taken from samples 4, 5 and 6 (width of samples is 20 mm). Hardness testing has been performed on sample 7.

4. RESULTS AND DISCUSSION

Hardness results, according to Vickers HV10, are presented in *figures 6* and *7*, while comparative tensile strength results for specimens 1, 2, 3 and 1', 2', 3' with notches in the soft and hard layer are presented in *table 1*.

Hardness results for butt and fillet welds showed that highest values of hardness occur in transition zones between weld metal and the heat affected zone.

Analysis of fracture surfaces of specimens on which tensile strength tests were performed showed that the strength of the soft layer has a greater effect on static endurance of welded joints than the strength of the hard layer.

5. CONCLUSION

Lower hardness of the soft layer of the welded joint has a greater effect on tensile strength of the welded joint under conditions of static axisymmetrical loading. Also, based on performed tests, it can be concluded that deformation and strength of the welded joint under conditions of plannar loading increase tensile strength under static load.

It can be generally concluded that the use of welded structures made of quenched and tempered steel C45 with hardness HV10 > 400 and tensile strength UTS > 600 MPa is purposeful only if the stress concentration is low ($\alpha_s \leq 2$) and if there are no residual stresses due to welding.

ACKNOWLEDGMENT

The authors wish to thank the Serbian Ministry of Education and Science and technological development for funding the project EVB: TR 35002.

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