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STUDY ON THE MECHANICAL AND RADIATION-SHIELDING PROPERTIES OF BORIDED AISI 304 STAINLESS STEELS

ŠTUDIJA MEHANSKIH LASTNOSTI IN ZAŠČITNIH SPOSOBNOSTI NERJAVNEGA JEKLA AISI 304 PRED SEVANJEM

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The boriding effect on the tensile properties, microhardness and radiation shielding has been studied. While boriding increased the hardness of the AISI 304 steel from 240 $HV_{0.1}$ to the maximum value of 1 740 $HV_{0.1}$, the elongation and the maximum stress clearly showed decreasing values. Borided specimens were more capable at stopping the high-energy photons and boriding improved the radiation-shielding properties of the AISI 304 steel. From the obtained results, it has been concluded that the borided AISI 304 stainless steel can be used as radiation shielding for γ-rays.

Keywords: boriding, radiation shielding, mechanical properties, stainless steel

Preučevan je bil učinek boriranja na natezne lastnosti, mikrotrdoto in zaščito pred sevanjem. Medtem ko boriranje poveča trdoto jekla AISI 304 iz 240 $HV_{0,1}$ na maksimalno 1740 $HV_{0,1}$, raztezek in maksimalna napetost izkazujeta padajoče vrednosti. Borirani vzorci so bolj odporni proti zaustavljanju visokoenergijskih protonov. Boriranje jekla AISI 304 poveča zaščito pred sevanjem. Iz dobljenih rezultatov lahko sklenemo, da je jeklo AISI 304 mogoče uporabiti za zaščito pred sevanjem rentgenskih žarkov.

Ključne besede: boriranje, zaščita pred sevanjem, mehanske lastnosti, nerjavno jeklo

1 INTRODUCTION

Austenitic stainless steels have high chromium contents and are commonly used as engineering materials.[1,2] Considering their use as engineering materials, the main problem with austenitic stainless steels is their relatively poor wear resistance, yield strength, fracture and impact toughness.[3,4] In recent years, extensive studies have been carried out on the improvement of the mechanical properties of these materials. Stainless steels are found to be well suited and established for surface treatments such as nitriding and boriding.[5] One of the surface-treatment techniques is boriding, a thermo-chemical surface treatment in which boron atoms diffuse into the surface of the work piece to form hard borides with the base material.[6–9] Corresponding to this, Tabur et al.[10] showed that the borided steels exhibit a surface hardness of over 2000 HV and provide an improved abrasive and adhesive wear resistance due to the hard boride phases and a diffusion of boron into the steel substrate, respectively.

In addition to the microhardness studies, it has been shown that tensile properties change with boriding due to a surface modification as expected when considering a plastic deformation of materials. Corresponding to this, it has been shown that the Young's modulus increases with an increase in the boriding processing time.[11] The increase in the boriding time from 2 to 6 h causes an increase in Young's modulus from 125 GPa to 241 GPa, from 240 GPa to 396 GPa and from 276 GPa to 397 GPa. Finally, according to the mechanical investigation, the optimum mechanical properties were obtained after 2 h of the boriding processing time. One can understand that the mechanical properties change with boriding due to a surface modification as expected when considering a plastic deformation of materials.

In recent years, boron has been used as an alternative for radiation shielding, although heavy metals such as lead have been used for this purpose.[12–14] According to[14], the borided AISI 316L and microalloyed stainless steels, especially in the middle energy region, have radiation shielding properties that are similar to those of lead, the standard shielding material. In the above-mentioned studies, the linear attenuation coefficients of steel were measured at photon energies of (662, 1170 and 1332) keV. It was clearly seen that the radiation shielding properties of steel were improved with a boriding process. Over the past 40 years, boriding has become an increasingly better surface-protection method. Thus, most of the previously reported experimental studies of borided steels have been devoted to mechanical properties. No study on the radiation shielding of borided AISI 304 stainless steels has been reported in the literature. The main goal of this study is to investigate the radiation-shielding properties of borided AISI 304 stainless steels.

2 EXPERIMENTAL METHODS

The substrates used for this study were the AISI 304 stainless steels. The chemical composition of the test material is listed in **Table 1**.

The boriding of the AISI 304 steels was achieved in a solid medium using the powder-pack method. In this method, a commercial Ekabor-III boron source and an activator (ferro-silicon) were thoroughly mixed to form the boriding medium. The test samples and pack were then heated in an electric resistance furnace for 3 h at 1200 K under atmospheric pressure. After this process, the borided samples were removed from the furnace and cooled in air. Borided steels were sectioned from one side and prepared metallographically with emery paper up to 1200-grit and then polished, using alumina pastes 3 µm. The surfaces of the polished samples were etched with 4 % Nital before the tests. The thicknesses of the diffusion layers of borided AISI 304 steels were observed with optical microscopy.

Borided steels were tested for tension with a universal tester with a capacity of 5 kN and a gauge length of 11 mm. The hardness measurements were made using a Vickers microhardness tester with a load of 100 g. Finally, to investigate the radiation-shielding properties of borided AISI 304 steels, the linear attenuation coefficients (µ) of steel were measured before and after boriding the steel at photon energies of 662 keV and 1250 keV obtained from ^{137}CS and ^{60}Co γ-ray sources, respectively. For this purpose, the γ-rays through the steel were detected using a gamma spectrometer that consists of an approximately 76 mm × 76 mm NaI(Tl) detector connected to a multichannel analyzer (MCA). The detector system communicates with a PC using the Genie 200 software. If N and N_0 are the measured count rates in the detector with and without an absorber of thickness x (cm), respectively, then the absorption coefficient μ can be extracted with the standard equation:

$$N = N_0 e^{-\mu x}$$

The slope of the ln (N/N_0) versus x plot gives μ. Further experimental details were described in[15].

3 RESULTS AND DISCUSSION

As seen in **Figure 1**, optical examinations revealed that the boride layer on the surface of the steel has a columnar morphology due to many alloying elements in the AISI 304 stainless steel.

The boride-layer thickness varied between 15 µm and 20 µm. In other words, the rate of the boron diffusion into the surface of a substrate was low. The thickness of the transition region was also very small (the average of 100 µm) and the grain growth was not introduced in the transition regions of borided steels. This is because boron does not dissolve significantly in the boride layer during the boriding.

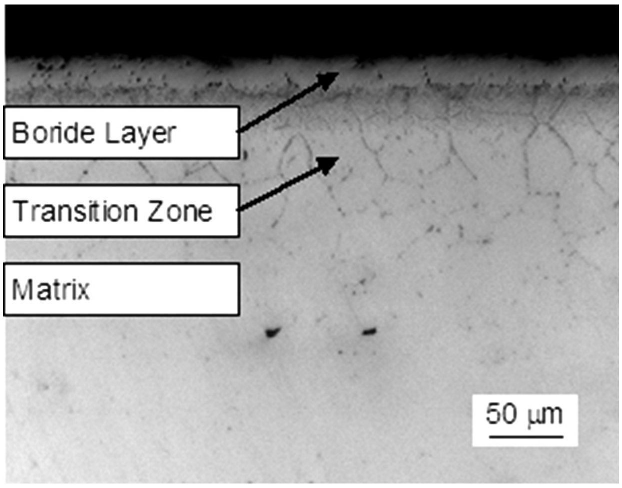

Figure 1: Optical micrograph of a cross-section of the borided AISI 304 stainless steel

Slika 1: Posnetek prečnega prereza boriranega nerjavnega jekla AISI 304

To compare the mechanical properties of borided and untreated AISI 304 stainless steels, elongation and microhardness tests were performed on the samples. While the microhardness values in the matrix varied between 241 $HV_{0.1}$ and 285 $HV_{0.1}$, they reached 1099–1123 $HV_{0.1}$ and 1650–1740 $HV_{0.1}$ in the transition zone and the boride layer, respectively. We say that the

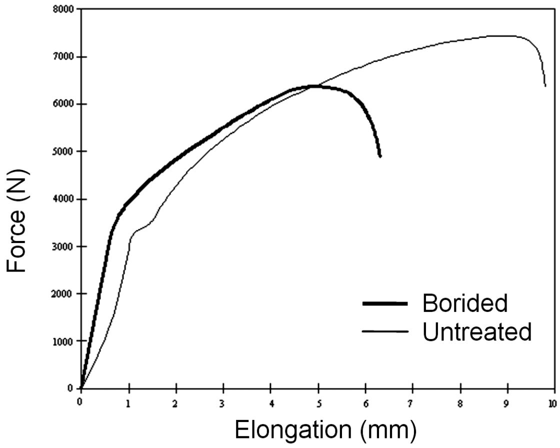

Figure 2: Load-elongation curve of borided and untreated AISI 304 stainless steels

Slika 2: Krivulja sila – raztezek boriranega in neobdelanega nerjavnega jekla AISI 304

Table 1: Chemical composition of the AISI 304 stainless steel (w/%)

Tabela 1: Kemijska sestava nerjavnega jekla AISI 304 (w/%)

C	Ni	Cr	Mn	P	S	Si	Cu	Mo	Nb	Fe
0.044	8.03	18.26	1.5	0.032	0.0003	0.47	0.38	0.38	0.022	Bal.

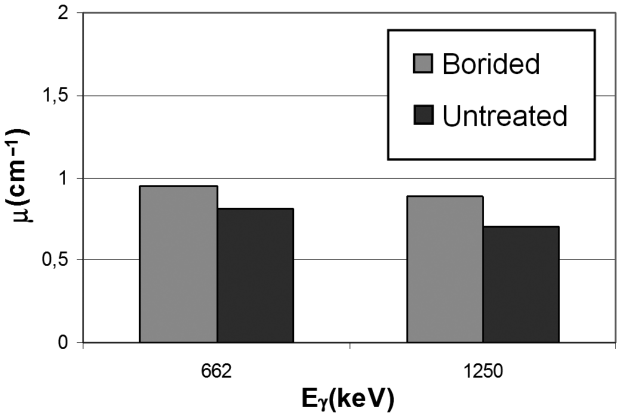

Figure 3: Linear-attenuation coefficients for borided and untreated AISI 304 stainless steels
Slika 3: Linearni koeficient slabljenja pri boriranem in neobdelanem nerjavnem jeklu AISI 304

microhardness values of the boride layer are higher than those of the matrix because of the presence of a hard Fe_2B phase. Meanwhile, a high microhardness value is mainly due to the mono phase (Fe_2B) in the boride layer.

In addition to the microhardness results, boriding also affects the tensile properties of AISI 304 steels. It can be seen on **Figure 2** that there is a minor increase in the yield stress in the borided steels in comparison with the untreated ones. In general, it has been indicated that the boriding process increases the yield stress due to a surface modification, as obtained from the microhardness results.[16,17] In the present study, it is evident from this figure that both the maximum stress and elongation are decreased drastically by a factor close to 15 % and 25 %, respectively. On the basis of these results, we can say that the microstructure has become very coarse occurring in a brittle mode after the boriding. The same results have been also obtained for many other borided steels.[11,18,19]

Now let us consider the radiation-shielding properties of borided AISI 304 stainless steels. The linear attenuation coefficients (μ) of the steel were measured at photon energies of 662 keV and 1250 keV obtained from ^{137}CS and ^{60}Co γ-ray sources, respectively. This measurement was performed before and after the boriding. This is shown in **Figure 3** where it can be clearly seen that the boriding processes increased the linear attenuation coefficients. We say that borided AISI 304 stainless steels can be used as radiation shielding in many industrial applications. However, the increase in micrometers with the boriding is limited due to a small diffusion layer of the borided AISI 304 stainless steel. By comparing the experimental results obtained with the present study with the results for the borided AISI 316L [14] and microalloyed stainless steels,[20] we can say that in our case the increase in micrometers is smaller than in the other cases. From these results, we also concluded that a thicker boride layer is needed to stop higher energy photons and that the boriding improved the radiation-shielding capability of the steel. It has to be remembered that the increasing temperature and time increase the boride-layer thickness of borided steels resulting in an excellent radiation-shielding performance.

4 CONCLUSIONS

To sum up, the maximum stress and elongation clearly showed a decrease, while the yield stress displayed a slight increase. In addition, the microhardness and linear-attenuation coefficient increased because of the hard boride phases in the boride layer and the boride-layer thickness.

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