Abstract

In the present study, the effect of the performed welding processes on the mechanical properties, resistance to abrasive wear and dynamic loads in the zone of the welded joint and the base material of high-strength Hardox steels is considered. The above metallic materials are alloyed with boron, which, when added in amounts considered negligible (0.002%) for the other alloying elements, sharply increases hardenability. The first studies on the effect of this additive on steel properties date back to the 1930s, when the Al-Si-Zr-Ti ferroalloy introduced into steel melting contained alloying elements that inhibited the negative effect of boron on hardenability, resulting in obtaining bainitic steels with strengths reaching 1,200 MPa. Subsequently, this element began to be widely used for economic reasons, when wars caused restrictions in the availability of expensive elements, such as chromium, nickel and molybdenum.

Mass production of steels with improved resistance to abrasive wear began in the 1950s. At that time, the Japanese steel mill JFE Steel Corporation released JFE EVERHARD steels, which were recommended for use on machinery components of the mining, construction, transportation, cement or agricultural industries. The above group of steels is also used nowadays for dump truck bodies, excavator buckets, chute hoppers and hooks.

In Europe, production of the first steels with improved abrasion wear resistance with added boron began in 1970. At that time, the Swedish concern SSAB-Oxelösund produced Hardox 400 steel, which was characterized by high hardness and strength, despite its low carbon content of about 0.15%. It should be noted that this is probably not coincidental, as the Swedish history of the mining and metallurgical industry has a centuries-old tradition. Due to the availability of wood and rich deposits of iron ore of exceptional purity, Sweden already accounted for about half of European steel production in the 17th century. Today, as part of the HYBRIT project, which assumes a zero carbon footprint in steel production due to the use of electricity and hydrogen instead of fossils needed to heat the ore during reduction processes, Sweden is leading the way in the use of modern low-carbon technologies in steelmaking.

Hardox steels were imported to Poland in 1996, while the first information in national publications dates back to 2004. It quickly gained recognition and began to be widely used in the mining industry. Exploitation tests of Hardox steels used for the liner plates of the bucket wheel chute of the KWK-1500s excavator working at the Turow mine confirmed their superiority over previously used materials (including 18G2A steel with an applied Fe-Cr-C surfacing layer). Among the grades with similar properties there are Brinar, Raex, Perdur, Creusabro, Relia, Dillidur, Armox steels.

Excavator buckets, bucket wheel components, hoppers and belt conveyors are also exposed to dynamic load conditions, so it is believed that in addition to high hardness, plastic properties (*A*, *Z*) and impact strength should be an additional classification criterion for the material. Other requirements take into account corrosion resistance, as well as technological aspects, including satisfactory weldability. However, some unfavorable changes were noticed in martensitic steels supplemented with boron after welding tests, in spite of the manufacturer's declared satisfactory *CEV* value of the steel, which resulted in a significant reduction of the service life of parts made of these materials. Variable microstructural changes, and in some cases, incorrect heat treatment, distinctly reduced the abrasive wear resistance of these steels and resulted in a radical reduction of their mechanical and functional properties. As an example, a blade made of Hardox 400, mounted on an excavator bucket with the use of welding techniques, was worn out in a time twofold shorter than the one made of 18G2A (P355N) steel. However, the most intensive wear was not observed in the area of the base material, but instead in the broad heat-affected zone and the welding material.

On this basis, starting from the generally accepted assumption that high mechanical and plastic parameters are responsible for the resistance of steel to abrasive wear processes, it can be pointed out that as a result of microstructural changes arising in the welding process, there is a dramatic reduction in all functional characteristics. Obtaining a martensitic microstructure, which determines the achievement of high strength properties of the material, is problematic immediately after the welding process. Moreover, in the area of the heat-affected zone there is a so-called microstructural notch, manifested by a decrease in mechanical properties by as much as 50%. With regard to the above, the author of this paper decided to analyse more extensively the possibility of welding low-alloy martensitic steels with boron (using Hardox 450 and Hardox Extreme as an example), assuming that similar mechanical indices to the base material are obtained in the zone of the alloying material and in the heat-affected zone. The results of the research are presented in three chapters:

1. The first research part of the paper focuses on the material science analysis of selected Hardox steels in the as-delivered state.

2. In the second research part of the work, the results of tests on the properties of the alloying material, the heat-affected zone and the base material zone are reported.

3. In the third research part of the paper, there are presented the results of ballistic resistance tests of Hardox 450 steel welded joints against 7.62 × 39 mm nb. wz. 43 rifle ammunition with PS bullets and 7.62 × 54R mm nb. kb. LPS machine gun ammunition.

In each case, the tests carried out on the base material and welded joint included microscopic identification of the structures, studies of the grain size of the former austenite, tensile strength *Rm*, impact strength and fractographic analysis as a function of temperature, resistance to abrasive wear in the presence of loose abrasive and soil abrasive mass.

Based on the results of the study, material characteristics of Hardox steels and their welded joints under different heat treatment variants were developed, and a proposal was formulated for their application to ballistic body components, which are assembled by welding techniques. Recommendations are also made for the welding technology of Hardox 450 and Hardox Extreme steels and the subsequent heat treatment of welded joints.