LOW-ALLOY STEEL ELECTRON BEAM HARDENING

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Abstract

Surface hardening is a process of forming high hardness layer at the surface of metal object, thus improving wear resistance without the need for hardening whole section. It allows reduce stress, deformations and cost of the finished product compared to through thickness hardening. Electron beam due to high heating rate makes it possible to obtain very thin layers with required properties. Also, because of the ease of dynamic deflection and focusing, hardening of components with complex geometries is possible. This paper presents the results of metallographic and hardness test of electron beam hardened C45 grade steel shaft.

Keywords: Hardening, electron beam hardening, electron beam, steel, surface treatment, C45 steel, case hardening

1. INTRODUCTION

Electron beam surface hardening involves the excitation and emission of electrons from a cathode usually made of tungsten or a tungsten alloy. These electrons are accelerated at a very high voltage, then deflected and directed into the work chamber using electromagnetic coils. As a result of bombarding the surface of the workpiece with electrons, its temperature increases by converting kinetic energy into thermal energy. In order to obtain a martensitic structure, it is necessary to heat the surface layer of the component 30 - 50 K above the austenitizing temperature and then provide a cooling rate greater than critical for the material. For this to be possible, the ratio of quenched to unquenched mass must be large enough to ensure that the heat is removed quickly enough. Hardening only the top layer of the component reduces deformation and the occurrence of stresses, in addition, it reduces energy consumption and thus the cost of manufacturing the component [1-11].

Advantages of electron beam hardening are [1-6]:

- metallurgical purity of the process (the process is carried out under vacuum),
- precise, computer-controlled beam deflection and focusing, enabling hardening of components with complex geometries
- higher heating speeds than in the case of other technologies, reaching even 109 K/s, which enables heating the surface of the element faster than its ability to receive heat, resulting from the thermal conductivity of the material
- precise regulation of the process parameters,
- high precision and repeatability of the process,
- easy automation,
- high energy efficiency reaching over 90%.

The C45 steel (1.0503) used in this study is one of the most commonly used industrial upgrading steels. It is characterized by good hardenability. Due to its properties, it is widely used for tools and machine elements such as shafts, spindles, gears, axles, knives, hubs, injection moulds, rods and, for example, pump impellers [10-12]. The authors of [13] studied the effect of tempering time and temperature on the properties of AISI 1045 grade steel (equivalent to C45 grade steel). The samples were quenched from 850 °C at which they were annealed for 30 min. The cooling medium was water. After quenching, the samples were annealed at 900, 950 and 1000 °C for 1, 2 or 3 hours. The sample annealed at 900 °C for 2 hours showed the best properties. The achieved hardness after heat treatment was about 900 HV. In the paper [14], samples of AISI 1045 grade steel were annealed for 60 min at 880 °C and then quenched in aqueous solutions with concentrations of 10, 15, 20, 25% polyvinylpyrrolidone. After quenching, the measured microhardness of the samples were 910, 874, 844, 830 HV, respectively. The highest microhardness was obtained after quenching in the solution with the lowest concentration of polyvinylpyrrolidone. In work [15], 20 mm diameter shafts made of C45 grade steel were induction hardened. Using a feed rate of 20 mm/s, a frequency of 27 kHz, and a power of 31 kW, a hardening depth of less than 2 mm was achieved. The hardness measured ranged from 650 to 750 HV. With the use of laser hardening, using a 500W Nd:Yag laser, the authors of the work [16] managed to obtain hardness in the range of 700 - 800 HV with a depth of hardening reaching 1.9 mm. In the case of work [17], the use of CO2 laser for hardening elements of steel C45 made it possible to obtain very thin hardened layers with a thickness not exceeding 0.2 mm. The maximum hardness measured was 567 HV.

In paper [18], the effect of electron beam quenching on the properties and structure of AISI D3 tool steel was studied. As a result, layers of about 0.4 mm thickness were obtained. The highest hardness of about 1400 HV0.1 was obtained for the sample quenched at the highest speed, while the lowest hardness of less than 1000 HV0.1 was obtained for the sample quenched at the lowest speed. The measured hardness of the parent material was 650 HV0.1. A transition layer with a reduced hardness of approximately 400 HV0.1 was observed in each of the samples. The electron hardening technology has been successfully used in the automotive industry. The research [19] carried out at Isuzu Motors Ltd. consisted of the local application of an electron beam to the sample and the study of the effect of changing the beam current intensity, as well as the time of this application, on the depth of the hardened layer. The material used in the tests was 34CrMo4 steel. The maximum hardened depth obtained was 0.9 mm. The frictional wear resistance measured was twice as high as that of an unhardened component. The test results were so satisfactory that it was decided to apply the electron method to hardening of Isuzu B6 engine tappets, as well as the contact surface of the gearbox synchroniser locking ring. In work [20], the electron hardening process was used to reconstruct turbine blades. In order to restore the original properties of the components, the stealite layers were ground off and then subjected to an electron beam surface hardening process. After the electron hardening process, the surface hardness was about 700-800 HV0.03 which made it possible to continue using the blades. According to the authors of the paper, the cost of the process was fifteen times lower than the cost of manufacturing a new blade. The paper [21] studied the effect of using different modes of beam oscillation on the properties of the obtained hardened layers. It was shown that the deflection mode has little effect on the maximum hardness, however, the use of deflection not only in the direction perpendicular to the direction of motion, but also in the parallel direction, results in greater grain growth. The geometric profiles of the stitch cross-section are different for each of the oscillation patterns used. The authors indicated that the quenching rate only affected the depth of the hardened layer, which increases as the rate decreases. The maximum hardness obtained was 740 HV0.5, while the hardened layer depths ranged from 0.1 - 1.5 mm. The authors of the paper [22], in which the results of the optimization of the oscillating electron beam hardening process were presented, showed that:

- the heating rate increases linearly with increasing electron beam power while keeping the sample travel speed constant;
- the heating rate increases with the sliding speed while keeping the electron beam power constant;
- the cooling speed is strongly dependent on the sliding speed while keeping the beam power constant;

- the cooling speed shows little dependence on the electron beam power while keeping the sliding speed constant.

The paper [23] also presents the results of research on optimization of electron quenching process. The authors performed mathematical simulations of the influence of process parameters on the microstructure and depth of hardened layers, and then performed technological tests on real components. During the trials, the components were hardened using an oscillating beam. The depth of hardening ranged from 0.3 to 1.1 mm and the highest measured surface hardness was 60 HRC. Based on the results, the authors showed that among the analysed parameters, the resulting electron beam power had the main effect on the cooling rate and thus the surface hardness. The hardening depth, on the other hand, depends on the energy density of the electron beam on the surface of the hardened object.

2. EXPERIMENTAL PROCEDURE

The hardening tests were carried out at Lukasiewicz Welding Institute in Gliwice using CVE EB756 model XW 150:30 with a maximum power of 30 kW at an accelerating voltage of 150 kV. The hardened elements in the form of shafts with a diameter of 17 mm and a length of 200 mm were made of C45 grade steel (1.0503). **Figure 1** shows, how the elements were mounted, as well as a schematic of the electron beam hardening process.

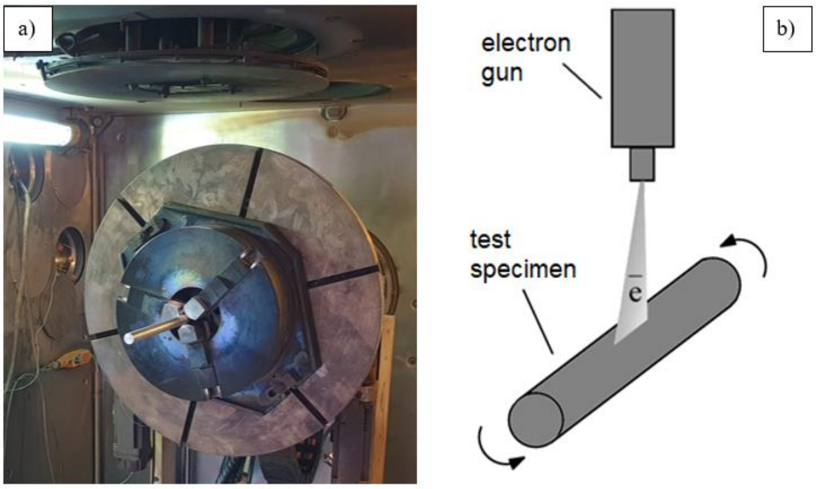

Figure 1 a) Method of fixing the shafts in the three-jaw chuck; b) Scheme of the electron beam hardening process

The operation conditions were as follows: 60 kV for acceleration voltage, 1.589 m/min for the scanning speed which was limited by shaft diameter and the speed of turntable, 25, 26, 27, 28 and 29 mA respectively for beam current. The surface of no specimen was melted during process. Transverse sections of all electron beam traces were cut as specimens for metallographic examination by optical microscopy (OM) or scanning electron microscopy (SEM). All specimens were polished and etched using 2% Nital solution. Microhardness was measured as a function of depth below surface and width of the hardened layer using a Vickers hardness tester under a load of 0.1 kg.

3. RESULTS AND DISCUSSION

The microstructure of the test steel in the delivery state contained pearlite and ferrite as shown in **Figure 2a**. **Figure 2b** shows the transverse section of one of the specimens (25 mA for electron beam current). There are clearly visible 3 zones. The first layer very darkly etched forms a hardened layer on the surface of the sample. The area below these layers is brightly etched and forms very thin transition layer. Both these layers forms a region near the surface called HAZ (heat affected zone), which has clearly undergone a series of phase transformations. The area below that region shows microstructure of parent metal which means it was unaffected by the process. As seen in **Figure 3a**, the microstructure of the hardened layer consists mostly of martensite, whereas the transition layer is a mixture of perlite and martensite as shown in **Figure 3b**.

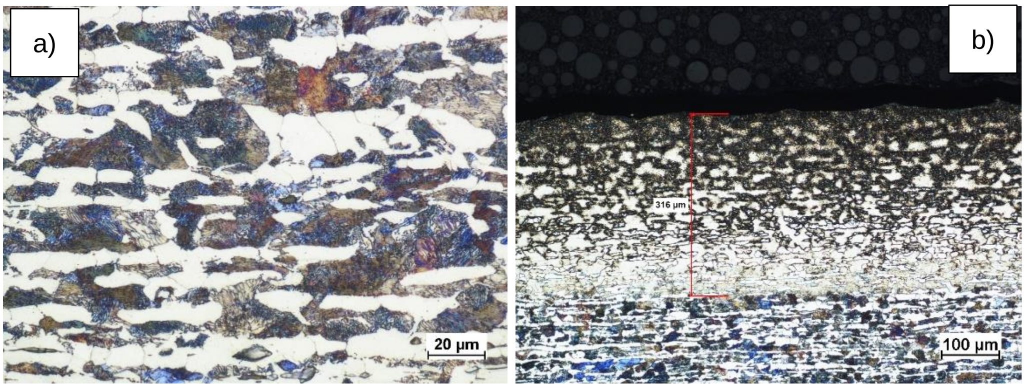

Figure 2 a) Microstructure of base material; b) transverse section of 25 mA specimen

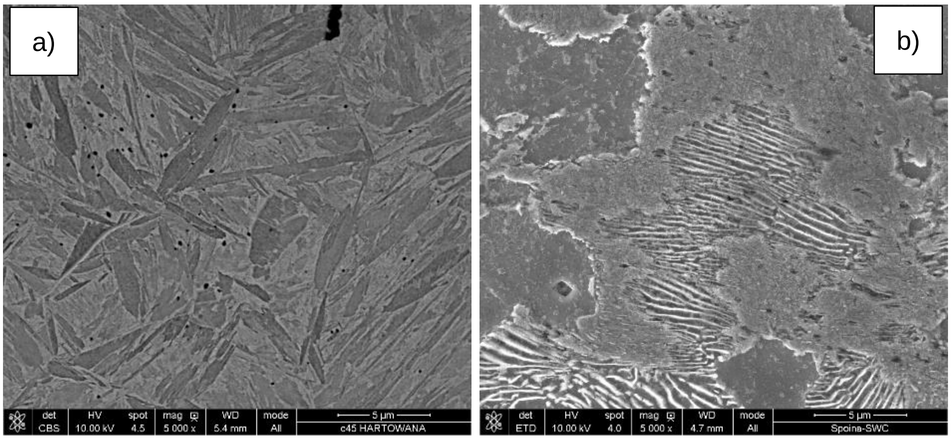

Figure 3 a) Microstructure of hardened layer; b) Microstructure of transition layer

Table 1 summarizes the results of the measured HAZ depth alongside the maximum measured hardness for each specimen. **Figure 4** and **5** show hardness as a function of depth from surface and width of the hardened layer for picked specimens (25 mA and 29 mA for beam current). As can be seen, the hardened region has width of around 10 mm and depth of HAZ from surface in range of 0.3 up to 0.45 mm whereas effective hardening depth (effective case depth) is in range of 0.15 to 0.3 mm.

Table 1 Results of electron beam hardening

No.	Electron beam current (mA)	Beam power (W)	Depth of HAZ (mm)	Maximum measured hardness (HV0.1)
1	29	1740	0.447	1039
2	28	1680	0.353	944
3	27	1620	0.326	960
4	26	1560	0.326	1035
5	25	1500	0.303	1102

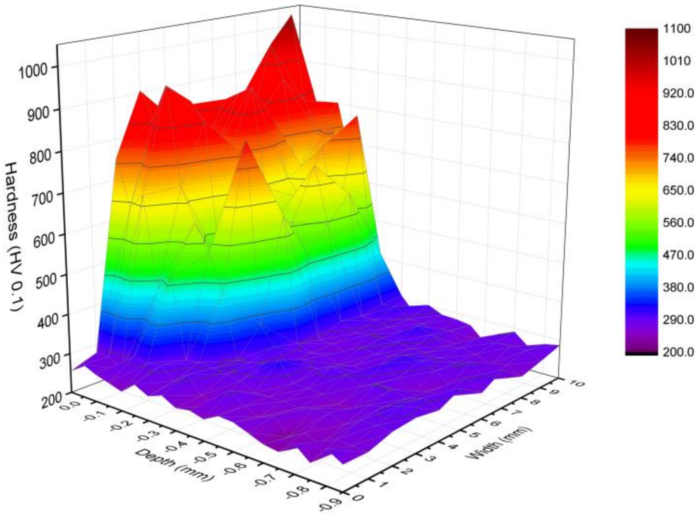

Figure 6 Microhardness (HV0.1) map for specimen 1 (29 mA for beam current)

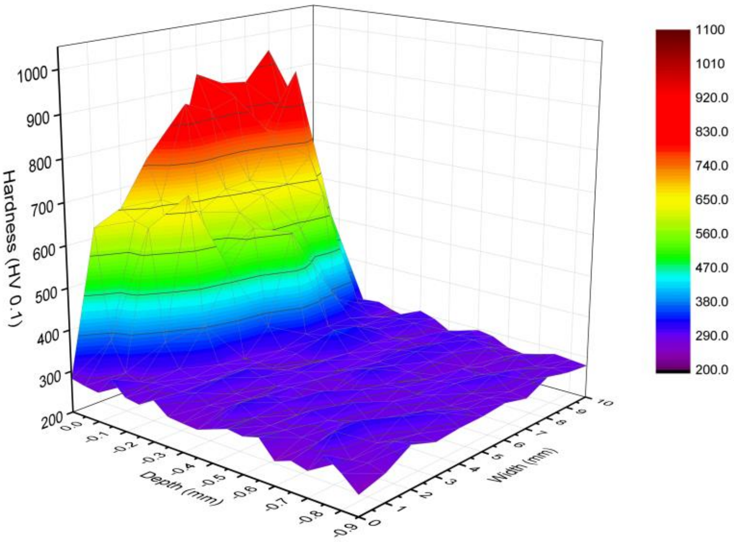

Figure 7 Microhardness (HV0.1) map for specimen 5 (25 mA for beam current)

4. CONCLUSION

Electron beam surface hardening (EBH) of C45 grade steel has produced excellent. The maximum hardness level achieved is well beyond capabilities of conventional methods, at the same time surface of specimens has not degraded. The microstructure of hardened layers consisted of martensite. Both HAZ and effective case depth increases with increasing the electron beam current, however, the highest hardness measured was on the sample with the lowest current (25 mA).

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