INCREASING THE HEAT-RESISTANCE OF X210CR12 STEEL BY SURFACE MELTING WITH ARC DISCHARGE IN VACUUM

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Abstract

The paper introduces the results from experiments for surface quench hardening by hollow cathode arc discharge in vacuum. The used method is an alternative to traditional laser and plasma methods for surface hardening. The paper presents the influence of the working parameters and the following tempering on the microstructure, dimensions and hardness of the hardened surfaces.

Keywords: Vacuum technology, surface heat treatment, hollow cathode arc, surface melting

1. INTRODUCTION

Surface quench hardening allows attaining high physical and mechanical properties of the surface layers and to retain unchanged those of the bulk of a product. Induction hardening, flame, plasma and laser hardening are carried into practice [1], the latter two being widely used for hardening of tools surfaces when the hardening has to be carried out without melting in order to keep the dimensions of tools. According to, intensive plasma-arc treatment leads in most cases to partial or full surface melting, and especially in high-carbon and high-alloyed steels forms large amounts of retained austenite with relatively low hardness. The possibilities for reducing retained austenite amount are related to several processes: cryogenic hardening, high-temperature tempering and deformation induced transformation. Hollow cathode arc discharge (HCAD) is a possible alternative to above described energy sources, used for surface hardening. HCAD is a high-current, low-voltage electron beam with gas autofocus and by its nature it occupies an intermediate position between the electron beam and plasma-arc. HCAD is stable at current magnitudes between 5 and 500 A, working pressures ($1 \div 10^{-2}$) Pa and debit of the plasma-forming gas 0.3 ÷ 3.0 mg/s. The maximum of the heat flow density in the heated zone is within $5.10^3 \div 10^5$ W/cm^2, and that makes it one of the most effective energy source, only laser and electron beam being more effective [2-4].

HCAD is mainly used for welding, overlay welding, brazing and soldering. Nevertheless, in the specialized literature information about its use for heat treatment and the possible results from it is missing. The purpose of the present work is to investigate the possibility for surface heat treatment of tool steel X210Cr12 with hollow cathode arc discharge in vacuum, and the influence of the working parameters on the hardness of the treated surfaces, as well as the effect of the next heat treatment on the hardness and heat-resistance of the treated surfaces to be established.

2. MATERIALS AND METHODS

The present work introduces results from experiments for surface hardening by HCAD in vacuum. The experiments were carried out in a semi-industrial installation [5]. The hardened layers were produced in two ways - 1) using multi-pass melting and 2) melting by discharge scanning on the treated surfaces, controlled by magnetic system. In the first case, the treated items were moved in a straight line along the X-axis with a fixed speed, and at the end were shifted by 2.0 mm, 2.5 mm and 3.0 mm along the Y-axis, afterwards were again moved along X-axis. As a result, hardened surfaces composed by overlapping hardened layers were formed. In the second case, besides movement along the X-axis, the discharge was oscillating along the Y-axis/normal to the X-axis. The discharge oscillations were controlled by a magnetic system that allowed to alternate the

frequency and the oscillations magnitudes of the discharge, and that way hardened areas, differing in width and in overlapping, were produced. The magnetic system and its electrical control scheme are described in [6]. Specimens from X210Cr12 steel were studied. The hardness of the as-received steel was HV1 ≈ 210. The specimen dimensions were 100x80x10mm (length x width x height). The used working parameters are presented in **Table 1**. The pressure was 3 Pa, the diameter of the hollow cathode was 3.5 mm, and the debit of the plasma - forming gas, flowed through the cathode, was 2.5 l/h.

Table 1 Working parameters for surface hardening

Hardening mode	Current, A	Rate of movement along the X-axis, mm/s	Scanning frequency, Hz	Total discharge deviation, mm
Using multi-pass melting	100	11	-	-
Using discharge scanning	120	3.3	1; 2; 3; 4	8-10

After multi-pass melting the shifted by 2.0 mm specimen was intense cooled to 10°C in inert gas, and the shifted by 2.5 mm and 3.0 mm specimens were air-cooled to room temperature. After the treatment with scanning discharge all samples were intense cooled in inert gas to 10°C. To increase hardness and to investigate heat-resistance two specimens - one, produced by multi-pass treatment with shift of 2.5 mm and one, obtained by discharge scanning with frequency of 4 Hz, were heated to different temperatures in the range of 300 - 650°C, held for 2 h and then air-cooled. The dimensions of the formed zones and their hardness were measured on macrosections, etched with 10% HNO_3 in ethanol. The hardness measurement was carried out in the melted zones. The microstructures were investigated after etching with 4% HNO_3 in ethanol using magnification of 500x.

3. RESULTS AND DISCUSSION

Zones with changed structure, similar to those formed after welding, were observed on specimens' macrosections after multi-pass melting (**Figure 1**). The observed decrease in the depth of the individual zones with increase in the number of passes (**Table 2**) was in correlation with the extent of overlapping of the individual zones, i.e. with the shift of the treated specimens. As the results in **Table 3** show, the treatment with hollow cathode arc discharge with multi-pass melting led to surface quench hardening. That effect was more prominent for the intense cooled to 10°C (2.0 mm shift) sample.

a) b)

Figure 1 Macrosections of the treated samples: a) with 2.0 mm shift; b) with 3.0 mm shift

Table 2 Dimensions of the hardened zones after multi-pass melting

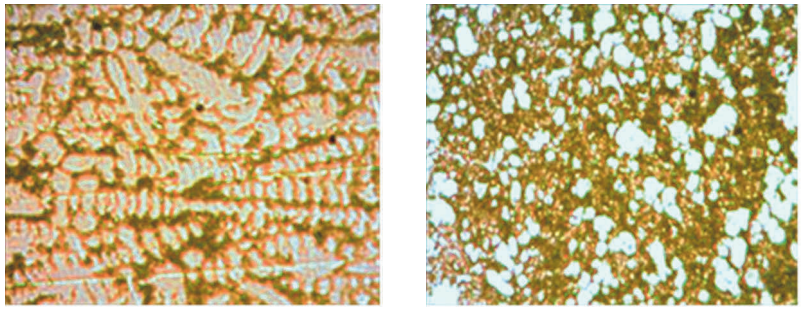
Shift	1st pass depth, mm	2nd pass depth, mm	3rd pass depth, mm	4th pass depth, mm	Total width, mm
2.0 mm	0.91	0.9	0.44	0.51	9.23
2.5 mm	0.75	0.72	0.70	0.36	9.38
3.0 mm	0.63	0.63	0.52	-	8.57

The higher hardness of the intense cooled to 10°C sample (2.0 mm shift) was result of the difference in the final cooling temperatures. The final cooling temperatures affected the degree of martensitic transformation, i.e. the retained austenite quantities. Thus the higher hardness values for the specimen quenched to 10°C indicated martensitic transformation that occurred to a greater extent, and hence - for a smaller retained austenite quantity.

Table 3 Mean hardness values of the different zones of treated surfaces after multi-pass melting

Shift	1st pass HV1/HRC	2nd pass HV1/HRC	3rd pass HV1/HRC	4th pass HV1/HRC
2.0 mm	861/65.9	832/65.0	857/65.8	785/63.5
2.5 mm	608/55.5	568/53.3	536/51.6	530/51.2
3.0 mm	628/56.8	633/77.0	623/56.5	-

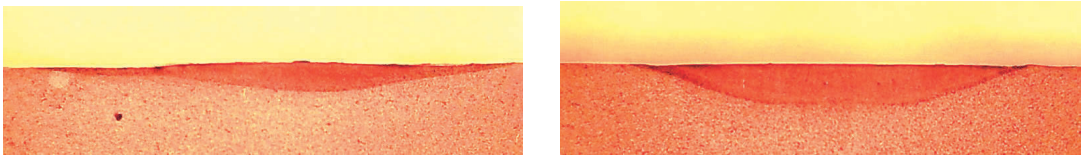
The cooling conditions for air-cooled specimens allowed more retained austenite in their structure; and this is evident from **Figure 3** that represents the microstructures of the melted, partially melted and the heat-affected zones in air-cooled specimen (2.5 mm shift) after multi-pass melting with HCAD and quenching. The melted zone was with fine columnar dendritic (**Figure 2a**) with austenite dendrites extending from the partially melted zone to the surface. That structure is typical for high-speed crystallization following the melting with highly concentrated heat flows [7]. Etching revealed primary austenitic dendrites and eutectic between them. Austenite, formed during rapid solidification, is supersaturated in carbon and chromium; that plays a crucial role in austenite stabilization at room temperature. According to [8, 9] in rapidly solidified high-chromium tool steels metastable supersaturated austeinite is present at room temperature; and up to 60% of retained austenite in high-carbon steels after quenching is not transformed [10]. The measured hardness values of 55.5 HRC suggested some austenite did transform into martensite. The volume fractions of the different phases could not be precisely established. The microstructure of the partially melted zone after surface heat treatment contained retained austenite, martensite and incompletely dissolved carbides. Retained austenite quantity decreased towards the heat affected zone. The heat-affected zone (**Figure 2b**) contained martensite with varying carbon and chromium concentration and carbides in altering quantities. Due to temperature in the base metal being lower than the typical quenching temperature for X210Cr12 (960-980°C), the martensite carbon content was lowered and the measured hardness value of 51-53 HRC in the heat-affected zone was lower than the one in the melted zone.



a) b)

Figure 2 Microstructures x500 of: a) the melted zone; b) heat-affected zone in the air-cooled specimen (2.5 mm shift) after quenching

Macrosection observations (**Figure 3**) and dimensions of the formed zones (**Table 4**) after treatment by discharge scanning indicated a tendency for increase in depth and decrease in width of the formed zones with increasing scanning frequency. That tendency point to heat concentration in smaller surface areas during melting with higher scanning frequencies. Nevertheless, that did not influence significantly the measured hardness values, as shown in **Table 4**.



a) b)

Figure 3 Macrosections of the treated by discharge scanning specimens: a) 1Hz; b) 4 Hz

Comparing depth of the melted zones of the samples treated by discharge scanning with the depth of the intense cooled to 10°C multi-pass melted sample (2.0 mm shift) showed formation of deeper zones with changed structure after first and second passes of melting. That was indicative for higher heat concentration when the melting was carried out without discharge scanning and 2.0 mm shift of the sample. In consequence, the cooling rate was higher. Thus, the highest hardness value for the specimen treated by multi-pass melting with 2.0 mm shift was measured. The hardness values of the two tempered samples (the one, treated by multi-pass treatment with shift of 2.5 mm and the other, treated by discharge scanning with frequency of 4 Hz) are presented in **Table 5**, and are compared to values found in the literature (**Figure 4)**. Up to tempering temperatures of 520÷530°C the measured hardness values for the air-cooled specimen (2.5 mm shift) were lower than those for the intense cooled to 10°C (4 Hz). That resulted from the higher retained austenite amount in the former due to the higher final cooling temperature after melting. Practically equal hardness values were measured after tempering at temperatures of 520÷530°C for both specimens. Initially, a small hardness decrease at temperatures below 500°C was observed for both specimens; it was provoked by the well-known processes of the first tempering stage. Afterwards the hardness was increased by secondary hardening, with maximum hardness values at tempering temperatures of 520°C. The air-cooled specimen (2.5 mm shift) demonstrated larger hardness increase as the secondary hardening process concurred with retained austenite transformation. Tempering temperatures, higher than 550°C, resulted in rapid carbides coagulation and thus, in hardness decrease as shown in **Figure 4** and in **Table 5**.

Table 4 Dimensions and mean hardness values in transverse direction of the melted zones of treated by discharge scanning samples

Scanning frequency, Hz	Depth of the melted zone, mm	Widht of the melted zone, mm	HV1(HRC)
1	0.49	9.88	770 (62.9)
2	0.54	9.09	750.2 (62.1)
3	0.64	8.23	770.8 (63)
4	0.8	7.18	756.8 (62.4)

Table 5 Mean hardness values after tempering at different temperatures

Specimen	HV1/HRC										
	After quenching	300°C	400°C	500°C	520°C	530°C	540°C	550°C	560°C	600°C	650°C
cooled to 10°C (4 Hz scanning)	756.8/ 62.4	720/ 61	720/ 61	772/ 63	786/ 63.5	772/ 63	733/ 61.5	613/ 56	595/ 55	544/ 52	490/ 48
air-cooled (2.5 mm shift)	568/ 53.3	544/ 52	595/ 55	720/ 61	767/ 62.8	762/ 62.6	720/ 61	643/ 57.5	583/ 54.5	544/ 52	497/ 49

The microstructures of the different zones in air-cooled specimen (2.5 mm shift) after tempering at 520°C are shown in **Figure 5**. The temperature increase to 520°C led to significant increase in carbon and chromium atoms mobility and precipitation of disperse special carbides. This resulted in hardness increase in the melted

zone, as shown in **Figure 3** and in **Table 6**. The hardness increase was also due to retained austenite transformation and martensite formation. The microstructural changes after tempering in the partially melted zone and in the heat-affected zone were similar, but the hardness increase was smaller. That was due to: 1) the lower retained austenite quantities and 2) the lower concentration of alloying elements in martensite, that resulted in $(Fe,Cr)_7C_3$ carbides formation. The measured hardness values were 64-65 HRC in the partially melted zone and up to 51-52 HRC in the heat-affected zone.

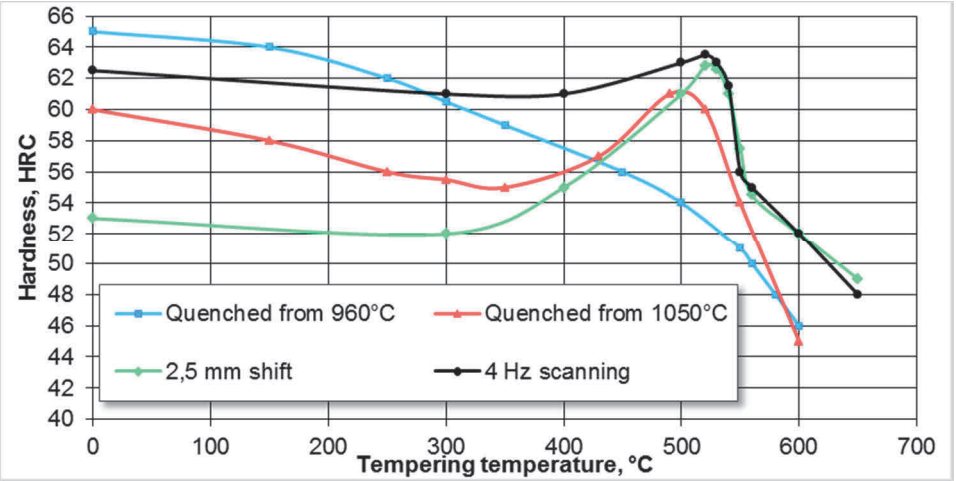
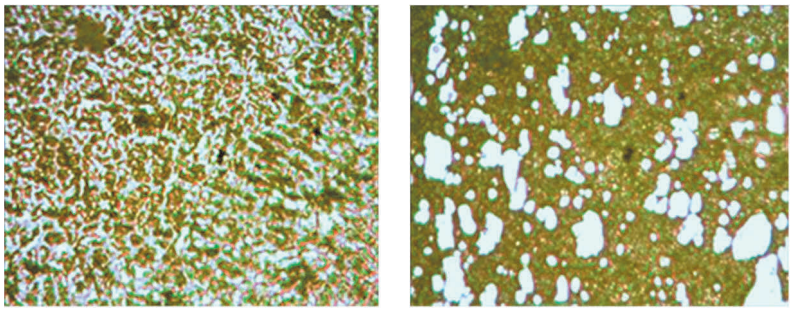


Figure 4 Specimens hardness after tempering at different temperatures compared to X210Cr12 hardness data, found in the literature (adopted from [11])



a) b)

Figure 5 Microstructures x500 of: a) the melted zone; b) partially melted zone; c) heat-affected zone in the air-cooled specimen (2.5 mm shift) after tempering at 520°C

4. CONCLUSIONS

Based on the results of the experiments in this study, the surface melting of X210Cr12 tool steel with hollow cathode arc discharge can be used as a process for surface hardening.

The following findings of this research can be summarized:

1) Hollow cathode arc discharge treatment in vacuum, using multi-pass melting or melting by discharge scanning, allows to obtain surface hardened zones.
2) Increasing the number of melting passes decreases the depth of the hardened zones and that is in correlation with overlapping extend.
3) Discharge scanning frequency influences the dimensions of the hardened zones: increasing scanning frequency has tendency to increase the depth and decrease the width of the zones.

4) The different final cooling temperatures after melting of X210Cr12 tool steel by hollow cathode arc discharge determine significant differences in hardness values after quenching. The intense cooling to lower temperatures is related to higher martensite amount and higher hardness after quenching.
5) After melting by hollow cathode arc discharge and cooling - intense to 10°C or in air to room temperature - the microstrucutre consists of martensite, retained austenite and special carbides.
6) Tempering at 520°C and 530°C increases the hardness of X210Cr12 up to 64-65 HRC, regardless of the final cooling temperature after quenching.
7) The studied process for surface hardening increases the heat-resistance of X210Cr12 tool steel from 480°C to 530°C.

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