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INFLUENCE OF ELECTROMAGNETIC INDUCTION HEATING ON GROWTH KINETICS OF CARBURIZED LAYERS IN LESS COMMON CARBURIZING MEDIA

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This paper aimed at study of growth kinetics particularities of carburized layers obtained on Cr-Ni-Mo low alloy steel carburized in less common carburizing media such as carburizing paste and urban fuel gas in the presence of electromagnetic induction heating with medium frequency currents.

The influence of thermochemical processing on carbon transfer intensity from carburizing medium to steel in the presence of electromagnetic induction heating was analyzed and the acceleration of carburizing process kinetics was observed.

This phenomenon is more intense for carburizing in carburizing paste which possesses a particularly high availability of active carbon compared with carbon availability of the urban fuel gas. The morphological aspects of carburized layers (crypto-crystalline martensite, bainite, ledeburite) found by optical and electronic microscopy have confirmed also the acceleration of the carbon mass transfer processes during carburizing in less common carburizing media in the presence of electromagnetic induction heating with medium frequency currents.

Keywords: carburizing, electromagnetic induction heating, growth kinetics

1. Introduction

The electromagnetic induction heating of metallic materials is a complex process consisting in electromagnetic phenomena and effects (electromagnetic induction – Faraday and Neumann laws, thermal effect - Joule – Lenz law, pelicular effect, proximity effect, loop effect, end effect and other) and heat transfer processes (thermal conduction – Fourier law) that cause the change of metallic materials properties [1...4].

The electromagnetic energy developed in the superficial layer of metallic materials by the presence of the induced currents, converted by Joule-Lenz effect into heat, lead to increasing of surface electronic emissivity and to enhancing the ionic adsorption mechanism effect, phenomenon that determine the acceleration of thermochemical processing in the presence of electromagnetic fields [5].

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The rapid heating provided by the electromagnetic induction heating (heating rates between 100°C/sec and 900°C/sec [4]) and in relation to these, the low heating times, influences the position of the austenite transformation temperatures which shift to higher values as to assure the driving force for the diffusion process during austenitizing; the germination rate increases, a finer grain size austenite develops and, after cooling, a fine martensite with a higher microhardness in comparison with that obtained during conventional heating and cooling [4, 6, 7] is obtained taking into account also that a uniform distribution of the carbides in steel during austenitizing has to be kept [6, 7].

The fine austenite, obtained through electromagnetic induction heating, is characterized by an increasing of the grain boundaries (the total size of the grain boundaries is higher) and an increasing of the crystalline defects number and thus the diffusion through grain boundaries and through the crystalline imperfections is strengthened and the mass transfer processes are intensified.

Similar observations with regard to the carbon diffusion processes enhancement in the presence of the electromagnetic induction are given in the reference [4] , where is shown that a case depth of 0,4 mm can be attained in 1 min at 1200°C during paste carburizing in the presence of the electromagnetic induction heating.

The paper underlies specific issues in relations to the growth kinetics of carburized layers developed on Cr-Ni-Mo low alloyed steel in the presence of the electromagnetic induction heating with medium frequency currents.

2. Experimental

The purpose of experimental carburizing researches was to study the influence of presence of electromagnetic fields generated by heating of steel parts in less common caburizing media (carburizing paste and urban fuel gas) using medium frequency induction currents on the growth kinetics of carburized layers of Cr-Ni-Mo low alloyed steel.

The experiments were performed on Φ30x100mm samples, executed from annealed rods of Cr-Ni-Mo (21NiCrMo2) low alloyed steel with the chemical composition according to chemical analysis: 0,2%C; 0,26%Si; 0,76%Mn; 0,43%Cr; 0,22%Mo; 0,51%Ni; P and S below 0,027%; each sample has an inlet for introducing the Pt-PtRh thermocouple used for temperature control.

The carburizing media used for experiments were carburizing paste (homogeneous mixture of fine powdered wood coal, sodium and calcium carbonates, potassium ferrocyanide and waste heat treatment oil) and urban fuel gas (natural gas diluted for urban demand) with a CH_4 content of 75%-95% CH_4.

To perform the electromagnetic heating, a four-coiled inductor powered by a rotary generator at a frequency of8000 Hz which operates on the magnetic circuit reluctance principle was built; the power used during electromagnetic heating was varied in the limits 1-2 KW depending on chosen temperature.

In the case of carburizing experiments performed in urban fuel gas, the samples were introduced in a graphite crucible having an internal diameter with 20 mm higher than the sample diameter, the urban fuel gas being supplied in this enclosure.

The thermochemical processing parameters were temperatures in the range 900°…1000°C and isothermal holding times of 3..7 min. The cooling was realized in water, directly in the inducer after power shuts down.

The carburized and quenched samples were investigated by optic microscopy using a Neophot 21 microscope and by electron microscopy using a TESCAN – VEGA XMU-8 scanning electron microscope.

The effective case depth of carburized and quenched layer was considered to be the distance from the surface to the zone where the microhardness is 550$\mu HV_{0.1}$ and was determined by a Reichart microhardness tester attached to a Reichert microscope.

3. Results and discussions

Previous works in the field of carburizing in less common carburizing media have shown that the carburizing paste activity is particularly increased at the beginning of the isothermal holding times being significantly higher in comparison with the urban fuel gas activity [9, 10].

This observation has been confirmed also by the actual carburizing results obtained in the carburizing paste in the presence of the electromagnetic induction heating with medium frequency currents.

Thus, a noticeable increasing (about 9 times) of total case depth of the carburized layer from 70 microns at 900°C/5min to 620 microns at 1100°C/5 min. was obtained during carburizing in carburizing paste in the presence of electromagnetic induction heating (as seen in Fig. 1).

The evolution of carburizing case depth of 21NiCrMo2 steel during carburizing in the presence of electromagnetic induction heating with medium frequency currents can be described with the following relation:

$$\delta(\mu m) = 1.62 \cdot 10^{-31} \cdot T^{11.04} \quad (1)$$

obtained by statistical processing of the experimental data for isothermal holding times of 5 minutes, with a determination coefficient of R^2=0,998 and a correlation coefficient of R=0,998.

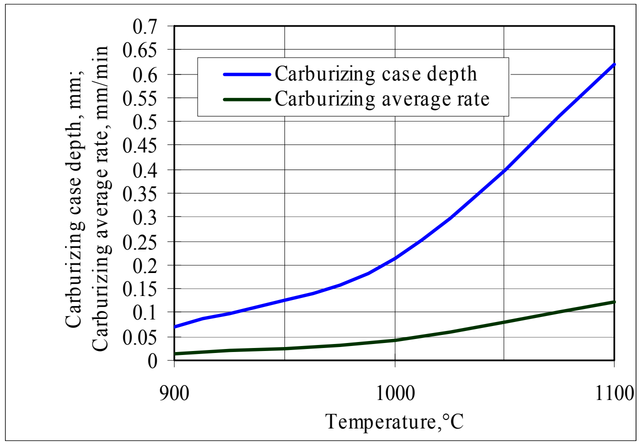


Fig.1. Growth kinetics of carburized layers on 21NiCrMo2 steel carburized in carburizing paste in the presence of electromagnetic induction heating; isothermal holding time: 5 minutes.

The first term takes into account that 99,8% of the variations of the carburizing case depth for the Cr-Ni-Mo steel taken into analysis can be explained by the temperature variations, clearly for constant activity of the carburizing media during isothermal holding times of 5 minutes and the second term shows the relationship between the two variables – the carburizing temperature, respectively the carburizing case depth.

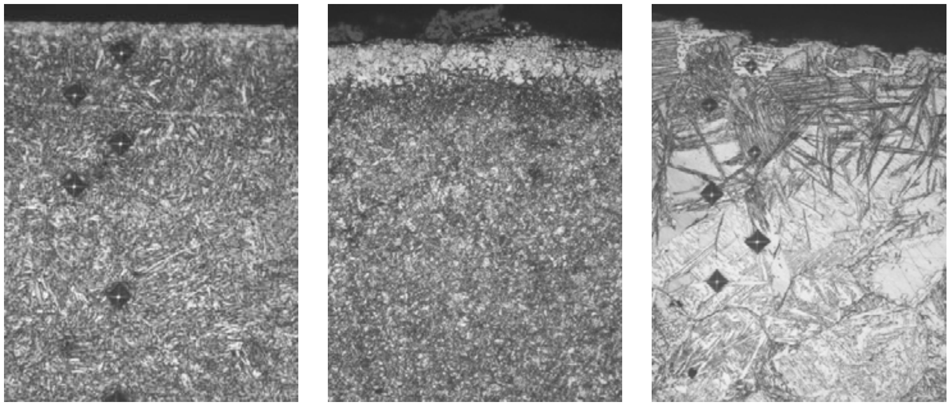
In these conditions, the carburizing average rate can be expressed as it follows:

$$V(\mu m/\min) = 7.09 \cdot 10^{-32} \cdot T^{10.93} \tag{2}$$

obtained by statistical processing of the experimental data for isothermal holding times of 5 minutes, valid for investigated Cr-Ni-Mo steel, carburized in carburizing paste in the presence of electromagnetic induction heating with medium frequency currents (f = 8000 Hz).

The maximum microhardness determined after carburizing in paste and cooling in water spray, directly in the inducer is about 700…800 $HV_{0,1}$, at a distance of 30μm from sample surface and the non-carburized core maintains its microhardness of about 300 $HV_{0,1}$.

The high microhardness of the carburized layers is caused by the presence of the martensite (Fig. 2) which has a high carbon concentration (in the absence of a high concentration of carbon in the martensite of analyzed Cr-Ni-Mo steel, the maximum microhardesses values are below maximum 450 HV according to the information provided by the transformation diagrams).



T=900°C/5min T=1000°C/5min T=1100°C/5min

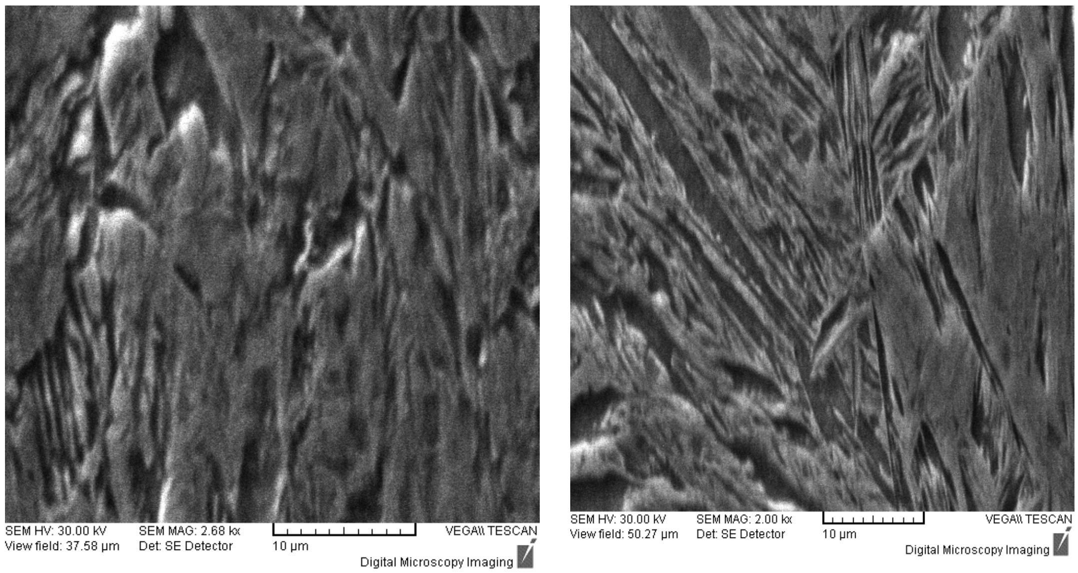
Fig.2 Micrographs of the carburized and quenched layers obtained on 21NiCrMo2 steel.Carburizing medium: carburizing paste.Heating: electromagnetic induction; Quenching: in water;Etching reagent: nital 2%; Magnification:200:1

The high level of carbon concentration in the layer causes a shift of the undercooled austenite transformation curves to the right (equivalent to hardenability augmentation), therefore the probability of occurrence of martensite in the carburized layer is increased too. The temperature rise influences directly the morphology of martensite, which changes from crypto-crystalline aspect at a relatively low temperature of 900°C to the coarser aspect at a higher temperature, of 1100°C. The core structure remains bainitic (lower bainite) with a morphology which depends also on temperature.

Note. The carbon concentration variation in the carburized layer and implicitly in martensite, lead to slight decreasing of the martensite microhardness with reduction of the carbon concentration.

The electron microscopy has revealed the morphology of quenched martensite, respectively of the lower bainite steel specific to21NiCrMo2 steel, the morphological similarities of the two constituents being highlighted (Fig. 3).

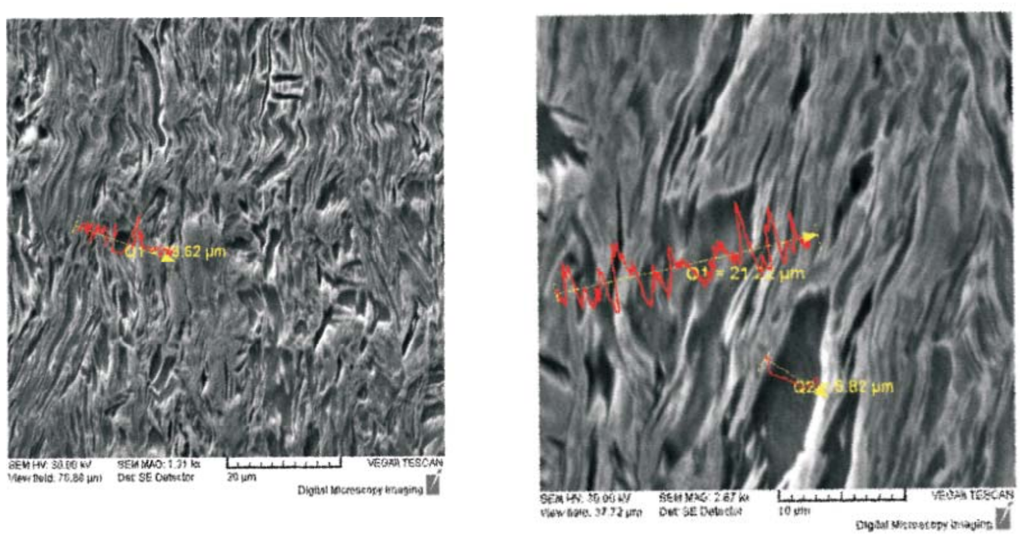
The qualitative aspect of the microhardnesses profiles (underlined by the different perceptiveness to the etching of the different microvolumes) registered in one zone of the martensite and in two zones of bainite obtained in the carburized layer of the 21NiCrMo2 steel after carburizing in carburizing paste and quenching in water, in accordance to the carbon distribution in those zones was also shown by SEM microscopy (Fig. 4).



Martensite obtained after carburizing in carburizing paste at 1000°C/5min and quenched in water

Lower bainite obtained after quenching in water from 1100°C/5min (structure of non-carburized core)

Fig.3 SEM micrographs of the carburized and quenched layer (surface and core) obtained on 21NiCrMo2 steel. Heating: electromagnetic induction; Quenching: water



Martensite obtained after carburizing in carburizing paste at 1000°C/5min, quenched in water

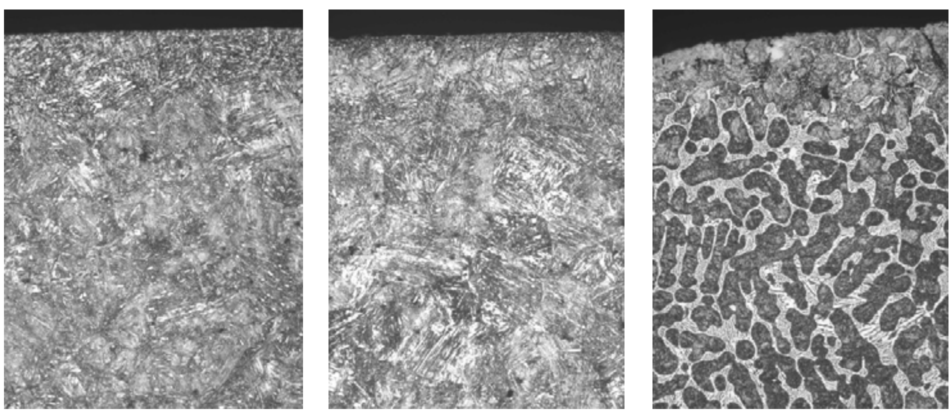
Bainite obtained after carburizing in carburizing paste at 1100°C/5 min, quenched in water

Fig.4 SEM micrographs and qualitative profiles of microhardnesses of the carburized and quenched layer obtained on 21NiCrMo2 steel. Heating: electromagnetic induction; Quenching: water

If the chemically active medium used for carburizing is the urban fuel gas and this gas is freely "washing" the surface of the sample placed in the crucible, the carbon potential developed in the vicinity of surface is lower than that generated by the decomposition of carburizing paste in contact with metallic surfaces.

In this case, for the analyzed 21NiCrMo2 steel, which has an appropriate bainitic hardenability, the carbon concentration in bainite is increasing (the carbon is re-distributed into carbides and also into the bainitic ferrite carbides), without creating the condition of obtaining the martensite through quenching; the shift to the right of the bainitic curve is insufficient to allow the obtaining of cooling rates higher than the bainitic critical cooling rate in the specific conditions of cooling.

All experiments carried out in the temperature range of 900°...1100°C for isothermal maintaining time of 5 minutes in urban fuel gas did not lead to the obtaining of martensite in the carburized and quenched layer, after each treatment variant the lower bainite characterized by higher microhardness (higher carbon content) in comparison with the core microhardness being found (Fig. 5).



900°C/5min 1000°C/5min 1100°C/3min

Fig. 5 Micrographs of the carburized and quenched layers obtained on 21NiCrMo2 steel. Carburizing medium: urban fuel gas. Heating: electromagnetic induction ; Quenching: water; Etching reagent: nital 2%; Magnification:200:1

A different situation was reported after carburizing at 1100°C/3 min, when due to overheating, caused by incorrect position of the sample in the inductor coil, the local melting has occurred with correspondent acceleration of the diffusion of carbon in superficial layers and as consequence the ledeburite was found.

Another interesting aspect noticed by microscopy in the proximity of the superficial layer of the sample carburized in urban fuel gas at 1100°C/3min under inductive heating is: the initiation of the decarburization phenomenon, respectively the carbon concentration has attained a level below the minimum concentration of carbon required for the appearance of ledeburite. As result, in this case, the coarse lower bainite and carbides separations, most of these of cementite type (alloyed cementite), were also found in the superficial layer.

The morphological aspects specific to ledeburite and the qualitative microhardness profile closely correlated with the distribution of carbon in the ledeburite phases on a distance of about 50 microns were also shown by electron microscopy (Fig. 6), confirming once again the existence of this constituent in the carburized and quenched layer due to a procedural error.

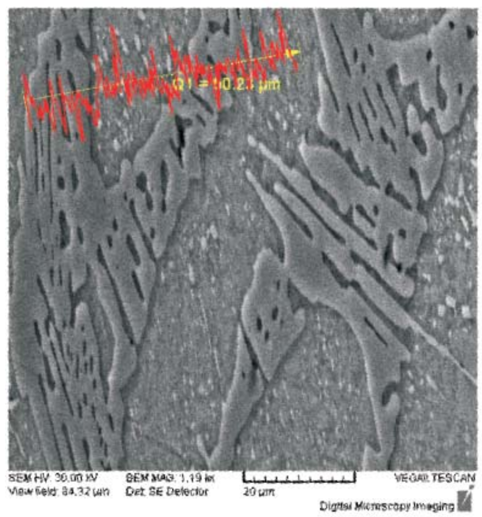


Fig.6 SEM micrograph and qualitative profile of microhardnesses of the carburized and quenched layer obtained on 21NiCrMo2 steel. Carburizing medium: urban fuel gas. Carburizing parameters: 1100°C/3 min; Heating: electromagnetic induction; Quenching: water.

The size of the zones affected by the re-distribution of carbon is similar to that obtained during carburizing in paste using electromagnetic induction heating with medium frequency currents, but to become an opportunity, the carburizing in urban fuel gas under inductive heating requires more technological strictness than the paste carburizing [5, 9,10].

The morphological aspects of carburized layers (crypto-crystalline martensite, bainite, ledeburite) highlighted by optic and electron microscopy also confirmed the distinct intensifying of carbon mass transfer processes during carburizing in low common caburizing media in the presence of electromagnetic induction heating.

The analized carburising results have proved the particular acceleration of kinetics of carburizing in less common carburizing media in the presence of electromagnetic induction heating with medium frequency currents (f=8000Hz) and are supported by other previous carburising results (in the case of carburizing in carburizing paste in the presence of electromagnetic induction heating (f=2000Hz) the carburizing average rate at 1080°C/45 min was 21.3 mm/min [5] compared to 11.8×10^{-3} mm/min attained at 1000°C/45 min during carburising in carburizing paste using conventional heating [8, 9], both carburizing rates being determined by mathematical modeling) and by other data quoted in the specialized literature [10].

6. Conclusion

In the presence of the electromagnetic fields (electromagnetic induction heating) takes place a particular acceleration of growth kinetics of the carburized layers.

In this respect, the carburizing process in less common carburizing media using electromagnetic induction heating with medium frequency currents provides both carburizing case depths and average rates superior to those reported for carburizing in the less common carburizing media, using conventional heating.

In the presence of the electromagnetic field generated by induction heating, the carbon diffusion coefficient and adsorption rate in austenite at various temperatures are approximately two orders of magnitude higher compared to those determined during conventional gas carburizing (for example, for heating in electric or gas furnaces) [5], on the one hand because of the increasing of the diffusion on the grain boundaries (by increasing the heating rate, a fine grain is maintained up to high temperatures) and also by increasing of the diffusion in volume, by means of defects and on the other hand due to much higher processing temperatures.

The causes are related to the presence of electromagnetic field influence on the carburizing medium (adjacent to surface zone), carburizing medium - metallic material interface and surface zones of the product subject to thermochemical processing, where the interaction between the inductive and induced currents due to the proximity effect occur.

The carburizing in less common carburizing media using the electromagnetic induction heating with medium frequency currents can be an opportunity but the implementation must be carefully prepared and carried out in order to avoid undesirable phenomena such as overheating which may lead to local melting.

The carburizing paste can be a very useful active medium for carburizing in the presence of electromagnetic heating with medium frequency currents but only for parts with simple geometries and small series; for large series of parts, the carburizing in urban fuel gas can be a convenient option if a rigorous control of the process is assured.

The carburizing process using the electromagnetic induction heating with medium frequency currents is effective for processing times which are relatively limited, depending on chosen carburizing temperatures. An inappropriate correlation of the processing parameters - frequency current, temperature and isothermal maintaining time can cause the decreasing of the carburizing rate and improper thermochemical processing.

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