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Induction Surface Hardening of 42CrMo4 Steel Tubes Designed for Rotary Percussive Drilling Equipment

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Abstract. 42CrMo4 steel tubes are subjected to multiple induction heat treatments to obtain various hardened layer depths after spray water quenching. Current frequency, induction unit power and coil movement velocity along the tube axis are under consideration. The hardened layer depth is estimated along the transverse direction of the tubes using metallographic studies and microhardness measurements. An empirical equation is obtained for the hardened layer depth as a function of the induction heat treatment parameters. The laboratory test results are employed to develop the technology of the production of 42CrMo4 steel tubes designed for rotary percussive drilling equipment. The service life of induction hardened tubes during abrasive wear resistance field tests is approximately twice as long as that of conventionally nitrided ones.

INTRODUCTION

Rotary percussive drilling equipment parts have a demanding requirements for high toughness, fatigue strength and wear resistance, since they are operated under severe conditions of static and impact loads and high abrasive media [1…3]. The mechanical properties of the products are obtained by proper material selection and bulk heat treatment [4…6]. Conventionally, to obtain abrasive wear resistance, several surface hardening methods are employed, namely, carburization [7…9], nitriding or carbonitriding [10…12], laser hardening [13] and induction surface hardening [14…16]. These methods have some disadvantages, for example, a distortion of carburized parts, a long nitriding time, expensive laser hardening equipment. In case of induction heating, a number of process parameters are to be obtained [17]. These parameters can be calculated using numerical models [18…21]; however, varied experimental conditions and unpredictable fitting coefficients cause incorrect results in practice. Moreover, the majority of calculation methods do not consider the initial microstructure of the steel, the grain growth rate, austenite inhomogeneity, the cooling capacity of the sprayer. On the other hand, induction surface hardening has a number of advantages [17]. They are short process time, insignificant decarburization and oxidation, smaller distortion compared to case hardening and carbonitriding, low operating costs and the absence of stand-by costs, lesser energy consumption than during alternative processes, and process gases not required.

In the available literature there is a lack of data concerning the microstructure of rotary percussive drilling tubes and its effect on the mechanical properties and service life of the product (for example, its drilling distance). The present paper demonstrates an approach to the determination of the induction heating parameters and compares the microstructure and service life of induction surface hardened tubes and commercially nitrided ones.

EXPERIMENTAL

Commercially produced hot-rolled Ø150×14 mm 42CrMo4 steel tubes, 1000 mm long, were under consideration. The chemical composition of the steel was as follows: C – 0.41; Cr – 1.05; Mn – 0.65; Mo – 0.20; S, P – max. 0.035 mass %, respectively. The tubes were heated in a furnace to 850 °C, quenched in industrial oil with the temperature of 40 °C and tempered at 525…575 °C for 3…4 hours. The higher tempering temperature was

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applied in the case of the tubes to be nitrided to avoid tempering of the core metal during the diffusion stage [22]. After the preliminary heat treatment, the tubes were machined to a diameter of 146 mm.

The nitriding was carried out in an electric batch furnace at 500…550 °C. The furnace atmosphere was dissociated ammonia, and the nitriding potential was controlled by means of an oxygen probe [23]. The duration of the nitriding process was 18…24 hours.

The induction surface hardening was conducted by means of industrial equipment with the following technological parameters: current frequency f of 25…440 kHz; induction unit power p of 85…140 kW; the gap between the induction coil and the tube surface, g, of 4 mm; coil movement velocity along the tube axis, v, of 0.5…6.5 mm/s. The induction coil was a two-turn spiral of a copper tube. The heated surface of the tube was quenched by means of a water sprayer mounted on the bottom of an induction coil. Thus the scanning of induction surface hardening was implemented. The tubes were rotated during induction heating and subsequent quenching to provide a uniform depth of the hardened layer.

The microstructural features of the heat treated tubes were identified using optical microscopy. The microhardness measurements were carried out with the loads in the range of 10…1000 g and with 0.05…0.25 mm intervals along the transverse direction of the tubes. The hardened layer depth was assumed as a point with the mean hardness between the surface and core hardness values. The mechanical properties of the tubes were measured using standard procedures, i. e., ASTM E18 for Rockwell hardness measurements, ASTM E8 for tension tests, ASTM E23 for Charpy impact strength tests.

The field tests of the nitrided and induction surface hardened tubes were conducted in the same service conditions. The drilling was performed using a down-the-hole pneumatic hammer with the air pressure of 2.1 MPa, the rotation velocity of 15…35 r/min and the feed force of 8.3 MPa. The outer diameter of the tubes was estimated with the accuracy of 0.1 mm after a certain drilling distance, which was determined with the accuracy of 0.25 m. The main parameters of the service life of the tubes were the drilling distance m and the rate of the outer diameter reduction due to abrasive wear, mm/m.

RESULTS AND DISCUSSION

The initial microstructure of the hot-rolled 42CrMo4 steel tubes was coarse-grained ferrite and pearlite with the hardness of 25…27 HRC. After the preliminary heat treatment (oil quenching and tempering), the microstructure of the tubes was fine secondary sorbite with the hardness of 34…38 HRC for the tubes to be induction hardened and 30…35 HRC for the tubes to be nitrided. The bulk heat treatment provided the required strength ($\sigma_B > 1000$ MPa) and toughness (KCV > 70 J/cm^2) of the tubes.

The conventional gas nitriding led to the formation of a thin nitrided layer on the inner and outer surfaces of the tubes. The microstructure consisted of a white surface compound layer and carbonitride precipitations at the grain boundaries in the diffusion zone. Its presence indicates that the nitriding temperature and/or the nitrogen potential were/was higher than optimal for the 42CrMo4 steel under consideration. On the other hand, the lower values of the nitriding temperature and/or the nitrogen potential would significantly increase the duration of the diffusion stage to obtain the 0.5…0.6 mm layer depth (up to 48 h and more [22]).

The white compound layer depth on the nitrided tube surface was estimated by optical microscopy to be 0.005…0.010 mm, and its microhardness was 800…850 HV_{10}. The depth of the diffusion layer was 0.5…0.6 mm with the hardness near the surface 660…700 HV_{100}. It is considered [24] that the presence of a white nitrided layer with a high hardness and a low friction coefficient reduces the abrasive wear of products and increases the service life of machine parts. On the other hand, carbonitride precipitations on grain boundaries embrittle the steel and cause failures of parts [25].

After induction surface hardening with the varied parameters of the process, the hardened layer with various depths was obtained on the surface of the tubes. In most cases, the microstructure of the hardened layer was fine-grained martensite with a hardness of 56…59 HRC. After the treatment with $v < 0$ 8 mm/s ($f = 440$ kHz, $p = 120$ kW), coarse-grained martensite was formed in the surface layer. Conventionally, this microstructure sufficiently reduces the toughness of steel [26]. The core microstructure after the induction surface hardening was fine secondary sorbite formed during the preliminary heat treatment.

The increase of the induction coil movement velocity greatly affects the depth of the hardened layer. For example, when $f = 440$ kHz and $p = 120$ kW, the increase of the induction coil movement velocity from 0.5 to 1.6 mm/s led to the reduction of the hardened layer depth from 3.70 to 0.85 mm. This is due to a decrease in the volume unit heating time with the increase of the induction coil movement velocity, so the hardened layer became thinner [17].

By the regression analysis of the experimental data, the analytical equation for the hardened layer depth h was obtained as a function of the induction heat treatment parameters,

$$h = (3.928 + 0.00318p - 0.00257f - 2.01193v^{1/4}). \quad (1)$$

The adequacy of Eq. (1) was evaluated and the ratio of the table value of the Fisher criterion to the calculated one was 40. The calculated values are in a good agreement with the experimental data. Note that Eq. (1) is valid only in case of the considered experiment conditions. In any other conditions (for example, tube diameter or steel grade) it is necessary to conduct additional experiments to validate the fitting parameters of the equation.

The induction hardening equipment parameters for the required hardened layer depth of the 42CrMo4 steel tubes under consideration were calculated using Eq. (1). In case of the highest current frequency of 440 kHz and the induction unit power of 120 kW, the required hardened layer depth (2.0 mm) would be obtained when v = 0.8 mm/s. However, the microstructure analysis revealed that the low v values caused the formation of coarse-grained martensite in the surface of the tube. To prevent the overheating of the tube surface, the induction coil movement velocity should be increased and, at the same time, the current frequency should be reduced and the induction unit power should be increased. The required hardened layer depth and microstructure would be obtained with the following numerically defined technological parameters: f = 25 kHz; p = 140 kW; v = 5.5 mm/s.

The induction hardened tubes were compared with conventionally nitrided ones during the field tests. Figure 1 shows the reduction of the outer diameter D of the induction hardened and nitrided tubes in the bottom part (closest to the drill bit) and in the opposite part of the tube. It is evident that the service life of the induction hardened tubes is longer (approx. 6000 m, Fig. 1a) than that of the nitrided tubes (approx. 3500 m, Fig. 1b). The wear rate had two distinct stages, namely, the stage of the wear of the surface hardened layer and the stage of the core metal wear.

Low wear rate was during the first stage (approx. 0.001 mm/m) until the hardened layer was completely removed by the abrasive particles from the surface of the tubes. During the second stage, the wear rate was increased up to 0.003…0.004 mm/m for the bottom part of the tubes and up to 0.002 mm/m for the top part. The second wear rate stage is associated with the wear of the tube core, which had a lower hardness compared with the hardened layer. In case of the induction hardened tubes, the first stage of wear lasted during approx. 3500 m of the drilling distance, and for the nitrided ones, this stage was approx. 1400 m. This was due to the greater depth of the induction hardened layer compared with the depth of the nitrided layer. The wear of the top part of the tubes was lesser during the first and the second wear stages than the wear of the bottom part. This was due to the energy loss of abrasive rock particles while they were transported from the drilling point to the top of the tube [27].

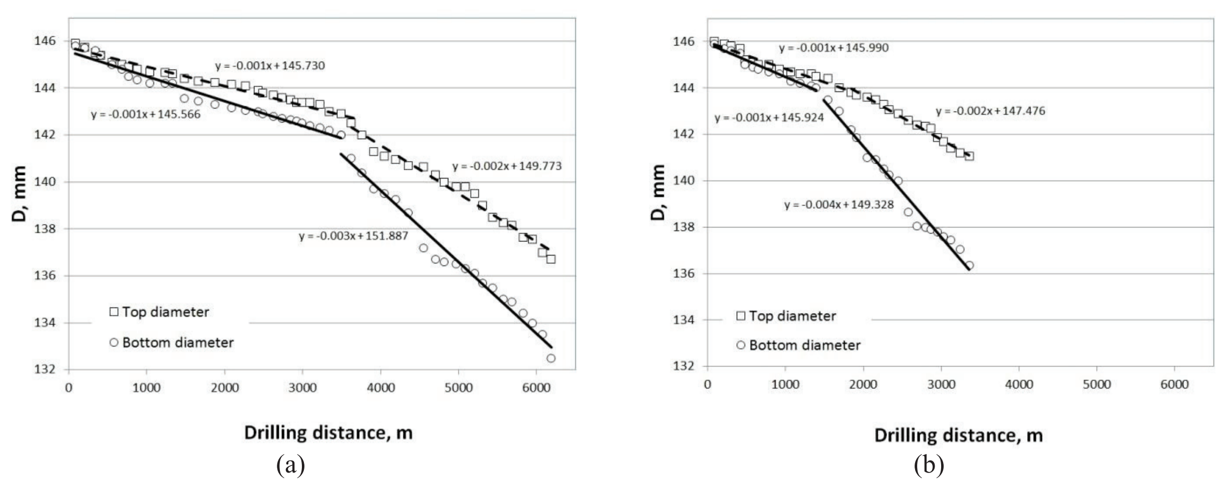

FIGURE 1. Reduction of the outer diameter of (a) induction hardened and (b) nitrided tubes during the field tests

The average service life of the nitrided tubes was approx. 3500 m, and the main reason of failures was the formation of cracks on the surface. Probably, the cracks started in the stress concentration zones formed due to the grain-boundary precipitation of carbonitride particles [25]. The induction hardened tubes had greater service life (approx. 6000 m) and were replaced only because of critical thinning.

SUMMARY

1. The empirical equation has been obtained for the depth of the hardened layer of 42CrMo4 steel tubes as a function of the induction heat treatment parameters (current frequency, induction unit power, induction coil movement velocity). The calculated values of the hardened layer depth are in a good agreement with the experimental data.

2. The induction hardening equipment parameters for the required hardened layer depth (2.0 mm) and microstructure (fine-grained martensite with a hardness of 56…59 HRC) have been determined: the current frequency, $f = 25$ kHz; the induction unit power, $p = 140$ kW; the induction coil movement velocity, $v = 5.5$ mm/s.

3. The service life of the induction hardened tubes was approx. 2 times as long as that of the conventionally nitrided ones, because of the greater depth of the hardened layer and the absence of coarse carbonitride particles at the grain boundaries.

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