

# EFFECT OF THERMAL-CYCLIC DEFORMATION AND HEAT TREATMENT ON THE STRUCTURE AND ELECTRICAL PROPERTIES OF C<sub>73</sub>

ВЛИЯНИЕ ТЕРМОЦИКЛИЧЕСКОЙ ДЕФОРМАЦИИ И ТЕРМИЧЕСКОЙ ОБРАБОТКИ НА СТРУКТУРУ И ЭЛЕКТРИЧЕСКИЕ СВОЙСТВА СТАЛИ C<sub>73</sub>

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**Abstract:** The results of the effect of preliminary thermal-cyclic deformation on the microstructure of hot-rolled low-carbon steel Cm3nc are presented. It is shown that the regime of thermal-cyclic rolling leads to a decrease in the average grain size of ferrite from 8 to 6 microns in comparison with the structure of steel after industrial production. There is a decrease in the size of pearlite colonies and their volume fraction in the structure of steel after using thermal-cyclic deformation. The results of the effect of heat treatment: normalization and tempering on the electrical resistivity of the hot-rolled carbon steel sheet Cm3nc produced using thermal-cyclic mode of deformation processing (DTCT). DTCT preliminary thermal-cyclic was rolled (5 cycles at a reduction of 10-15 % in each cycle and cooled to a temperature below the Ar1). And normalizing annealing was carried out in the range from 100 to 900 °C increments to 100 °C for 1 hour. The possibility to reduce the magnitude of the specific electrical resistance of the hot-rolled steel manufactured using DTCT mode through the use of subsequent normalizing at 700 °C on average 10 %, and by annealing – no more than 5 %. A further increase in the time of normalization at 700 °C to 3, 5 and 10 hours has no significant effect on the value of the electrical resistance of the steel subjected DTCT. However, the downward trend in resistivity is maintained. Overall reduction of electrical resistivity of the hot-rolled steel Cm3nc by using mode DTCT and subsequent normalizing at 700 °C for 1 hour is more than 12 %.

**KEYWORDS:** STEEL, STRUCTURE, DEFORMATION, THERMAL-CYCLIC ROLLING, ANNEALING, NORMALIZING, ELECTRICAL RESISTIVITY.

## 1. Introduction

In the field of electro-technical material engineering low-carbon steel can be attributed to the most available and cheap materials exhibiting good mechanical tensile properties. However its application is restrained by increased specific electric resistance compared to copper and aluminum alloys. It is well-known that for structurally sensitive properties, that together with mechanical characteristics include specific electric resistance, a combined impact of temperature and deformation is efficient [1-5]. To such impacts one can attribute deformation thermal-cyclic treatment (DTCT), which is represented by thermal-cyclic treatment combined with various types of deformation in the range of low or high temperatures [1,6]. Such combined treatment leads to intensification of diffusion processes occurring at preset temperature fluctuations with application of stresses and deformations, accumulation of structural changes occurring in cycles and connected with bulk effects of phase transformations, difference in thermal-physical characteristics of phases etc. Ultimately these processes provide for formation of optimal structure and improvement of physical and mechanical properties of steels, cast irons, aluminum alloys and other materials [6-15]. A reserve for reduction of specific electric resistance could be subsequent thermal treatment to obtain better equilibrium structure with reduced amount of crystallographic defects and lower level of internal stress [12,17], normalizing and annealing in the first place. Therefore the objective of the study was researching impact of various modes of normalizing and annealing onto specific resistance of hot-rolled C<sub>73</sub>nc steel, manufactured with application of DTCT.

## 2. Material and methods

Low carbon commercial quality C<sub>73</sub>nc steel served as material for research. The steel was produced at "Novokuznetsk integrated steel plant (NKMK)" JSC. Chemical composition of

steel was determined on ARL 4460 emission spectrometer. Results are presented in Table 1.

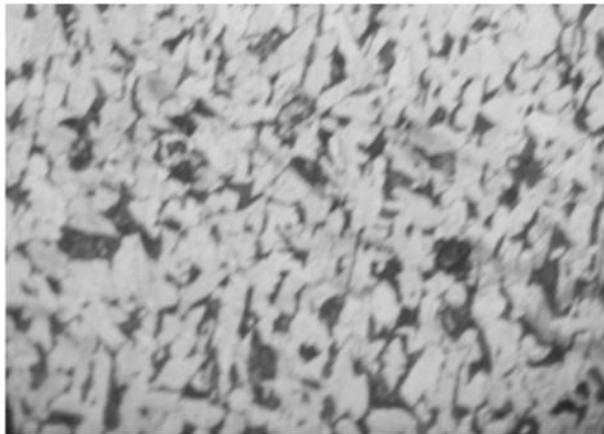
In order to roll sheet with application of DTCT a slab was cut out from ingot with dimensions of 165×500×1800 mm. Thermal-cyclic rolling of slab was performed at "NKMK" JSC on sheet rolling mill 500. One cycle of thermal-cyclic slab and billet rolling included heating up to 1300 °C, holding for 2-2,5 h, reduction of 10-15 % and air-cooling down to temperature below A<sub>r1</sub>. There were 5 treatment cycles performed, at that in the 1<sup>st</sup> and 3<sup>rd</sup> cycles cooling was down to 500-550 °C, and in the remaining cycles – down to 50-100 °C. Reduction by cycles was performed by the pattern of 165→140→120→110→100→90 mm and further down to sheet thickness of 5 mm according to "NKMK" JSC sheet rolling mill process. Upon reaching breakdown length of 2500 mm it was cut into two halves 1200-1250 mm each. Samples were cut out from the sheet received with the dimensions of 5×20×100 mm and thermally-cyclic rolled down to thickness of 4, 3, 2 and 1 mm over 1-5 treatment cycles. Rolling was performed on the laboratory mill of 20 kW capacity with plain rolls of 250 mm diameter. Prior to deformation the samples were heated to 850 °C and held during 30 minutes, cooled down to rolling temperature of 750 °C. Reduction ratio in cycles for various thicknesses equaled 20, 25, 30 and 50 % correspondingly. Annealing of sheet samples was performed in resistance furnaces SNOL 2.2, 5.2/12,5-II. Optical microscopes LaboMet-II and OLYMPUS-GX51F were used for studies of steel microstructure, and NORMA M88a unit assembled on the basis of Thompson bridge circuit was applied to measure electric resistance. Samples for electric resistance measurement had square section with 1-5 mm sides and 100 mm length. Procedural error of specific resistance measurement made 0,05·10<sup>-8</sup> Ω·m.

**Table 1.** Chemical composition of treated Cm3nc steel

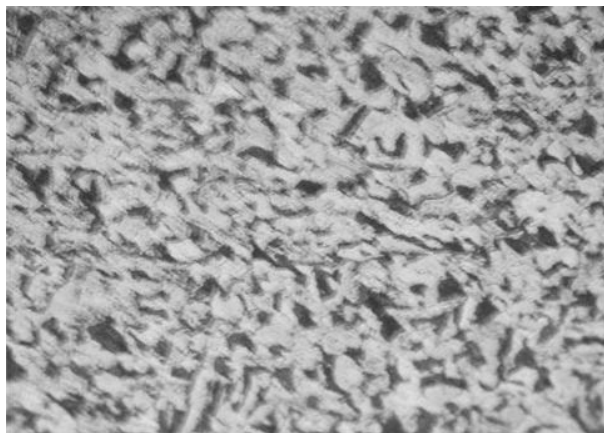
Steel grade	Heat №	Elements ratio, % (weight.)								
		C	Mn	Si	P	S	Cr	Cu	Ni	Fe
C <sub>73</sub> nc	060886	0,19	0,54	0,07	0,013	0,028	0,3	0,07	0,03	rem.

### 3. Results and discussion

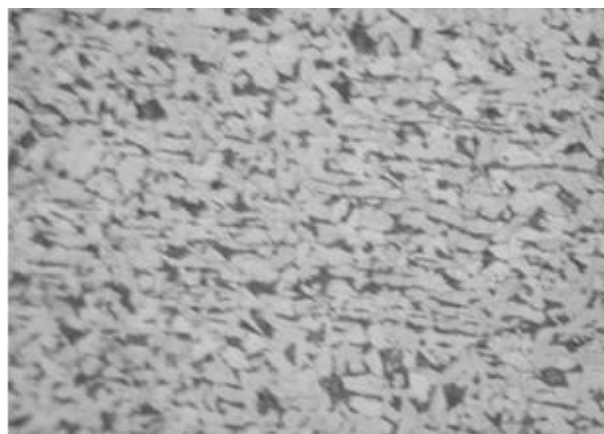
Microstructure of hot rolled sheet from Cr3nc steel rolled in industrial mode and with application of thermal-cyclic deformation consists of evenly distributed ferritic grains and pearlite colonies [12]. However, preliminary thermal-cyclical rolling leads to certain reduction of ferrite average grain size from 8 down to 6  $\mu\text{m}$  compared with grain within structure of a sheet produced in industrial mode, as well as to reduction of pearlite colonies size and their volume ratio (fig. 1).



a



b

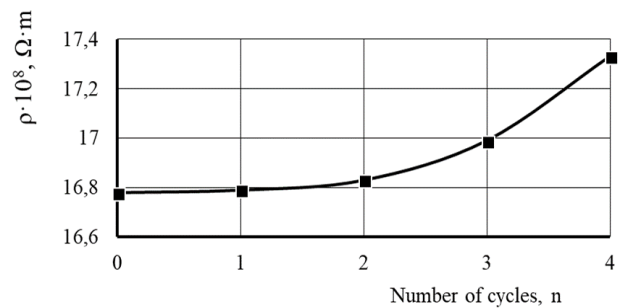


c

**Fig. 1** – Effect of deformation thermal-cyclic treatment onto microstructure of sheet Cm3nc steel, produced by a – industrial process (sheet thickness 5 mm); b – with application of preliminary thermal-cyclic rolling (sheet thickness 5 mm); c – with application of preliminary and subsequent thermal-cyclic rolling (sheet thickness 1 mm);  $\times 200$

Determination of specific electric resistance of sheet steel indicated that after preliminary DTCT (rolling) its value is  $16,8 \cdot 10^{-8}$

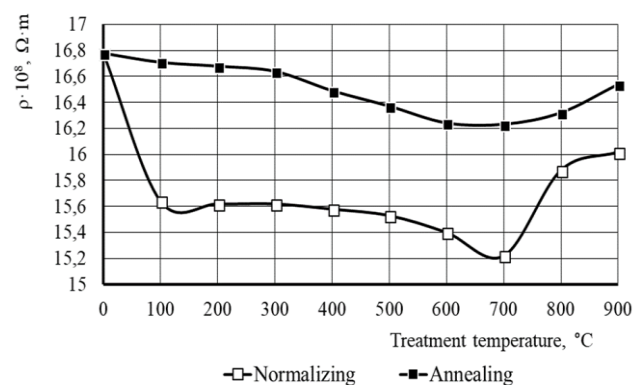
$\Omega \cdot \text{m}$ , which is 3-5 % lower, than in sheet steel of industrial production. Effect of deformation cycles onto specific electric resistance of steel produced with DTCT, at further thermal-cyclic rolling from 5 to 1 mm is shown in fig. 2.



**Fig. 2** – Effect of number of deformation cycles onto specific electric resistance of hot rolled Cm3nc steel produced with application of DTCT

It can be noted that increasing the number of deformation cycles increases specific resistance of rolled sheet, which is apparently related with extension of grain junction lines in structure of deformed steel and incomplete relief of work hardening in thin sheets. For instance, determination of average size of ferrite grains and pearlite colonies displayed their reduction after the 4<sup>th</sup> deformation cycle down to value of 2-3  $\mu\text{m}$ . At that, increase of deformation degree in cycle leads to more intensive growth of specific electric resistance of samples cut out of rolled material.

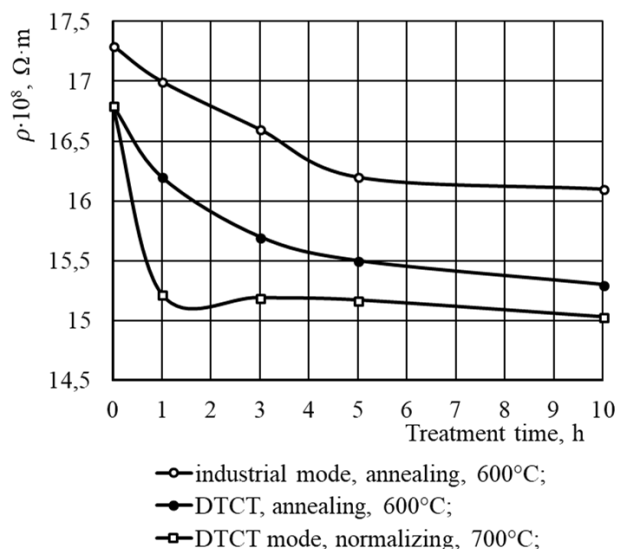
A reserve for reduction of specific electric resistance of hot rolled steel could be subsequent thermal treatment that allows obtaining better equilibrium structure compared to deformed metal condition [17]. Therefore the effect was studied of temperature and normalizing and annealing time onto the value of specific resistance of hot rolled Cr3nc steel. Treatment temperature was altered within the range of 100 to 900  $^{\circ}\text{C}$  with pitch of 100  $^{\circ}\text{C}$  and holding time of 1 h. Results of determining specific resistance of samples from hot rolled Cr3nc steel in normalized and annealed states are drawn in fig. 3.



**Fig. 3** – Effect of annealing and normalizing temperature onto specific electric resistance of hot rolled Cm3nc steel produced with application of DTCT

It is established that with the increase of treatment temperature for both normalizing and annealing modes value of specific electric resistance is reduced until temperature reaches 700 $^{\circ}\text{C}$ . At that in normalized samples specific electric resistance is 6 % lower compared to the annealed ones, and its absolute value makes  $15,22 \cdot 10^{-8} \Omega \cdot \text{m}$ . Increase of specific electric resistance of steel with the increase of normalizing and annealing temperature up to 900  $^{\circ}\text{C}$  may be related with coalescence at this temperature of cementite present in pearlite component after DTCT in dispersed form.

Further on the effect was studied of holding time of steel samples at optimal treatment temperatures: for normalizing –700 °C, for annealing – 600 °C. Optimal treatment temperature corresponds to minimal value of specific electric resistance of samples. Results of determining specific resistance of sheet Ст3пс steel produced in industrial mode and with application of DTCT, after annealing and normalizing at various holding times, are shown in fig. 4.



**Figure 4** – Effect of thermal treatment time onto specific electric resistance of sheet Cm3nc steel produced in industrial mode and DTCT mode

It is demonstrated that sequential increasing of holding time at annealing and normalizing up to 10 h leads to reduction of specific electric resistance of sheet industrial steel and steel produced with application of DTCT. Variation regularity of specific electric resistance at annealing for experimental and industrial steel is the same: however, reduction level varies. After annealing DTCT treated steel has specific resistance 5÷6 % lower, and minimal value corresponds to annealing time of 10 h and makes  $15,3 \cdot 10^{-8}$  Ohm.m.

Increasing of normalizing time at 700°C up to 3, 5 and 10 h does not significantly affect the value of specific electric resistance of hot rolled steel produced with application of DTCT, although retains a trend to its reduction. Thereby overall reduction level of specific electric resistance of hot rolled steel due to application of DTCT mode and subsequent normalizing at 700 °C within 1÷10 h averages 10-13 %.

#### 4. Conclusions

1. Application of preliminary thermal-cyclic rolling allows reducing specific electric resistance in sheet Ст3пс steel by 3÷5 % compared to industrial mode.

2. Application of high reduction ratios (20-50 %) in DTCT cycles for hot rolled Ст3пс steel to produce sheet of less than 5 mm thickness leads to increase in specific electric resistance in proportion to number of cycles and degree of deformation.

3. Combination of DTCT with subsequent annealing at 600 °C within 1÷10 h for hot rolled Ст3пс steel reduces specific electric resistance by 4-6 % on average as compared to industrial production process.

4. Introduction of sequential normalizing at 700 °C within 1÷10 h allows reducing the value of specific electric resistance of DTCT treated hot rolled Ст3пс steel by the average of 9-10 %.

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