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The Impact Factor of Metal Science And Heat Treatment is 0.566.

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THERMAL AND THERMOMECHANICAL TREATMENT

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USE OF THERMOCYCLING DEFORMATION FOR RAISING THE OPERATING PROPERTIES OF LOW-CARBON STEEL

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The effect of thermocycling deformation and subsequent heat treatment on the microstructure and mechanical properties of low-carbon steels 10kp, St3ps and 20 is studied in cast condition and after rolling. Metallographic analysis of the steels is performed using an optical microscope at a magnification of ×140 and ×500. The microhardness of the structural components is measured. The mechanical properties of the steels are determined in tensile tests. It is shown that after the thermocycling treatment above the temperature Ac_3 all the structural components are refined. The strength of the forgings after the thermocycling treatment, quenching and low tempering increases by a factor of 1.7 – 2.4 at a satisfactory level of ductility.

Key words: low-carbon steel, ferrite, pearlite, thermocycling forging, strength, ductility.

INTRODUCTION

Mechanical and physical properties of metallic materials, reliability and endurance of constructions and machine parts are enhanced successfully by traditional heat treatments and by treatments combining different impacts on the metal during formation of billets and final products. These are methods of plastic deformation (including a severe one), ultrasonic and laser treatments, irradiation with electron beams, exposure to electromagnetic fields, etc. [1, 2]. However, many advanced methods of treatment of materials require special and expensive devices, are hard to conduct and not very efficient. Thermocycling treatment (TCT) processes are devoid of these disadvantages and are applicable to various classes of material, i.e., steels, cast irons, titanium and aluminum alloys [3 – 5]. TCT intensifies the diffusion processes and gives rise to favorable structural changes occurring during the treatment cycles and associated with phase transformations. These features of thermocycling provide formation of a fine-grained structure, an optimum structural and phase condition, and elevate the mechanical and physical properties of steels and alloys [6 – 14]. Accelerating the diffusion processes, a TCT used in a thermochemical treatment provides intense saturation of the surface of the parts with carbon, nitrogen, boron and other chemical elements. Researches in this direction are quite active [15 – 17].

The method of thermocycling deformation (TCD) combines thermocycling and thermomechanical treatment processes, which can be applied at low, intermediate and high temperatures. The process parameters of TCD may be divided into two groups. The first one comprises the number of cycles, the temperature ranges, the duration of the exposure to these temperatures, and the rates of heating and cooling of the billets. The second group involves the kind of the deformation, the temperature and the degree of the deformation in a cycle, and the total degree of the deformation. An optimum choice of the mode of TCD makes it possible to improve the physical and mechanical properties of the metal [18, 19] and to obtain deformed billets from alloys with a low process ductility, for example, cast irons [21, 21].

The mode of TCD is developed individually for every specific grade of steel, cast iron or aluminum alloy. The modes and parameters of the treatment for obtaining the specified physical or mechanical properties for one grade of material to be used under different operating conditions differ too.

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TABLE 1. Chemical Compositions of Cast and Deformed Samples of Low-Carbon Steels

Steel	Condition	Content of elements, wt.%								
		C	Mn	Si	Cu	Cr	Ni	N	S	P
10kp	Cast	0.10	0.39	0.01	0.12	0.01	0.04	0.005	0.016	0.019
	After rolling	0.11	0.37	0.01	0.13	0.05	0.08	0.005	0.019	0.016
St3ps	Cast	0.17	0.53	0.07	0.09	0.05	0.07	0.006	0.020	0.024
	After rolling	0.19	0.57	0.05	0.07	0.04	0.07	0.007	0.012	0.015
20	Cast	0.19	0.55	0.25	0.06	0.03	0.07	0.007	0.014	0.019
	After rolling	0.20	0.51	0.26	0.12	0.05	0.05	0.006	0.024	0.020

TABLE 2. Microstructural Parameters of the Steels after Thermocycling Deformation

Steel	n	d_f, µm	HV_f, MPa	P, vol.%
10kp	–	80 – 200	1000	26
	1	50 – 120	1050	24
	3	30 – 100	1080	22
	4	30 – 50	1100	21
	6	15 – 25	1120	16
St3ps	–	50 – 220	1180	42
	1	30 – 50	1290	41
	4	10 – 20	1300	40
	5	5 – 10	1440	37

Notations: n) number of deformation cycles; d_f) size of ferrite grains; HV_f) microhardness of ferrite; P) volume fraction of pearlite (± 2%).

The aim of the present work was to study the effect of thermocycling deformation involving a preliminary thermocycling forging of rolled billets at a temperature exceeding Ac_3 on the structure and mechanical properties of low-carbon steels 10kp, St3ps and 20.

METHODS OF STUDY

We studied low-carbon steels 10kp, St3ps and 20. The experimental ingots were produced at the oxygen steel-making plant of the "EVRAZ ZSMK" Company. The melt was cast into a cast iron mold with internal sizes 75 × 75 × 400 mm. In addition to the ingots, we studied billets cut from square-section rolled strips 150 × 150 mm and 100 × 100 mm in size. The chemical compositions of the steels in the cast and deformed conditions (Table 1) were determined using an ARL 4460 emission spectrometer. The hydrogen content was determined by the method of vacuum heating in a flow of carrier gas.

The thermocycling deformation of the ingots and of the rolled billets was performed at the thermal forge shop of the "EVRAZ ZSMK" Company in the mode of single-pass forging with flat strikers in a hydraulic forging press developing a force of 2000 tonf. Each cycle of TCD consisted of the following operations: (*1*) heating to 900 – 1000°C with a hold for 30 – 35 min (before the deformation in the first cycle, the billet was heated to 1050 ± 20°C for 40min), (*2*) free forging of the billets at 980 – 800°C, and (*3*) air cooling to 250 – 300°C; then the next cycle was implemented. The degree of deformation in each cycle was ε = 30 – 55%.

The deformation scheme for the ingots with cross section 75 × 75 mm forged for bars with a size of 15 × 15 mm consisted of 6 cycles; the billets with cross section 150 × 150 m were forged for bars with a size of 15 × 15 mm in 5 cycles. To obtain a plate with cross section 100 × 2 mm, the forging with a section of 35 × 35 mm was subjected to 5 more deformation cycles. The total degree of deformation after 5 – 10 cycles amounted to 98 – 99.5%. After each forging cycle, we took samples for analyzing the structure and the properties of the steels. The samples were cut from the deformed billets over the direction of the deformation. The microhardness of the structural components was measured with the help of a PMT-3 microhardness tester in accordance with the GOST 9450–76 Standard.

The microstructure of the steels was studied with the help of an OPTON optical microscope at a magnification of ×140 and ×500. The mechanical properties of the samples were determined by the standard methods [22]. The heat treatment was conducted in SNOL-type electric resistance furnaces.

RESULTS AND DISCUSSION

Effect of thermocycling deformation on the structure of the steels. The comparative metallographic analysis (qualitative and quantitative) has shown that the thermocycling forging changed the structure of the low-carbon steels substantially (Figs. 1 – 3; Table 2).

The structure of steel 10kp in the as-cast condition was represented by ferrite dendrites in the bottom part of the ingot and pearlite colonies on the dendrite boundaries (Fig. 1*a*). After 4-sec etching in a 4% alcoholic solution of HNO_3 the boundaries of the ferrite grains were virtually undetectable. The pearlite regions were mostly elongated. The volume fraction of pearlite was 26%. After the first deforma-

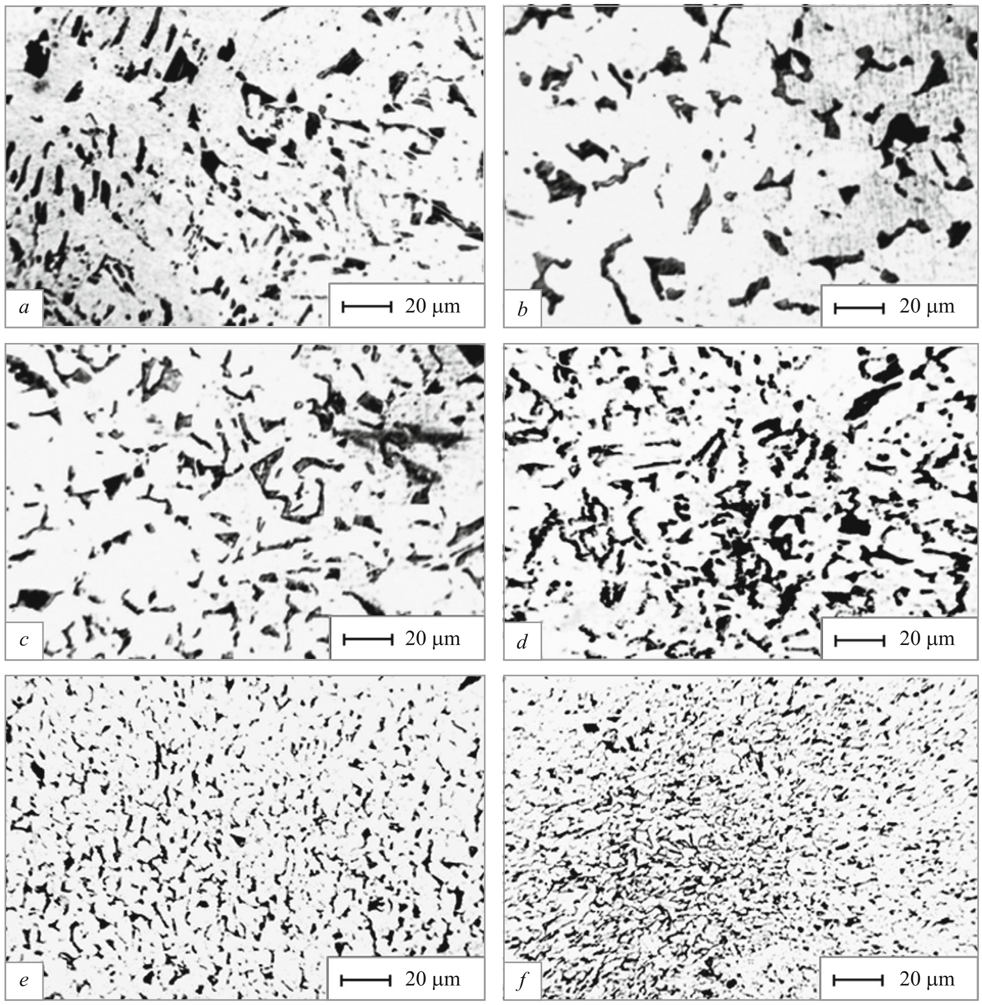

Fig. 1. Microstructure of steel 10 before and after thermocycling deformation: *a*) cast steel; *b*) one cycle of TCD, $\varepsilon = 40\%$; *c*) two cycles of TCD, $\varepsilon = 88\%$; *d*) four cycles of TCD, $\varepsilon = 96\%$; *e*) five cycles of TCD, $\varepsilon = 97\%$; *f*) six cycles of TCD, $\varepsilon = 99\%$.

tion cycle conducted at 950 – 850°C, the ingot acquired a structure composed of polygonal ferrite grains 50 – 120 μm in size and pearlite colonies (Fig. 1*b*). The content of pearlite in the central part of the forging decreased to 24% (Table 2).

Increase of the number of TCD cycles refined the structural components; the size of the ferrite grains after the third and fourth deformation cycles was 30 – 100 μm and 30 – 50 μm, respectively. The highest refinement of the structure occurred after the fifth and sixth treatment cycles conducted at 900 – 750°C. The size of the ferrite grains in the central part of the forging (a 3-mm-thick plate) after six deformation cycles was 15 – 25 μm; the sizes of the pearlite colonies became smaller, and the volume fraction of pearlite decreased to 16 – 18%. The total decrease in the volume fraction of pearlite exceeded 30% (Table 2).

The effect of thermocycling forging on the microstructure of cast steel St3ps (Fig. 2) was as follows. The structure of the cast steel was represented by ferrite dendrites and pearlite regions taking 42% of the volume (Fig. 2*a*). After the first deformation cycle ($\varepsilon = 49\%$) at 980 – 800°C, the volume fraction of the pearlite component in the structure of the central part of the forging remained virtually unchanged. The subsequent cyclic forging caused noticeable refinement of the ferrite grains and pearlite colonies. The pearlite regions had an obvious dominant orientation (Fig. 2*c*). Normalization of the forging at 900°C conducted after two cycles of TCD resulted in a more uniform distribution of the pearlite colonies. The volume fraction of the pearlite component did not change and amounted to 41%. After four cycles of forging ($\varepsilon = 88.4\%$), the ferrite grains became 10 – 20 μm in size. The pearlite regions were less etched, and the fraction of pearlite was 40% (Fig. 2*d*). After the fifth cycle of TCD, the structural components became spheroidized, and the size of the ferrite grains was 5 – 10 μm. When the temperature in the fifth cycle was shifted from 900 – 750°C to 950 – 800°C, the size of the ferrite grains in steel St3ps in-

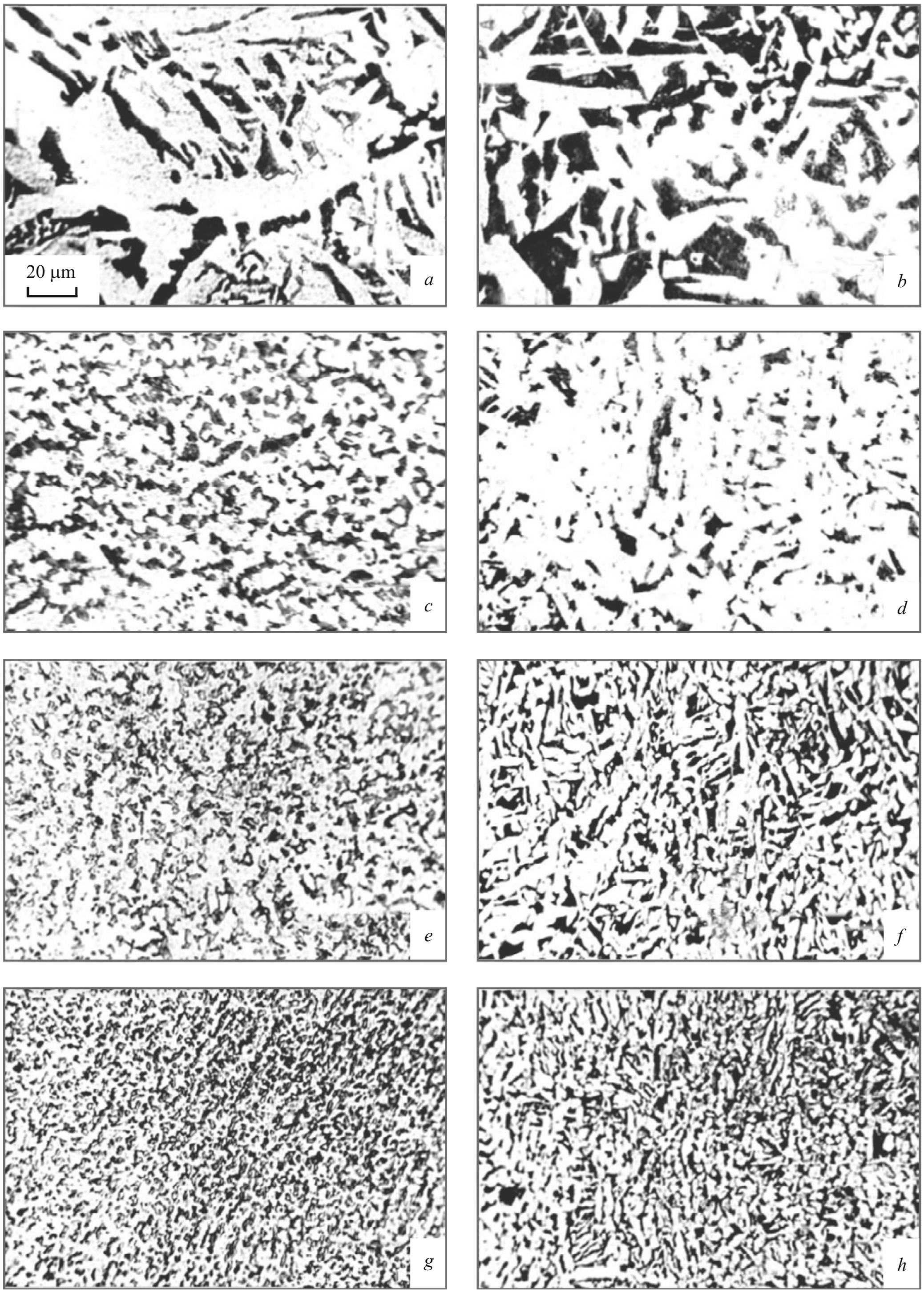

Fig. 2. Microstructure of steel St3ps before and after thermocycling deformation (TCD): *a*) after casting (initial condition); *b*) two cycles of CD, ε = 72%; *c*) four cycles of TCD, ε = 88%; *d*) five cycles of TCD, ε = 96%; *e*) after rolling (initial condition); *f*) one cycle of TCD, ε = 51%; *g*) three cycles of TCD, ε = 79%; *h*) five cycles of TCD, ε = 97%.

creased to 20 – 35 μm, and the fraction of pearlite decreased to 37%.

The cyclic deformation of billets from rolled steel 3ps conducted in the range of 950 – 800°C caused considerable changes in the structure after three cycles (Fig. 2*e* – *g*). The ferrite grains acquired an extended shape; the pearlite colonies stretched over the boundaries of the ferrite grains. The sizes of the ferrite grains after five cycles of TCD decreased

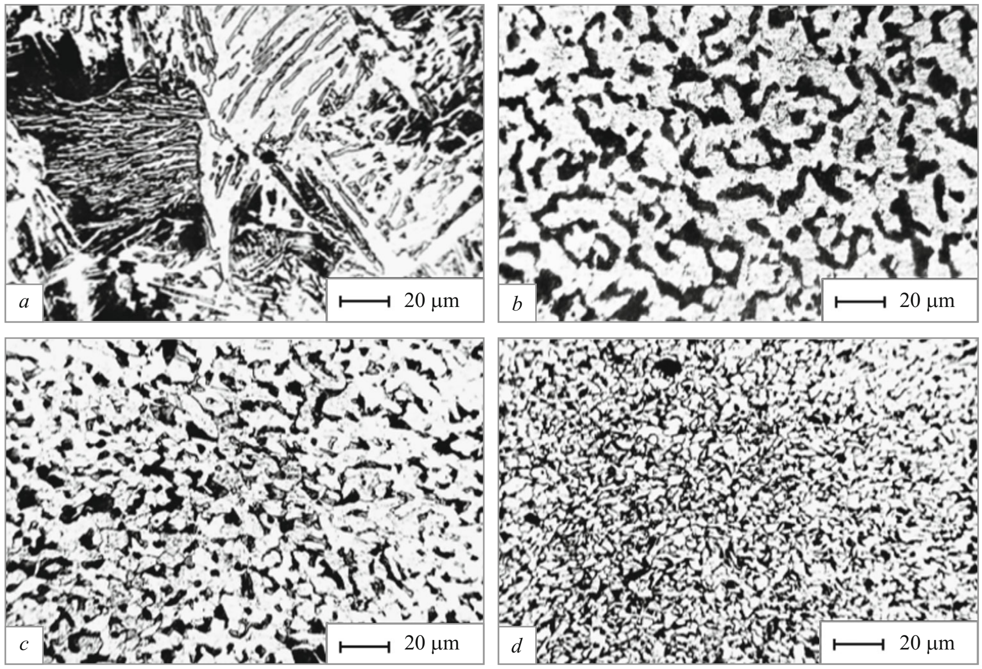

Fig. 3. Microstructure of steel 20 before and after thermocycling deformation: *a*) after casting (initial condition); *b*) one cycle of TCD, ε = 37%; *c*) two cycles of TCD, ε = 75%; *d*) five cycles of TCD, ε = 96%.

from 80 – 100 μm to 20 – 30 μm. The content of the pearlite component changed inconsiderably, i.e., from 41 to 37% (by 9%).

By the data of the metallographic study of steel 20 after TCD, its structure, which is dendritic in the cast state, undergoes considerable changes already after two cycles of TCD (Fig. 3*a* – *c*). The size of the ferrite grains decreases from 200 – 250 μm to 60 – 70 μm. When the number of the deformation cycles is increased, the structure is refined. Five forging cycles give ferrite grains 10 – 20 μm in size (Fig. 3*d*). It should be noted that the fraction of the pearlite component decreases in the process of TCD. In cast steel 20, the volume fraction of pearlite is 41% and decreases to 33 – 35% after five forging cycles.

Analyzing the results of the metallographic studies we established some regular features in formation of the structure of the steels under TCD. The deformation caused refinement of all the structural components, i.e., the grains of ferrite and the colonies of pearlite. The degree of refinement of the structure depended on the deformation temperature and on the number of cycles.

It has been shown that TCD of low-carbon steels lowers the volume fraction of pearlite in their structure. However, this change in the pearlite content is not connected with decarburization. By the data of the chemical analysis given in Table 3, the carbon concentration in the steels remains unchanged after the TCD. At the same time, the results of the gas analysis show that the concentration of hydrogen in the steels after five forging cycles is 38 – 50% lower than in the cast condition. The content of the diffusion-mobile hydrogen after the TCD of the rolled billets decreases less substantially, i.e., by 10 – 25%.

TABLE 3. Chemical Composition and Hydrogen Content in the Steels before and after Thermocycling Deformation

Steel	Initial condition	Content of elements, wt.%			[H], cm^3/100 g Me
		C	Si	Mn	
10kp	Cast	0.10/0.11	0.01/0.01	0.39/0.41	1.00/0.50
	After rolling	0.11/0.11	0.01/0.01	0.37/0.35	0.60/0.45
St3ps	Cast	0.17/0.18	0.07/0.07	0.53/0.53	1.20/0.75
	After rolling	0.19/0.18	0.05/0.07	0.57/0.53	0.75/0.60

Note. The numerators present the content of elements and of H ([H] per 100 g metal) before the thermocycling deformation; the denominators present the values obtained after the deformation.

TABLE 4. Mechanical Properties of TCD-Forgings from Low-Carbon Steels after Heat Treatment

Steel	Treatment	σ_r, MPa	δ, %	ψ, %
10kp	Rolling (initial condition)	375 – 410	34	67
	10 cycles of TCD	520 – 548	12 – 14	66 – 68
	TCD + quenching from 920°C (30 min)	825	6	57
	TCD + quenching from 920°C (30 min) + tempering at 200°C (1 h)	970	5	50
St3ps	Rolling (initial condition)	465 – 485	32 – 35	68
	10 cycles of TCD	510 – 550	16 – 19	65 – 69
	TCD + quenching from 880°C (30 min)	1434	4	17
	TCD + quenching from 880°C (30 min) + tempering at 200°C (1 h)	1350	5	41

Note. The samples were quenched in water and cooled after the tempering in air.

Comparing the dependences obtained by the methods of quantitative metallography and gas analysis we may state that the change in the volume fraction of pearlite in the process of TCD is the higher, the lower the hydrogen content in the steel after the thermocycling deformation.

Effect of thermocycling deformation on mechanical properties. The mechanical tests of the low-carbon steels performed before and after the TCD show that such deformation elevates their strength and lowers somewhat the ductility, i.e., the elongation decreases by a factor of 1.5 – 1.8 but the contraction changes very little (Table 4). The growth in the strength is explainable by decrease in the size of the ferrite grains and growth in their microhardness after the TCD (Table 2). Such changes in the properties give us grounds to expect that the joint action of thermocycling deformation and hardening heat treatment should raise the strength properties of the steels still more as compared to the properties of the commercial steels as delivered.

The results of the determination of the mechanical properties show that the preliminary TCD elevates the susceptibility of the low-carbon steel containing at most 0.11% C to hardening heat treatment. After the quenching with low tempering the ultimate strength of steel 10kp increases by a factor of 1.7 (to $\sigma_r = 970$ MPa), which is not attainable for a commercial steel. This substantial increase in the ultimate strength seems to be explainable by the considerable refinement of all the structural components after the TCD and by the enhanced diffusion mobility of the interstitial elements in the steel after the thermocycling, which influences the temperatures of the phase transformations [5]. By the data of the metallographic analysis, quenching from a temperature exceeding Ac_3 by 45°C stimulates formation of a structure of an intermediate bainitic transformation (Fig. 4). The banded pattern typical for the structure of the forgings disappears.

With increase in the carbon content the effect of hardening of the forgings becomes more manifested (Table 4). For example, the ultimate strength of the forgings from steel 3ps increases by a factor of 2.4 after quenching and low tempering (to $\sigma_r = 1350$ MPa). The values of the ductility parameters in this case are not high but acceptable for a structural material.

Thus, we have established that the joint action of thermocycling forging and quenching with low tempering increases the strength of the low-carbon steels poorly susceptible to a hardening heat treatment by a factor of 1.7 – 2.4, which is quite substantial.

CONCLUSIONS

Thermocycling forging of low-carbon steels 10kp, St3ps and 20 at a temperature exceeding Ac_3 causes refinement of all components of their structure. The degree of the refinement depends on the deformation temperature and on the number of the deformation cycles. Five cycles of deformation reduce the volume fraction of pearlite in the structure of the steels by 9 – 30%. The change in the volume fraction of pearlite is the higher, the lower the content of hydrogen in the metal.

The forgings subjected to thermocycling deformation have a higher strength than the billets deformed by the standard industrial modes at some lowering of the ductility parameters. Thermocycling deformation followed by a hardening heat treatment raises the strength of the steels by a factor of 1.7 – 2.4 at a satisfactory level of ductility.

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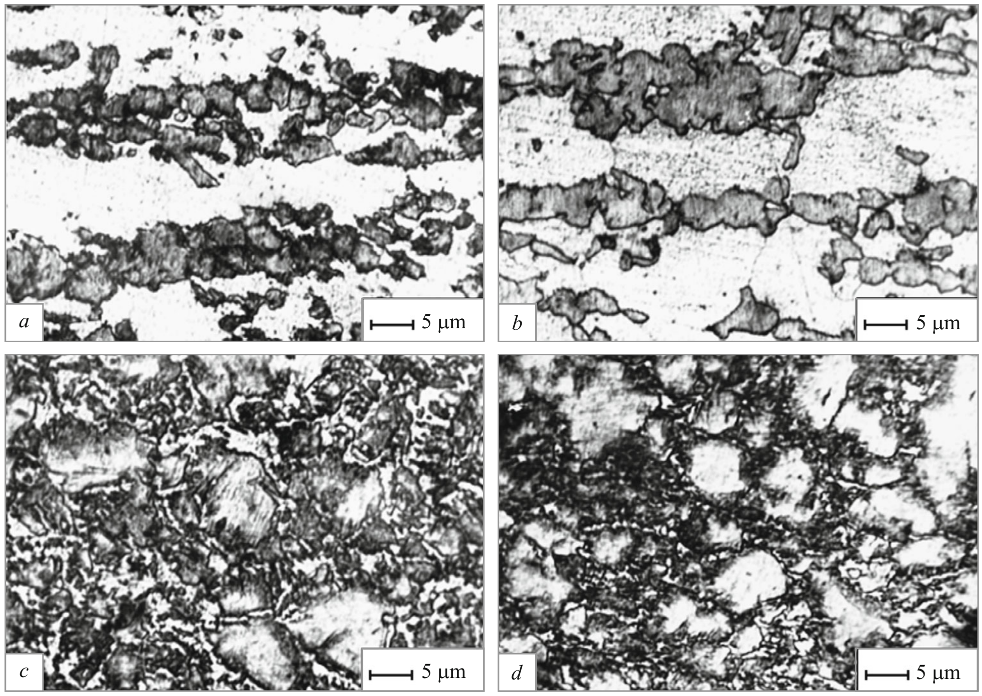

Fig. 4. Microstructure of forgings from steel 10 in different conditions: *a*, *b*) after forging (initial condition); *c*, *d*) after 10 cycles of TCD, water quenching from 920°C and 1-h tempering at 200°C; *a*, *c*) head of the sample; *b*, *d*) functional part.

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