

HARDENING LOW CARBON STEEL 10 BY USING OF THERMAL-CYCLIC DEFORMATION AND SUBSEQUENT HEAT TREATMENT

УПРОЧНЕНИЕ НИЗКОУГЛЕРОДИСТОЙ СТАЛИ 10 С ПОМОЩЬЮ ТЕРМОЦИКЛИЧЕСКОЙ ДЕФОРМАЦИИ И ПОСЛЕДУЮЩЕЙ ТЕРМИЧЕСКОЙ ОБРАБОТКИ

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Abstract: The results of the influence of preliminary thermal-cyclic deformation and subsequent hardening heat treatment on the microstructure and mechanical properties of hot-rolled sheet steel 10 are presented. It is shown that the use of preliminary thermal-cyclic deformation of the steel 10 stock material results in a fine-grained structure of a hot-rolled sheet (3 mm thick) produced by an industrial technology. Deformation occurred at a temperature above A_{C3} (1250 °C), with cooling to 200-300 °C during 10 cycles and the deformation ratio per cycle being 6-8 %. The magnitude of the overall reduction ratio was 1.90 and the total amount of deformation was 65-68 %. Such a treatment before sheet hot-rolling allows increasing the strength characteristics (tensile strength, yield strength) by almost 30 %. It has been established that the use of subsequent heat treatment (quenching, 900 °C, water and tempering 1 h, 600 °C) leads to a further increase in strength characteristics by 15-20 % while maintaining a sufficient level of ductility of sheet steel.

KEYWORDS: STRUCTURE, STEEL, DEFORMATION, MECHANICAL PROPERTIES, THERMAL-CYCLIC DEFORMATION, HARDENING

1. Introduction

To improve the quality, reliability and durability of parts, components and mechanisms it is necessary to use a comprehensive approach that includes both the creation of new materials as well as the development and implementation of efficient technologies that harden metallic materials. Traditional methods of hardening are often not sufficiently effective. This led to the development of technologies based on methods and modes that allow intensifying a number of physical and chemical processes through the use of features of structural transformations occurring in metals and alloys. Such technologies include deformation thermal-cyclic treatment (DTCT), which is a thermal-cyclic treatment combined with various types of deformation at low or high temperatures. Such a complex treatment leads to an intensification of diffusion processes at specified temperature oscillations with the application of stress and strain, the accumulation of structural changes occurring in the cycles and associated with volume effects of phase transformations, the difference in thermal characteristics of the phases, etc. as well as a change in the gas content in the alloys including hydrogen. As a result, these processes can form an optimal structure and improve physical and mechanical properties of the material [1-6]. The number of thermal cycles, the ranges of temperature, holding at extreme temperatures, heating and cooling rates of parts and pieces as well as the parameters of the deformation process such as form, temperature, the deformation ratio in the cycle and its total value can be used as the process control parameters to obtain fundamentally different structures, and, therefore, different material properties, while applying such treatments. Deformation thermal-cycling treatment can not only improve a number of physical and mechanical characteristics of metals and alloys, but obtain a deformed semi-finished products made of hypereutectic silumins with low plasticity through the use of thermal cycling deformation combined with annealing [7-10]. The development of heat treatment modes followed by DTCT modes is peculiar for each particular steel, cast iron, aluminum alloy grade and cannot be mechanically transferred from one material to another. There are no principal contraindications to the use DTCT for different materials hardened and not hardened by heat treatment. Therefore, the aim of the work was to study the effect of DTCT on mechanical properties of hot-rolled low-carbon steel 10 including preliminary thermal-cyclic deformation at a temperature above A_{C3} followed by rolling and heat treatment

2. Material and methods

Low-carbon fine steel 10 was used as a material in the study. The steel was made at the Novokuznetsk Iron and Steel Plant JSC

(Novokuznetsk, Russia). The chemical composition of steel was defined using the emission spectrometer ARL 4460 and is shown in Table 1.

Table 1. Chemical composition of steel 10

Steel grade	Element concentration, [%] (wt.)					
	C	Si	Mn	P	S	Cu
10	0.13	0.22	0.42	0.014	0.018	0.20

A slab of steel 10 with the sizes of 900×700×500 mm was subjected to hot cyclic forging through single-pass broaching by flat backups at the forge-thermal shop of the West Siberian Metallurgical Plant (Novokuznetsk, Russia) using a hydraulic forging press with the load of 2000 ton-force. The heating temperature for forging was 1250 ± 10 °C, the holding time in the furnace was 2 hours without preheating. The heating for deformation was carried out in a continuous gas furnace. Forgings were cooled in the air to a temperature of 200-300 °C. There were 10 cycles of forging with a deformation ratio in each cycle 6 ÷ 8 %. The average reduction ratio was 1.066. The reduction ratio for each cycle was calculated using the formula (1) [11].

$$(1) K = F_0 / F_k ,$$

where F_0 , F_k are initial and final values of the forgings cross-section area.

The overall reduction ratio determined using the formula

$$(2) K_{overall} = K_1 \times K_2 \times K_3 \times \dots \times K_n ,$$

where K_1 , K_2 , K_3 , ..., K_n are the reduction ratio per cycle of deformation.

The magnitude of the overall reduction ratio was $K_{overall} = 1.90$ and the total amount of deformation was 65 – 68 %. The workpiece height after thermocyclic forging was 365 ± 5 mm and the width was 500 ± 5 mm. Process parameters of thermal-cycling forging of steel 10 blanks for each deformation cycle are shown in Table 2.

Further the blanks were rolled to sheets 3 mm thick at the A.N. Kuzmin Novosibirsk metallurgical plant (Novosibirsk) using the hot-rolling combination mill 810 in according with TI 138-PZ-24-85 for hot-rolled sheet carbon steel 10. Before rolling the blanks were cut in the cutting slabs bay to obtain the desired thickness of 180 mm. Heating of the test blanks was carried out in the continuous gas furnace. The heating temperature for rolling was 1120 - 1250 °C and the holding time in the furnace was 2-2.5 hours. The billets were clogged through 5 passes in a two-roll reversing stand with horizontal rolls after pre-cleaning of the metal from slag and aligning of the strip in width in the roughing stands with vertical rolls. After finishing descaling in a two-roll mill the

resulting tackle was fed to a group of continuous finishing stands through a roller conveyor. This group consisted of five successive four-high stands where the stripe was pressed up to the preset thickness of 3 mm. The rolling speed was 4.5 m/s. The rolling mill 810 was equipped with a control system to monitor the rolled strips temperature and thickness. The rolling finishing temperature of steel 10 was 800 - 860 °C for a sheet 3-4 mm thick and 820-880 °C for a strip with a thickness greater than 5 mm. After rolling, coiling into a roll sheet was carried out on a floor type reel.

Mechanical characteristics of the rolled sheet was evaluated in the static tensile test of the plane specimens with a thickness of 3 mm and a working part length of 70 mm on the Instron 3369 machine according to GOST1497-84.

3. Results and discussion

The contamination of sheet specimens from steel 10 produced by an industrial mode and using thermal cycling forging to obtain

Table 2. Parameters of thermal cycling forging of steel 10 billets

Cycle	$T_{\text{forging, initial}}$, [°C]	$T_{\text{forging, final}}$, [°C]	S_{initial} , [mm]	S_{final} , [mm]	K_n
1	1250	1100	500×700	500×655	1.069
2	1250	1100	500×655	470×655	1.063
3	1250	1100	470×655	470×615	1.065
4	1250	1100	470×615	440×615	1.068
5	1250	1100	440×615	440×575	1.069
6	1250	1100	440×575	415×575	1.060
7	1250	1100	415×575	415×540	1.065
8	1250	1050	415×540	390×540	1.064
9	1250	1050	390×540	390×505	1.069
10	1250	1050	390×505	365×505	1.069

Comments: $T_{\text{forging, initial}}$, $T_{\text{forging, final}}$ are initial and final forging temperatures; S_{initial} , S_{final} are cross-sectional dimensions of the initial billet and the billet after forging; K_n is a reduction ratio in the n-cycle; $K_{\text{overall}} = 1.90$ is an overall reduction ratio

Heating for quenching and tempering of the specimens cut from sheets, was carried out in resistance furnaces SNOL 2.2, 5.2 / 12.5-II, and to measure the temperature a chromel-alumel thermocouple potentiometer DC PP-63 was used. An optical microscope OLYMPUS-GX51F was used to investigate the microstructure of the steel. Metallographic methods for determination the contamination of steel 10 sheets with nonmetallic inclusions was used in accordance with GOST 1778-70 [12].

an intermediate and final thickness of the rolled metal was evaluated. Grades of line and point oxides (alumina Al_2O_3 , silica SiO_2 , and the iron-manganese spinel $\text{MeO} \cdot \text{Al}_2\text{O}_3$ type), brittle, non-deformable and plastic silicates (aluminosilicates, silicates, iron, manganese and more complex compositions), and sulfides (mainly double sulfide of iron and manganese $(\text{FeMn})\text{S}$) located in the rolled metal of varying thickness (see Table 3) are defined by

Table 3. Assessment of contamination of hot-rolled sheet steel 10 made by an industrial mode and using DTCT with non-metallic inclusions

Sheet thickness, [mm]	Slice place	Score					sulfides
		Oxides		Silicates			
		line	point	non-deformable	brittle	plastic	
6	middle of the sheet	3/1	0/1	1/1	0/0	0/0	2.5/3
	edge of the sheet	0/1	3/2	0/0	0/0.5	0/0	1.5/1
5	middle of the sheet	0/2	3/3	0/1	1/0	0/0	2/1.5
	edge of the sheet	0/0.5	3/2	0/1	0.5/1	0/0	1/1.5
4	middle of the sheet	0/1	3/3	1/0	0/0	0/0	1.5/2
	edge of the sheet	1/0	0/1	1/1	0/0	0/0	1/1
3	middle of the sheet	0/0	2/1	1/1	0/0	0/0	1/1
	edge of the sheet	1/0	0/1	0/1	0/0	0/0	0.5/0.5
Average grade		0.6/0.7	1.8/1.8	0.5/0.8	0.2/0.2	0/0	1.4/1.5

Comments: the numerator shows the data for rolled sheet steel 10 manufactured using DTCT; the denominator - for sheet produced by an industrial mode.

This method involved the study of not-etched metallographic specimens cut along the rolling direction from the middle and end sections of the hot-rolled sheet of various thicknesses from 6 to 3 mm. Inclusion in microsections were viewed through an optical microscope at a magnification of 100 with a field of view diameter of 0.8 mm in one direction - from the end to the central area of the sheet. A score of nonmetallic inclusions in the samples was carried out for each type separately (oxides, sulfides and silicates) by comparison with standard scales for steels.

standard scales of nonmetallic inclusions (GOST 1778). It can be seen that, most of oxide inclusions including silicate and located along the rolling direction. The findings suggest that the hot deformation ratio and preliminary thermal-cyclic forging of billets has virtually no effect on the contamination and distribution of non-metallic inclusions in the cross section of strips of varying thickness. The distribution of inclusions in the rolling metal is mostly random and is determined by the part of the ingot a

particular slab is made of as well as by the steelmaking technology.

The preliminary thermal-cyclic forging that reduces the size of

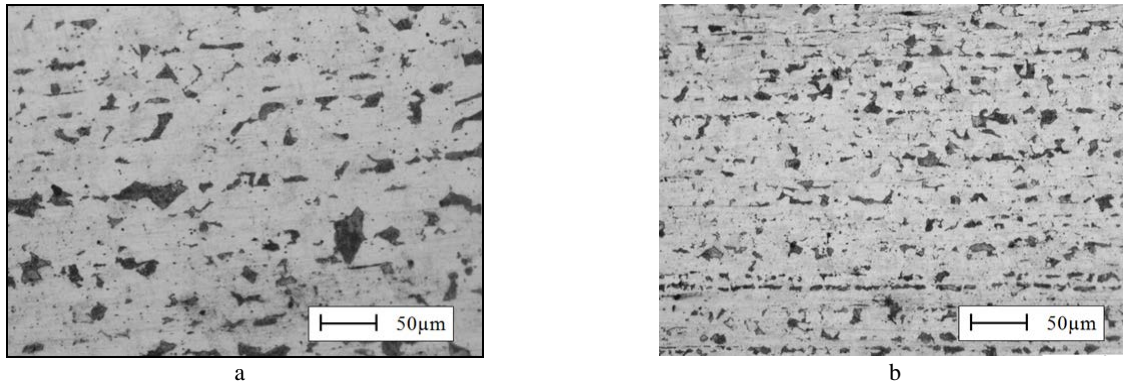


Fig.1. Microstructure of hot-rolled sheet steel 10 (thickness: 3 mm) manufactured by industrial technology (a) and using the preliminary thermal -cyclic forging (b)

A metallographic analysis of steel 10 specimens rolled using an industrial technology and using the DTST mode showed that preliminary thermal-cyclic deformation led to a decrease in the size and volume fraction of pearlite colonies as well as the degree of misorientation in the direction of rolling. The microstructure of hot-rolled steel 10 depends on the mode of production and is shown in Fig. 1. Obviously, the quantitative structure characteristics are largely determined by the scheme and mode of deformation. Thus, the use of preliminary thermal-cyclic forging prior to sheet hot rolling allows reducing the size of the steel 10 structure. The maximum size of pearlite colonies in the sheet with a thickness of 3 mm is reduced from 22×60 to 7×19 mm, and their average size decreased nearly 3-fold from 7 ± 2 to 20 ± 2 microns.

the steel 10 structure, increases the strength characteristics (tensile strength - σ_{ts} , yield strength - σ_{ys}) of hot-rolled sheet steel 10 by almost 30 % with a slight decrease in ductility (Table 4).

Further hardening of hot-rolled sheet steel may be associated with a subsequent heat treatment of an optimal mode. Therefore, the effect of the quenching temperature (holding time 0.5 hours) and subsequent high-temperature tempering (600°C , 1 h) on the microstructure and mechanical properties of hot-rolled steel 10 subject to DTSTO was investigated. The microstructure of the steel after hardening heat treatment is shown in Fig. 2. It was established that increasing the heating temperature for quenching from 860 to 900°C led to a significant refinement of the ferrite-cementite mixture in the structure of steel – sorbite formed after high-

Table 4. DTST influence on mechanical properties of hot-rolled sheet steel 10

State	Mechanical characteristics				
	σ_{ts} , [MPa]	σ_{ys} , [MPa]	δ , [%]	Ψ , [%]	Hardness, [HB]
Hot-rolled by industrial technology	370	305	26	42	127
Hot-rolled using the DTCT mode	478	390	24	38	170

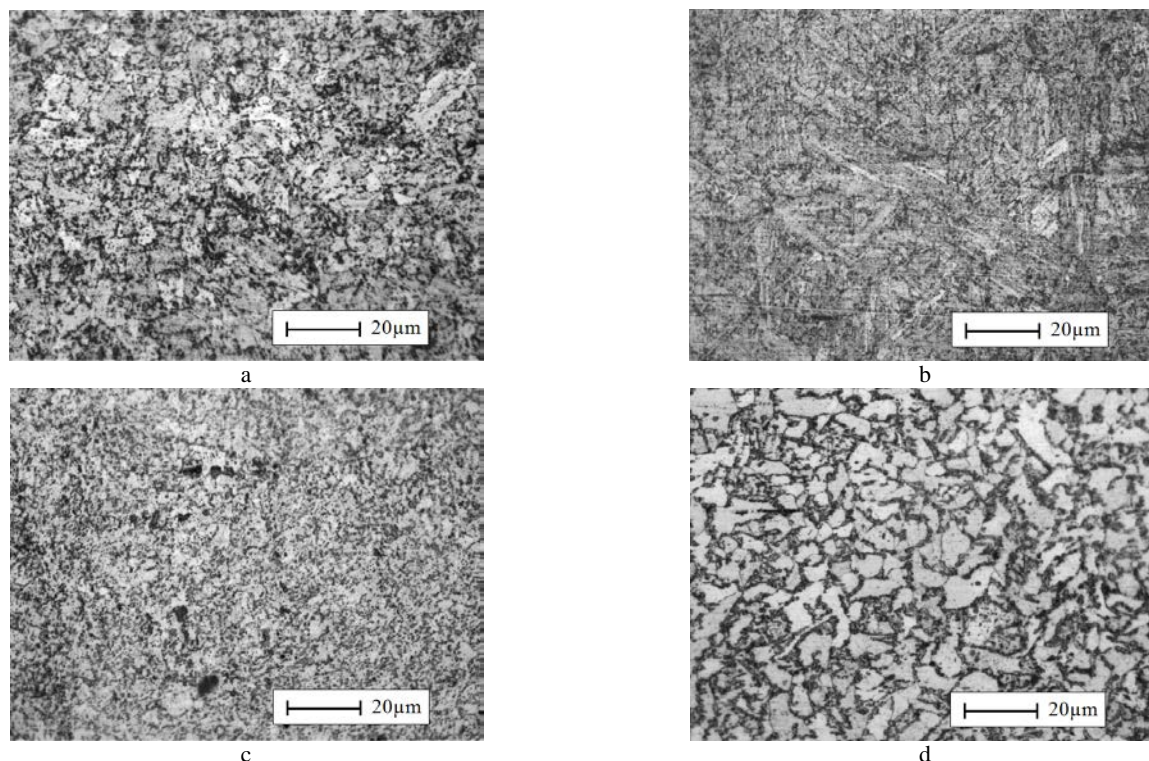


Fig. 2. The effect of the quenching temperature for 0.5 h and subsequent annealing at 600°C for 1 h on the microstructure of hot-rolled sheet steel 10 (3 mm thick) made with a preliminary thermal-cyclic forging: a - 880°C ; b - 900°C ; c - 920°C ; d - 940°C

temperature tempering. When quenching the specimens from 920 °C there are the first signs of coagulation and coarsening of cementite precipitates and, after hardening from 940 °C and tempering their size increases several times. Mechanical properties of hot-rolled sheet steel 10 made by DTST quenched from different temperatures and tempered at 600 °C for 1 hour are shown in Table 5.

Table 5. The effect of a quenching temperature (holding time 0.5 hours) and tempering (600 °C, 1 h) on the mechanical properties of hot-rolled steel 10 subjected to DTCT

Quenching temperature, [°C]	Mechanical properties				
	σ_{ts} , [MPa]	σ_{ys} , [MPa]	δ , [%]	Ψ , [%]	Hardness, [HB]
–	478	390	24	38	170
860	438	360	29	44	168
880	510	458	21	37	182
900	545	470	21	36	183
920	520	468	23	42	181
940	450	383	30	46	174

Data in Table 5 shows that the most optimal combination of strength and plastic characteristics of sheet steel 10 made using the preliminary thermo-cyclic forging mode is provided by hardening heat treatment: quenching, 900 °C, 0.5 hours, water and tempering 600 °C, 1 h. And after the above hardening mode the deformation resistance (σ_{ts} , σ_{ys}) of sheet steel increased by 15-20 % while the elongation reduced by 12 % remaining at a high level (over 20 %). At higher heating temperatures for quenching strength characteristics of steel are impaired, but ductility increases significantly. Such a change in the properties is associated with an increase in the size of cementite precipitates and their coagulation in the steel structure during tempering. Thus, the elongation of the specimens after quenching from 940 °C and tempering increased by 25 % compared to hot-rolled steel.

4. Conclusions

1. The preliminary thermal-cyclic forging does not increase the contamination of hot-rolled sheet steel 10 with nonmetallic inclusions whose number and distribution is determined by the slice place and steelmaking technology.
2. The use of preliminary thermal-cyclic forging for the production of hot-rolled sheet steel 10 provides a more fine-grained structure and improves its strength characteristics by almost 30 %.
3. Application of a rational mode of hardening and tempering (hardening at 900 °C for 0.5 h, water and tempering at 600 °C, 1 h) allows increasing strength characteristics (σ_{ts} , σ_{ys}) by 15-20 % while maintaining sufficient ductility of hot-rolled sheet steel 10 manufactured using DTCT.

5. Literature

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