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Thermocyclic deformation, annealing, and physical properties of low-carbon steel 10

Thermocyclic deformation, annealing, and physical properties of low-carbon steel 10

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Abstract. The results of the influence of thermocyclic forging and annealing in the range of 100 ÷ 900 °C on the microstructure, coercive force and linear expansion of steel 10. Hot cyclic forging was carried out on slabs 900×700×500 mm in size on the hydraulic press with a force of 20 MN under industrial conditions of ZSMK OJSC (Novokuznetsk). Subsequently, the billets were rolled on a 3 mm thick sheet at OAO NMZ (Novosibirsk). The use of preliminary thermocyclic deformation increases the coercive force by no more than 8%. The possibility of reducing the coercive force of sheet steel made using thermocyclic forging was shown to be almost 3 times lower than the initial untreated state due to subsequent annealing at 900 °C for 10 hours. In addition, this annealing mode reduces the average linear expansion temperature coefficient of sheet steel by 6% in the temperature range of the test 50-450 ºC.

1. Introduction

In most industries, the vast majority of blanks, parts and structural elements of products from various materials are used after hardening technologies – deformation, thermal or surface chemical-thermal treatments. However, increasingly stricter requirements for materials used in modern technology have led to the emergence of integrated technologies, including the combined use of various methods and techniques for the formation and management of the structure and, therefore, the properties of these materials. Such technologies include thermo-mechanical, mechano-thermal and more complex type – deformation thermocyclic treatment (DTT).

The technological modes of these treatments combine various types of cold and hot deformation with heating, holding at fixed temperatures and cooling over a wide range of speeds. In the literature, DTT is widely covered as a technology used for hardening ferrous and non-ferrous metals and alloys, including steel, cast iron and aluminum alloys [1-7]. Much less attention is paid to the problem of improving the electrical, magnetic, thermal and other physical properties of various materials. Such publications include the work of the authors [1.8-12].

One of the promising areas for the use of DTT can be the structural low-carbon steel properties that are close to the properties of some groups of soft magnetic materials, in particular commercially pure iron and electrical steel, combined with enhanced mechanical and technological properties. In addition, subsequent heat treatment, which affects its structure and the most important properties, can serve as an additional reserve for improving the properties of low-carbon steel.

For magnetically soft materials, such properties can be electrical, magnetic, and thermal (electrical resistivity, electrical conductivity, magnetization reversal loss at different frequencies, coercive force, coefficient of thermal expansion, etc.). Therefore, the aim of the work was to study the effects of preliminary thermocyclic forging and subsequent annealing on physical properties, in particular, coercive force and linear expansion of hot-rolled steel sheet 10.

2. Materials and methods of research

Low-carbon high-quality steel 10 was taken as a research material. Steel was smelted at NKMK OJSC (Novokuznetsk). The chemical composition of the experimental steel are shown in table 1.

Table 1. The chemical composition of the experimental sheet steel 10.

Steel grade	Components, weight. %									
	C	Si	Mn	P	S	Cr	Ni	Cu	As	Fe
10sp	0.13	0.22	0.42	0.014	0.018	0.05	0.04	0.20	0.06	res.

A slab of experimental steel 900×700×500 mm in size was subjected to hot cyclic forging. The forging scheme is a single-pass by platens with flat strikers with a blank setting-up. The slabs were deformed in the forging and thermal workshop of ZSMK OJSC (Novokuznetsk) on the hydraulic forging press with a force of 20 MN. The technology of thermocyclic forging is described in [10], and its main parameters and mode are given below. The heating temperature for forging was 1250 °C; the slab holding time in the furnace before forging was 2 hours (without taking into account the heating time). To heat the workpieces for deformation, a continuous gas furnace was used. The forgings were cooled in air to 200-300 °C. The number of forging cycles was 10, the degree of deformation in each cycle was 6–8%. The total degree of deformation was 65–68%, the total forging coefficient ~ 1.90. Subsequently, the blanks were rolled at OJSC “NMZ” n.a. A.N. Kuzmin (Novosibirsk) per sheet 3 mm thick at the rolling mill 810 according to industrial technology. The heating temperature of the blanks for rolling was 1120÷1250 °C, the holding time was 2÷2.5 hours. The technological mode of sheet manufacturing from steel 10 is described in more detail in [2].

Samples cut from the sheet were annealed in resistance furnaces of SNOL type. To study the steel microstructure the OLYMPUS GX-51F optical microscope was used. To determine the temperature coefficient of linear expansion (TCLE) of steel samples, a high-temperature dilatometer DIL 402C with a measurement error of $00{,}1 \cdot 10^{-6}$ K^{-1} was used. Determination of the coercive force was carried out on the KIFM-1 coercimeter with a flux probe on rectangular sheet samples with a thickness of 3 mm and a size of 90×120 mm. The measurement error was 4 A/m.

3. Results and discussion

One of the most important properties of soft magnetic materials is the coercive force, which determines the energy loss due to magnetization reversal of magnetic circuit elements. First of all, this applies to the cores of magnetic cores, transformers and other structural elements [13]. In this regard, the value of the coercive force was determined for hot-rolled steel 10, manufactured according to the industrial rolling regime and using preliminary DTT. In the first case, it amounted to 214 A/m, and in the case of using thermocyclic forging 232 A/m. Such an increase in coercive force due to the use of preliminary thermocyclic forging modes in the manufacture of hot-rolled sheet steel 10 can be explained by the changes occurring in its microstructure.

This is, first of all, grinding of ferrite grains and pearlite colonies oriented along the rolling direction, which is consistent with the results of metallographic studies carried out in [2]. Such a refinement of the structural components and, consequently, an increase in the length of the interphase grain boundaries, which are places of accumulation of crystal structure defects (dislocations, vacancies, etc.) in the structure of sheet steel 10 made using DTT, is the reason for the increase in its coercive force.

Quite often, in special fields of industry, magnetic elements operate at elevated and lowered temperatures, including the widespread plate-type stacked cores with an electrically insulating coating, sealed magnetic contacts (reed switches), and other similar products. Therefore, for the soft magnetic materials from which such products are made, one of the important characteristics is the characteristic

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of thermal expansion – the temperature coefficient of linear expansion (TCLE). Studies on the effect of thermocyclic forging on the linear expansion of steel 10 showed that the use of DTT practically does not affect the true thermal expansion coefficient. The magnitude of its change after cyclic forging and rolling on a sheet does not exceed 5% (figure 1). However, one can note a tendency for the coefficient to exceed the coefficient of low test temperatures (up to 300 °C) by 5% compared with the coefficient of hot-rolled steel of industrial manufacture and the opposite change in the thermal expansion coefficient for higher test temperatures (300-450 °C).

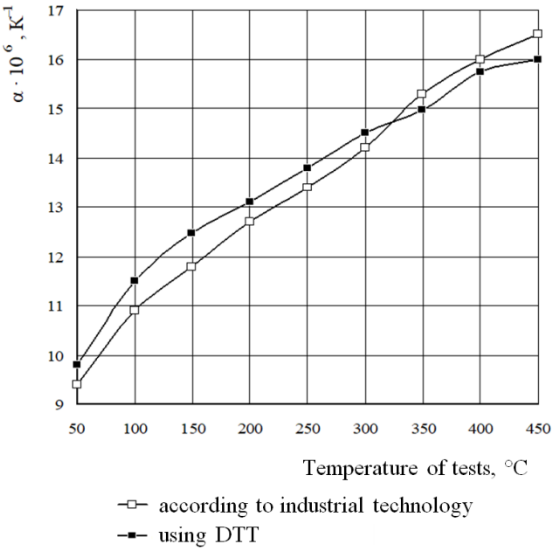

Figure 1. The effect of thermocyclic forging on the linear expansion of hot-rolled steel sheet 10 (sheet thickness 3 mm).

Further, the effect of subsequent annealing for 10 h on the physical properties of sheet steel 10 (thickness 3 mm) subjected to DTT was studied. It was found that an increase in the annealing temperature from 100 to 900 °C with an increments of 100 °C leads to a consistent decrease in the coercive force of steel (figure 2). Its intense decrease was noted at higher annealing temperatures starting from 600 °C. The minimum value of the coercive force corresponds to annealing at a temperature of 900 °C and is 83 A/m, which is almost 3 times lower than that of samples without heat treatment. Apparently, the decrease in the coercive force of sheet steel fabricated using DTT with an increase in the annealing temperature is explained by the general decrease in the level of stresses and defects in the crystal structure (vacancies, dislocations, etc.) formed in the metal as a result of the deformation and cooling modes used as well as a significant increase in ferrite grain and a slight decrease in the volume fraction of pearlite colonies.

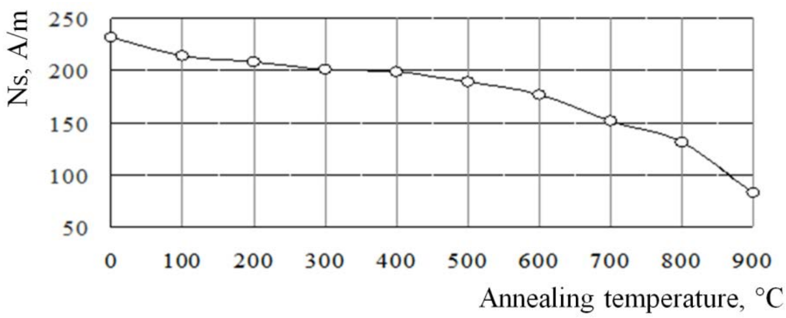

Figure 2. The effect of the heating temperature with cooling in the furnace on the coercive force of steel 10 made using DTT.

The curves of the temperature dependence of the linear expansion of steel 10 made using thermocyclic forging on the test temperature after annealing for 10 h at 600, 700, 800, and 900 °C and without heat treatment are shown in figure 3.

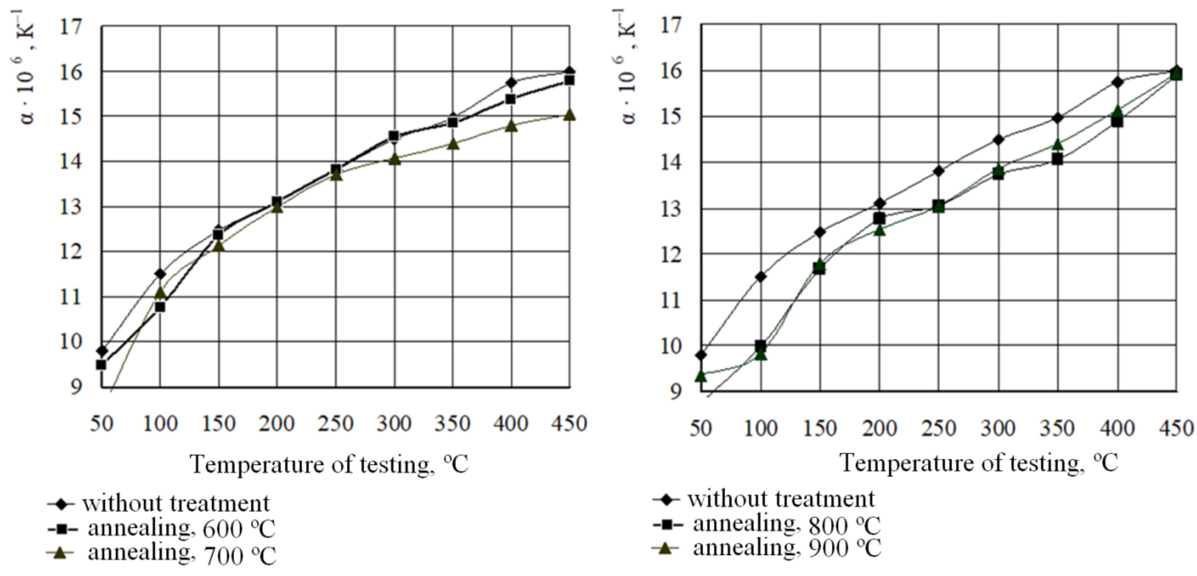

Figure 3. The effect of annealing temperatures at 600, 700 ºC (a) and 800, 900 ºC (b) with a holding time of 10 h on the linear expansion of hot-rolled sheet steel 10 made using DTT.

Based on the analysis of the temperature dependence curves of the true thermal expansion coefficient of steel 10 made using preliminary thermocyclic forging, after annealing for 10 h at 600, 700, 800, and 900 °C, graphical dependences of the average coefficient over the test temperature intervals on the annealing temperature are constructed (figure 4).

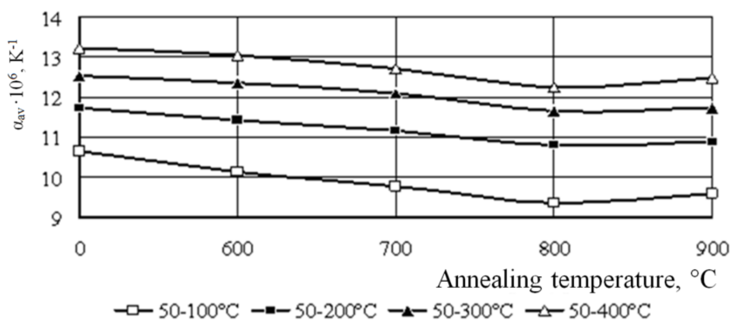

Figure 4. The effect of annealing temperature on the average TCLE in various temperature ranges for testing hot-rolled sheet steel 10 made using DTT.

The obtained dependences $\alpha - T_{test}$ and $\alpha_{av} - T_{test}$ makes it possible to conclude that the tendency of steel 10 to thermal expansion decreases after annealing at all studied temperatures. Moreover, annealing of steel at 800 and 900 °C reduces the temperature coefficient of linear expansion more significantly. This decrease averages over 6% in the entire temperature range of the testings (up to 450 °C). In addition, the most significant annealing at 800 and 900 °C reduces the average TCLE in the low temperature range of 50-100 and 50-200 °C. So, after annealing at 800 °C this decrease is 8 and 12%, and after annealing at 900 ° C – 7 and 12%, respectively, in comparison with thermally untreated samples.

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4. Conclusions

1. The use of thermocyclic forging for the manufacture of steel sheet 10sp (thickness 3 mm) increases the value of its coercive force by no more than 8% compared with the industrial mode and does not significantly affect thermal expansion.

2. The subsequent high annealing (900 °C) for 10 h of sheet steel 10 made using thermocyclic forging, allows its coercive force by almost 3 times to be reduced compared to thermally untreated steel, and also to reduce the true values of thermal expansion coefficient on average by more than 6% in the range up to 450 °C.

3. The largest decrease in the average coefficient of thermal expansion of steel 10 after this annealing mode for various test temperatures is observed in the low-temperature zone (from 50 to 200 °C) and amounts to 7-10% compared to its initial state.

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