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Improvement of quality indicators and elimination of chemical microinhomogenity of the rolled products made of mn-containing steel by the new thermal treatment modes

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Abstract
The tensile properties of normalized low alloy E36 steel after heat-treatment mode, which includes isothermal holding at the subcritical temperatures and subsequent normalization, were investigated. A solution of actual scientific and technical tasks such as the improvement of operational performance, elimination of the anisotropy of the mechanical and physical and chemical properties by optimizing the chemical composition and a homogeneous spatial distribution in the microstructure of the main alloying elements is given in the paper. Using the methods of the deep data analysis researching, the effect of production parameters (chemical composition and thickness of rolled metal) on the key indicators of the mechanical properties: ultimate strength, yield strength, percent elongation and impact resistance was investigated. Herein, the influence of thermal treatment on the chemical distribution of elements, microstructure, hardness and mechanical properties of the welded manganese steels were examined. It is established that in the process of isothermal holding in a two-phase area, there are intensive processes of grain-boundary diffusion; they lead to redistribution of the alloying elements. It is shown that there is increase of hardness and high plasticity conservation as a result of the preliminary heat-treatment. The results were obtained in accordance with the metallographic data about fine sized grain boundary pearlite areas formation during the isothermal holding.
Keywords: NORMALIZED LOW ALLOY STEEL, HARDNESS, STRENGTH, PLASTICITY, SUBCRITICAL TEMPERATURES

Introduction

Normalization is a very common type of thermal hardening of rolled structural steels for various purposes; they are used in construction, in the manufacture of pressure vessels, in shipbuilding. Thus, an increased complex of mechanical properties of both low-alloy steels and complex-alloyed high-strength structural steels is achieved. However, especially for metal products of increased cross-section, high levels of strength and resistance to impact fracture are not attained, a wide range of values of quality indices is observed, as well as crumbling up, especially in the complex-alloyed steels.

The existence of these problems is due to the insufficiently favorable microstructure in the state of delivery of the normalized steels such as the presence of ferrito-perlite striatlon, increased dimensions and nonspherical morphology of the colonies of perlite-like structures. The problem of further increasing and stabilizing all parameters of the operational pro- perties of steels is becoming relevant taking into account the high technological level of normalization as a method of thermal hardening, as well as the increasing use of low-carbon complex-alloyed high-strength structural steels with increased requirements for their resistance to impact fracture.

As a result of investigations [1, 2, 3, 4, 5], a substantial refinement and an increase in the uniformity of the microstructure of structural alloy steels by isothermal holding in subcritical temperature ranges were established. Regarding steel E36, an almost complete elimination of ferrito-perlite striatlon and a significant grinding and homogenization of the microstructure after isothermal holding at optimum temperatures near the critical point A_1 are shown. However, changes in the mechanical properties of steels after such heat treatment have not been investigated.

The paper **objective** is determination of the influence of preliminary heat treatment with holding at subcritical temperatures on the parameters of the mechanical properties of steel E36 in the normalized state.

Methods and results of the study

The sheets from steel E36 in accordance with GOST 5521-93 were investigated. Its chemical composition is given in Table 1.

Table 1. *(developed by the author)*
Chemical composition of the investigated steel E36,%

C 0.01	Mn 0.01	Si 0.01	S 0.001	P 0.001	Ni 0.01	AL_R 0.001	Ti 0.001	Nb 0.001	V 0.001	N 0.001
17	144	25	35	35	5-40	15-60	5-20	20-50	50-100	3-7

Specimens with the following dimensions 300× × 200 × 40 mm were used to conduct heat treatment with the research mode. They were selected in accordance with the current standard (GOST 7564-73). Thermal hardening of research workpieces was carried out under semi-industrial conditions by conducting preliminary heat treatment and final normalization. Preliminary heat treatment of the specimens was carried out according to a mode determined on the basis of the results of previous studies [2], the results of which showed the possibility of eliminating ferrite-pearlite striatlon and formation a highly disperse and homogeneous microstructure of low-alloy sheet steels by isothermal holding under optimal conditions at subcritical temperatures [2]. Experimental mode of preliminary heat treatment included: heating, isothermal holding at a temperature of 710 ± 5 °C for 2 and 4 hours followed by cooling in water. The final heat treatment was a normalization under the optimum mode for the investigated steel (T_n = 950 ± 5 °C; τ = 1÷ 2 min/mm). The list and parameters of the research modes are given in Table 2.

Table 2. (developed by the author)
Parameters of research modes of thermal treatment

№	Mode character	Preliminary treatment	Finish treatment
1	Industrial processing	-	T_n = 950 ±
2	Developed mode	710 ±	T_n = 950 ±
3	Developed mode	710 ±	T_n = 950 ±

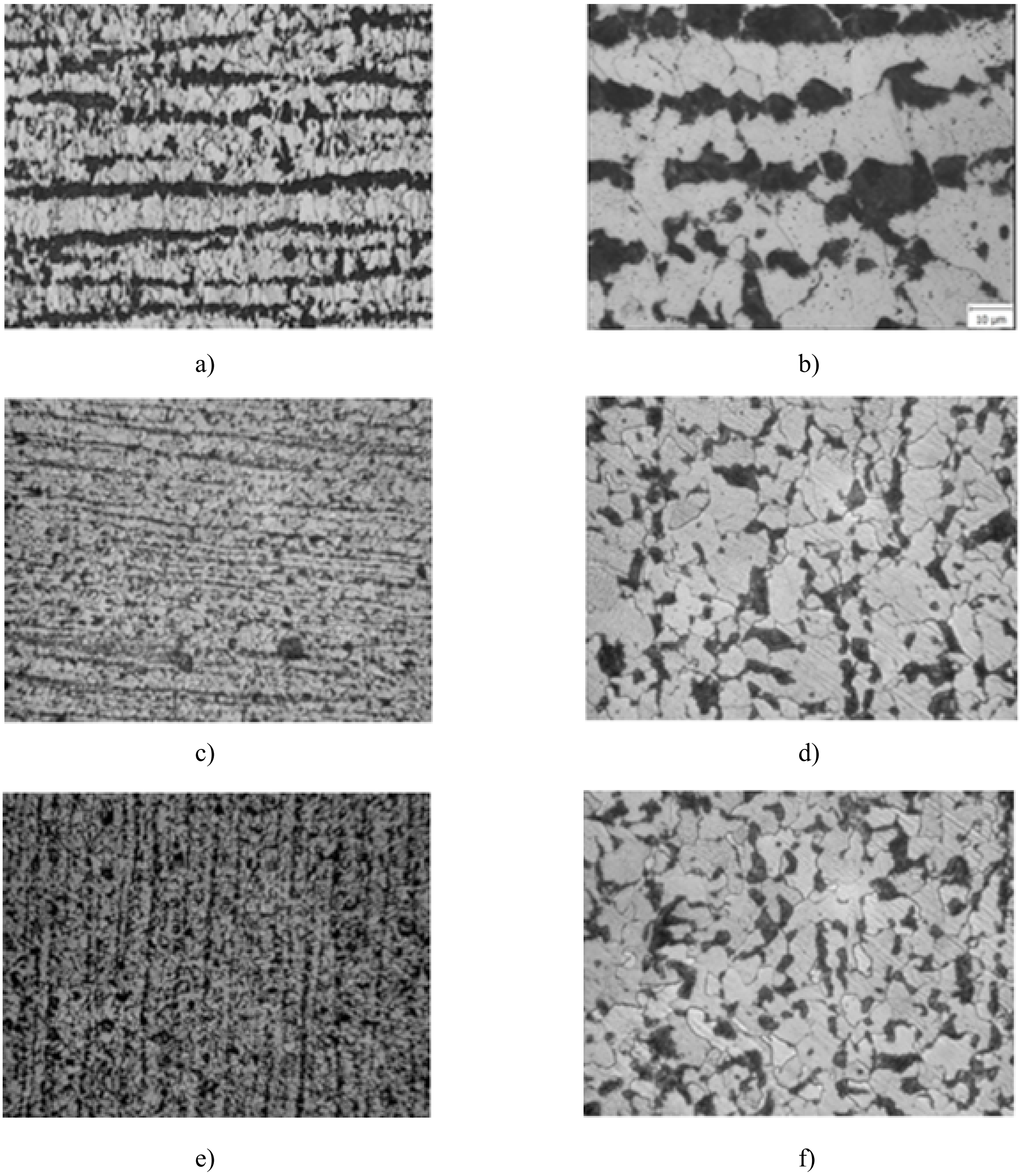

Figure 1. Characteristic section of the microstructure of steel E36 after thermal treatment with different modes:
a, b - industrial normalization (×100, ×500);
c,d – mode No2 (710±5oC, 2 hours)(×100, ×500);
e,f – mode No3 (710±5oC, 4 hours). (×100, ×500)

Metallographic studies were carried out after the thermal treatment. Grinding and polishing were carried out in accordance with generally accepted technics. Pickling of metallographic sections was performed in 4% solution of HNO_3. The microstructure was studied with the help of the Neofot-21 microscope with an magnification ×100 and ×500. The mechanical properties were determined by standard methods according to GOST 1497-84, GOST 9454. The striatlon rate was determined visually in accordance with GOST 5640-71. The distribution of the main alloying element – manganese between the structural components was determined by micro-X-ray spectral analysis according to the procedure given in [2].

The study allowed establishing that after normalization under industrial conditions (Fig. 1a, b), the structure of steel E36 is a ferrite-perlite mixture with a significant striatlon, which corresponds to 4-5 points in accordance with GOST 5640. The practically continuous perlite bands of great length are characteristic.

The average values of the perlite bands width, as well as the size of individual symmetrical perlite sections, are close to the size of the ferrite grain and correspond to the numbers No 7-8.

The character and morphology of the E36 steel structure are significantly changed after the thermal treatment with the research mode No 2, No 3 (Fig. 1c, d, e, f). First of all, as can be seen from Figure 1c, a significant decrease in the degree of ferrite-pearlite striatlon is observed up to 0-1 points. The continuous perlite bands are completely missing. In addition, grinding of ferrite grain and the size of individual perlite sections of symmetrical shape to No 9-10 are achieved. Attention is also drawn to the more globular shape of the individual perlite areas.

Based on the metallographic data, it can be concluded that the isothermal holding at subcritical temperatures, which precedes the final normalization, leads to the practical elimination of ferrite-perlite striatlon and grinding of the final microstructure of steel E36. The obtained results can be explained on the basis of data [2], according to which during the isothermal holding of low-alloyed, especially manganese-containing steels, the redistribution of chemical elements with an increased concentration within the perlite bands occurs due to intensive diffusion along the grain boundaries.

In the process of crystallization of alloy steels and alloys containing substitution elements, under real production conditions, dendritic liquation occurs. It is caused by the slow diffusion of the substitution elements (Mn, Cr, Ni, etc.) in the solid phase.

As a result, in certain volumes of the solid phase, at the separation boundaries of the dendritic crystals, an increased concentration of these chemical elements is established. In the process of further production, it remains which leads to the formation of a striped microstructure, which consists of elongated sections of ferrite and decomposition products of supercooled austenite. As a consequence, there is a significant reduction in the mechanical, operational properties of metal products, corrosion resistance, etc. In the process of isothermal holding near the critical point Ac_1, in the range from (Ac_1 - 20) °C to Ac_1, diffuse processes are developed in connection with the phase transformation $\alpha \rightarrow \gamma$. In this case, the diffusion of alloying and impurity elements is greatly accelerated, in particular, due to diffusion along the grain boundaries. As a consequence, the concentration of chemical elements in metal volumes is leveled at a high rate. Moreover, in the process of isothermal holding at subcritical temperatures, high-dispersed austenite crystals are formed in low-alloyed and medium-alloyed steels [3, 4].

Due to the increased solubility of most substitution elements in austenite in comparison with ferrite, an additional stimulus appears to accelerate the process of redistribution of the substitution elements between the α and γ phases. The set of the considered conditions allows us to achieve elimination of chemical heterogeneity with high efficiency and to approximate the structure to equilibrium. The achieved effect persists with further austenitization.

During the next austenitization, uniformly distributed sections with a high concentration of chemical elements that, in the process of further cooling in air or tempering with thermal improvement, play the role of new phase nuclei are remained in austenite. At the same time, austenite grain is crushed.

As a result of subsequent cooling in air, a structure is formed that contains newly generated in the above-mentioned areas dispersed perlite colonies and carbide phase particles, as well as spheroidizing, crushed pearlite colonies and carbide particles preserved from the previous initial structural state.

A similar structure containing highly dispersed and uniformly distributed carbide phase particles is also formed during tempering when thermal improvement. Thus, a fine-grained ferrite matrix is formed within which, there are fine, uniformly distributed spherical areas of decomposition products of the supercooled austenite or carbide phase particles. The obtained structure has increased levels of strength due to the fine grain, as well as plasticity and resistance to impact fracture, due to the favorable morphology of the excess structural constituents.

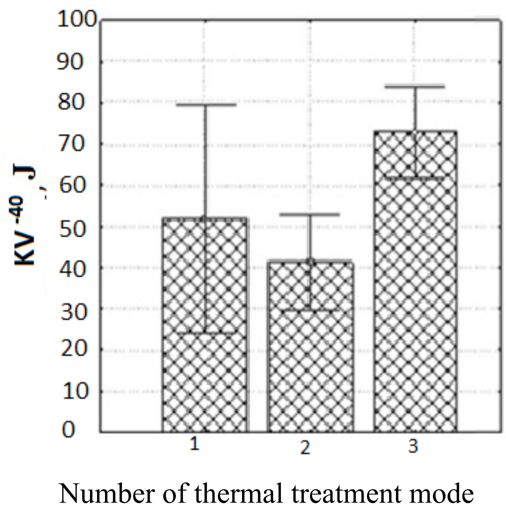

Figure 2. Effect of heat treatment on fracture performance for steel E36

The development of the diffusion processes considered ensures equalization of the chemical composition of steel, as well as the achievement of an extremely homogeneous distribution of structural components, provides a high complex of mechanical properties [5].

The results of mechanical tests after all the research modes of heat treatment were considered (Table 2). Influence of the research modes of heat treatment on the work of impact fracture is shown graphically in Fig. 2.

As can be seen from Figure 2, the homogeneity of the spatial distribution of manganese concentration has the main influence on the level of resistance to impact fracture and its stability.

The obrained results of laboratory studies, which relate to the impact fracture resistance at different temperatures, show that the highest and stable performance of failure is achieved after the heat treatment mode, which provides the most uniform distribution of manganese with high homogeneity of the distribution of other chemical elements.

It is necessary to emphasize the unambiguous nature of the results obtained to control the quality of research steel. At the same time, a direct comparison of the level of quality relative to impact fracture resistance for sheet metal after the research modes of heat treatment and the adaptation of industrial heat treatment are technically difficult to apply because the standard for impact bending tests of rolled industrial products is carried out on "longitudinal" (L) samples, that is, cut along the rolling direction.

At present, according to the requirements of the standard, samples for impact bending are tested along the rolling direction during the testing of sheet steel of shipbuilding steels. This is due to the inevitable, from the point of view of the developers of the standard, anisotropy of mechanical properties associated with structural heterogeneity. Obviously, the results obtained under such conditions will exceed the data corresponding to the research modes of heat treatment.

Numerous studies that have been conducted to determine the anisotropy of mechanical properties in rolled products made of low-alloyed manganese steels have shown that the value of the work of impact fracture of longitudinal samples is ~ 2 times higher than the values of the impact toughness of transverse samples.

The results of these studies showed that it was not necessary to carry out additional, costly material studies. For the reasons indicated above, only the transverse samples were tested, which guaranteed the level of properties of the higher ones than on longitudinal samples (Fig. 2).

After analyzing all modes of heat treatment, mode No. 3 was separated, which, with a probability of 95%, prevents embrittlement, that is, the level of fracture work does not decrease below 60 J. A confident conclusion can be drawn that it is the mode of heat treatment No 3 that ensures the complete excess of the requirements of the standard taking into account the literature data indicating that after testing, the values of longitudinal samples exceeds transverse several times.

From the above results, it can be concluded that the most favorable values of the fracture work for steel E36 have been achieved after preliminary heat treatment including isothermal holding at 710 ± 5 °C for 4 hours [9].

To carry out a multi-purpose complex analysis of the effect of the developed heat treatment on the structure and mechanical properties of the steels, a generalized table 3 will be compiled, which shows the obtained values of striatlon point, distribution of alloying elements and mechanical properties.

Table 3. *(developed by the author)*
Parameters of the investigated and industrial modes of heat treatment, results of structural and micro-X-ray studies and mechanical tests of steel E36

Parameters of the investigated heat treatment modes					Striatlon point	Mechanical properties			
No of heat treatment mode	Heating and isothermal holding temperature. T_h, °C	Duration of isothermal holding. τ_h, min/mm.	The finishing hardening thermal treatment (Normalization) T_A, °C	τ_A, min/mm		Flow limit, σ_{02}, MPa	Strength limit, $\sigma_в$, MPa	Percentage extension, δ	Impact fracture work. KV^{-40}, J
1	-	-	950	1.5	5	400	535	29	30
2	715	4	950	1.5	0-1	415	585	30	40
3	715	8	950	1.5	1-2	400	590	29	72

As follows from the table, carrying out isothermal holding at optimal temperatures in the range 710 ± 5 °C for 2 hours as well as further normalization at optimal temperatures T_A=As_3 + (10…20) °C, and holdings τ_A=1÷2 min/mm (mode No 2) provide achievement of a low degree of chemical and structural heterogeneity of steel in combination with high values of all parameters of mechanical properties. As follows from the data given in the table, the most favorable way of complex thermal treatment according to the mode No 3, which includes heating, isothermal holding in the temperature range 710 ± 5 °C for 4 hours.

The use of the proposed method allows eliminating the heterogeneous distribution of chemical elements of substitution and carbon along the boundaries of the former dendritic crystals; obtaining a homogeneous distribution of structural components; forming a highly dispersed final microstructure due to the fine grain of the matrix phase and the dispersed portions of the additional structural constituents (the transformation products of supercooled austenite, carbide particles).

Due to this, high, stable and isotropic values of all parameters of mechanical properties, low critical temperatures of brittleness are achieved and resistance to various types of alloyed steel alloying is increased.

Results

The actual scientific and technical problem of increasing the parameters of mechanical properties and eliminating the chemical microinhomogeneity of sheet steel made of low-alloy steel E36 in the normalized state is solved in the work due to preliminary heat treatment with holding under subcritical conditions.

Conclusions

1. It is shown that the phase transformation P→A begins at subcritical temperatures in the range from (As_1 - 20) °C to As_1 with formation, at isothermal hardening, at the boundaries of ferrite grains of finely dispersed austenite crystals, which upon cooling turn into highly dispersed areas of perlite.

2. A significant increase in the strength indices was observed in combination with maintaining high plasticity for normalized plates made of low-alloy steel E36 as a result of the use of preliminary heat treatment including isothermal holding at subcritical temperatures.

3. It is found that the most favorable method of complex thermal treatment according to the mode No 3, which includes heating, isothermal holding is in the temperature range 710±The results obtained on the basis of earlier performed metallographic studies are explained by the formation during the preliminary heat treatment at the boundaries of ferrite grains of highly dispersed sections of perlite-like structures, which ensure the generation of mobile dislocations during the entire process of plastic deformation.

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