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Phase composition of 30 CrMnSi tempered steel

Influence of heat treatment on the phase-structural condition of 30 CrMnSi steel was investigated. It was found that the main morphological component of the steel is the α -phase which consists of a mixture of lath (0.7) and plate tempered martensite (0.3). One half of the lath martensite is grained substructure. There is no grain substructure in the plate martensite. Residual austenite in the lath and plate low-temperature martensite is located on boundaries of martensite crystals in the form of long thin interlayers. The volume ratio of residual austenite equals to ~3 %. The biggest part of the γ -phase is located in the plate martensite, and the smallest part is located in the grained substructure lath component of the martensite. The average scalar dislocations density in the material equals to $\rho = 7 \cdot 10^{10} \text{ cm}^{-2}$, at that, the biggest part of dislocations is located in the form of dislocation charges (excess dislocations density $\rho_{\pm} = 6.3 \cdot 10^{10} \text{ cm}^{-2}$). The carbide phase is represented by M6C-type primary carbides. Carbide particles have a spherical shape, the average particle diameter equals to 0.5 μm , the volume ratio is ~1%. Cementite and secondary special carbides are not found. Carbons may be found in the α -solid solution (0.005wt.-%); the γ -solid solution is the second place of carbons localization (0.015wt.-%); in particles of carbide phases (0.14wt.-%). Apparently, almost half of the carbon is accumulated on defects of the crystalline lattice.

Keywords: heat treatment, phase composition, carbide phase, carbon atoms, dislocation.

Introduction

As it is known, a wide range of $\gamma \rightarrow \alpha$ martensite transformation products is found in the process of heat treatment in steels which differ from each other in terms of their morphology and crystal geometry, internal structure, generation temperature and kinetics [1–3]. Morphology and crystallography of sub-blocks in the lath martensite of low-carbon steel where lath martensite consists of packets, blocks, sub-blocks and laths were studied in the work [4]. In accordance with [5, 6] content of residual austenite and carbon redistribution in martensite steels depend on the cooling speed during heat treatment, and peculiarities of carbon redistribution in steel may be associated with a quasi-chemical «reaction». Nevertheless, in our opinion, an apparently insufficient attention is paid to the issue of carbon redistribution in the structure of medium-carbon steels and their phase composition during heat treatment.

With this regard the purpose of this work consists in classification of morphological features of the structure, volume ratio of α - and γ -phases as well as carbide phases and determination of carbon concentration in carbides, solid solution of 30 CrMnSi steel in the result of heat treatment.

Material and Experimental Procedure

The chemical composition of 30 CrMnSi steel in accordance with State Standard 4543–71 is 0.3wt.-% C; 0.8–1.1 wt.-% Cr; 0.8–1.1 wt.-% Mn; 0.8–1.1 wt.-% Si; and the balance is Fe. The chemical composition of 30CrMnSi steel according to the University Otto-von-Guericke, Magdeburg, Germany is 0.31 wt.-% C; 0.93 wt.-% Cr; 0.96 wt.-% Mn; 0.94 wt.-% Si and the balance is Fe. Heat treatment of steel samples was performed as follows: quenching from temperature 1050 °C and the subsequent tempering (400 °C for 6–10 hours) with a cooling rate of 20 °C/h.

Detailed description of the research methods is given in the work [7].

Results and Discussion

As shown by the conducted electron microscopic studies the main component in the structure of tempered steel is the α -phase (~96%) which represents a mixture of lath and plate tempered martensite (Fig. 1).

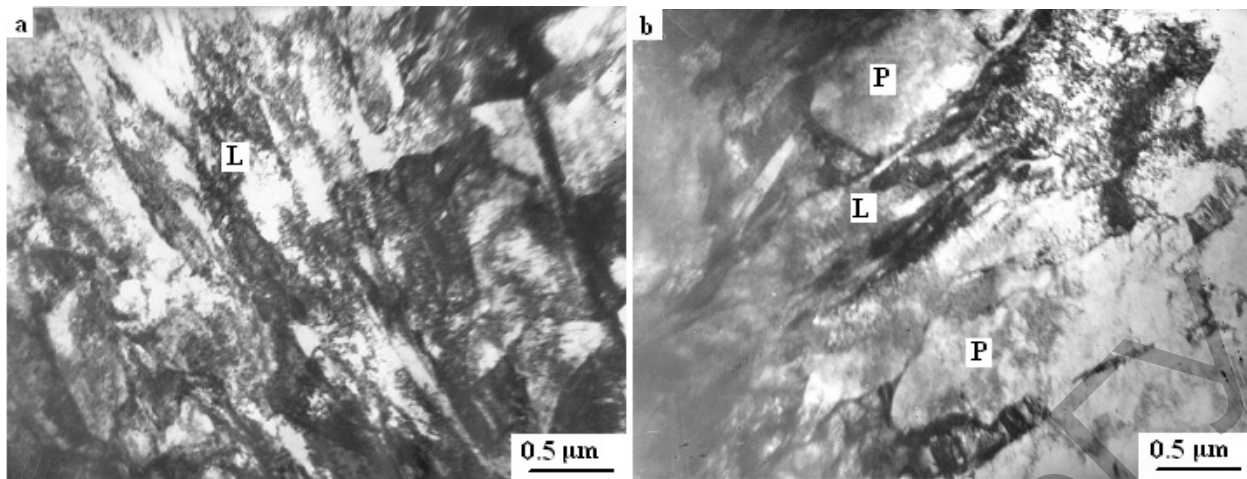


Figure 1. Electron microscopic images of the fine structure in the tempered 30 CrMnSi steel, a) lath tempered martensite (L); b) an admixture lath (L) and plate martensite (P)

At that, lath martensite represents 0.7 of the volume of the α -phase, plate — 0.3. There is no grain substructure in plate martensite (Fig. 1). One half of lath martensite is grained substructure (Fig. 2).

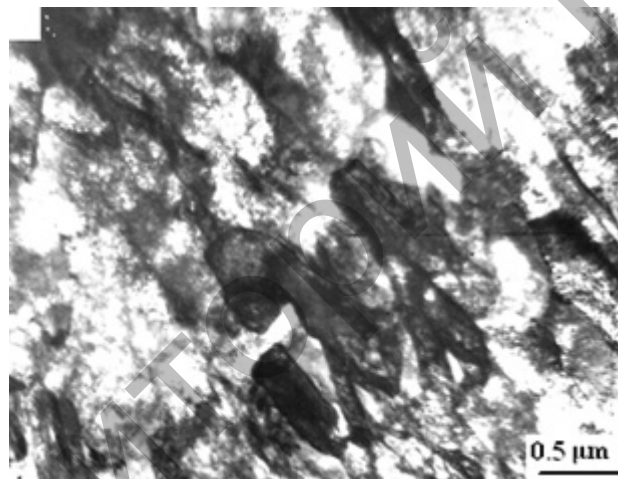
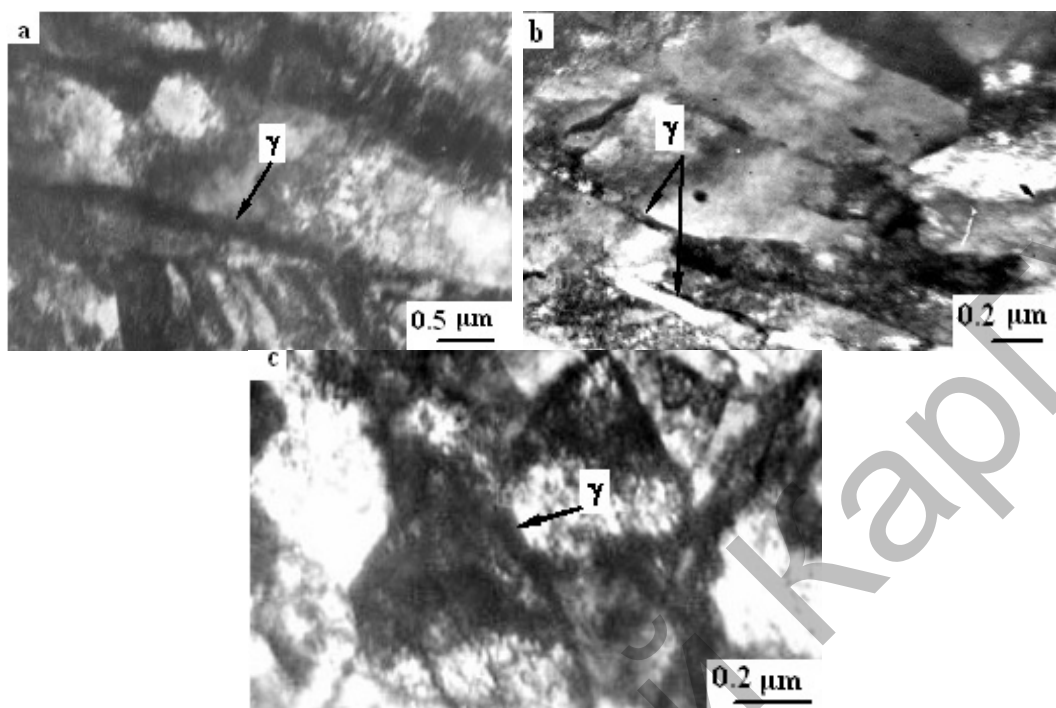


Figure 2. Electron microscopic image of the fine structure in the tempered 30 CrMnSi steel

This is because steel quenching causes accumulation of high scalar density of dislocations in it. The average scalar dislocations density in the material equals to $\rho = 7 \cdot 10^{10} \text{cm}^{-2}$, at that, the biggest part of dislocations is located in the form of dislocation charges (excess dislocations density $\rho_{\pm} = 6.3 \cdot 10^{10} \text{cm}^{-2}$). Rearrangement of the dislocation structure in the course of «steel self-tempering» in the process of quenching causes formation of grained substructure. Let us remind you that the grained substructure is a substructure which consists of a subboundary net (grains walls) and an internal space containing or not containing dislocations. Grained substructure of 30 CrMnSi steel shows its further development during deformation. As shown [7] in the process of hot rolling the surface layer of martensite steel sample is subject to especially strong deformation and temperature exposure resulting in complete destruction of the martensite structure formed after heat treatment, and the anisotropic structure (martensite laths and plates) turns into an isotropic (grain substructure) structure.

The γ -phase is the second morphological component of the steel in question, and is present in the material in the form of residual austenite formed, as mentioned above, in the result of in complete martensite transformation during quenching. Study using the electron microscopy has shown that residual austenite is located in the lath and plate low-temperature martensite on boundaries of martensite crystals in the form of long thin interlayers (Fig. 3). The volume ratio of residual austenite is $\sim 3\%$. Its biggest part (1.5 %) is located in plate martensite, and the smallest part is found in the grained substructure lath component of mar-

tensite (~0.5 %). The residual austenite is present in the non-grained substructure lath martensite in the volume of 1 %.



a) plates, b) non grain structure lath, c) grain structures

Figure 3. The layers of residual austenite (γ) along the boundaries of martensite crystals

Crystalline lattices of the residual austenite and the α -matrix are interconnected through the Kurdjumov-Sacks orientation relation [8, 9]. The Kurdjumov-Sacks relation shows that during the $\gamma \rightarrow \alpha$ transformation, first of all, crystalline lattices of phases tend to turn around less, i.e. the $\gamma \rightarrow \alpha$ transformation takes place on the spot, and, secondly, phases tend to arrange themselves in the space in a coordinated fashion, and if coordination does not take place, then this in coordination is eliminated by dislocations. The feasibility of the Kurdjumov-Sacks relation is supported by the selected area diffraction pattern and its indicated scheme shown in Figure 4. Let us analyze Figure 4 a-d in more details. The residual austenite (γ -phase) is present in the form of thin interlayers (Fig. 4 a) on boundaries of the martensite plate. Presence of the γ -phase is confirmed by the selected area diffraction pattern obtained from this section (Fig. 4 b), its indicated scheme (Fig. 4 c) and the dark-field image (Fig. 4 d) obtained in the reflex $[020]_{\gamma}$. As seen in the selected area diffraction pattern and its indicated scheme, the direction $[\bar{1}00]_{\alpha}$ corresponds to the direction $[\bar{1}10]_{\gamma}$ (coinciding directions in Figure 4 are marked with an arrow). It is also confirmed by solution of matrix equations:

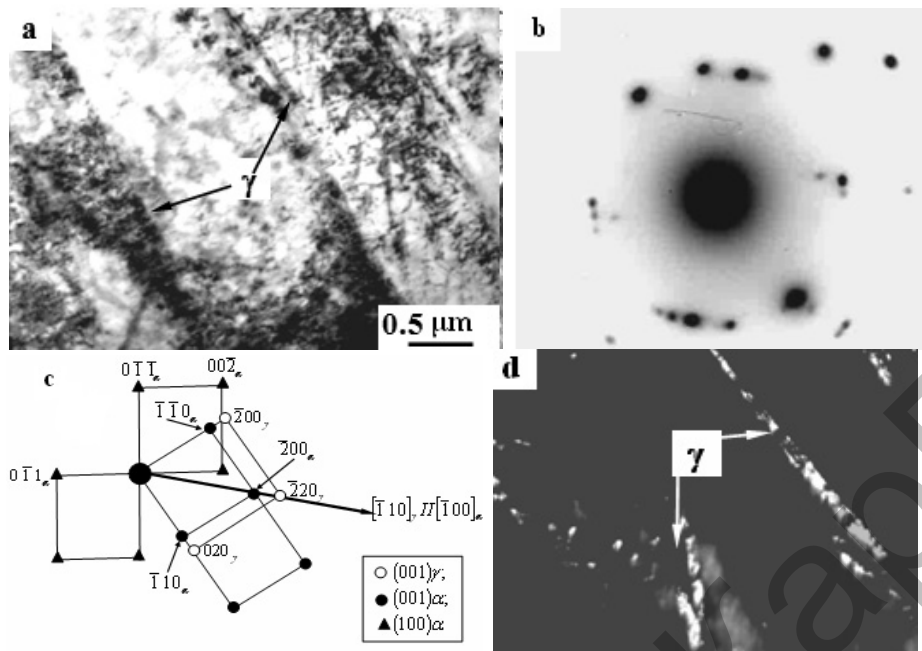
For planes:

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix}_{\alpha} = \begin{bmatrix} 1 & \bar{1} & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 2 \end{bmatrix} \cdot \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}_{\gamma} = (001)_{\alpha};$$

For directions:

$$\begin{bmatrix} h \\ k \\ l \end{bmatrix}_{\alpha} = \begin{bmatrix} 1 & \bar{1} & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \bar{1} \\ 1 \\ 0 \end{bmatrix}_{\gamma} = [\bar{1}00]_{\alpha}.$$

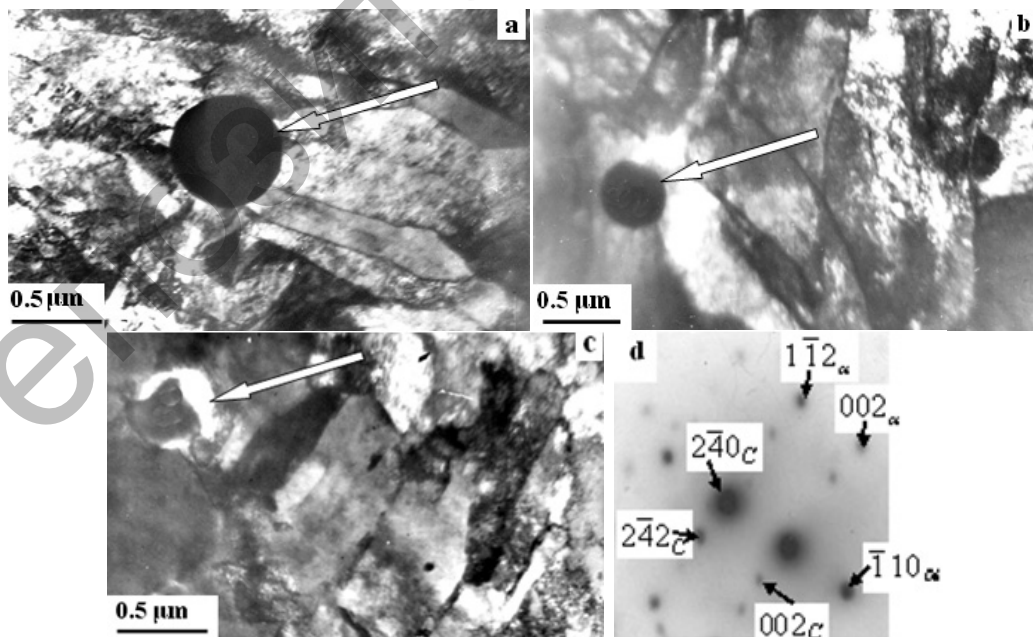
Thus, the solution of matrix equations show: $(001)_{\alpha} // (001)_{\gamma}$ and $[\bar{1}00]_{\alpha} // [\bar{1}10]_{\gamma}$, which is observed in the micro-electron diffraction pattern (Fig. 4 b).



a) bright-field image; b) micro-diffraction pattern; c) its indicated scheme, containing reflexes α - and γ -phase; interlayers of the γ -phase are marked with black arrows in (a) and white arrows in (d)

Figure 4. Electron microscopic images of the fine structure in the tempered 30CrMnSi steel. Alongside the lamellar – layers of residual austenite (γ)

The carbide phase is represented by M_6C -type primary carbides located in the material in random manner (Fig. 5). As seen in Figure 5, carbide particles have a spherical shape, the average particle diameter equals to 0.5 μm , the volume ratio is $\sim 1\%$. Cementite and secondary carbides are not found. Cementite is stable only under low tempering temperature and long tempering. Under the tempering temperature of $\sim 400^\circ\text{C}$ and duration of 6–10 hours, the volume ratio of cementite in the volume of martensite crystals is significantly low ($<0.5\%$), and it almost does not exist in intra-phase boundaries ($<0.1\%$).



a,c,d — bright-field images; b — indicated selected area diffraction pattern obtained from the particle in (a); reflexes belonging to the plane $(110)_\alpha$ of the α -phase and $(120)_K$ (M_6C -type carbide) are present

Figure 5. Microstructure of the tempered 30 CrMnSi steel. Primary M_6C -type carbide particles are marked with arrows

Redistribution of carbon atoms in the studied steel may occur for the following positions [10]: 1) carbons may be found in the α -solid solution which will be naturally oversaturated; 2) γ -solid solution is the second place of carbons localization; 3) in particles of carbide phases, and, finally, 4) in defects of the crystalline lattice (inside vacancies, in dislocation cores, in the form of Cottrell atmospheres around dislocations and on boundaries of cells and subboundaries).

Carbon concentration in the α - and γ -solid solutions is determined according to parameters of their crystalline lattices. The volume ratio of carbon localized in carbide particles is determined based on their volume ratio and stoichiometry. Concentration of carbon atoms on defects of the crystalline lattice is evaluated only indirectly — on the basis of the difference between the total content of carbon in the alloy and concentration of carbon in carbides and solid solutions.

The presence of carbon atoms in cores of dislocations may be detected experimentally only on the basis of presence of a vague contrast on dislocation lines. In our opinion, there is no quantitative theory for this phenomenon so far, but there are qualitative data showing that the contrast of dislocation lines becomes vague. As for presence of carbon atoms in vacancies and in subboundaries, there is no method of direct detection, apparently, so far. Concentration of carbon on defects was determined in this work using the following formula

$$C_{def} = C_0 - (C_\alpha + C_\gamma + C_{carb}),$$

where C_0 is the total content of carbon in steel.

It was established [10] that an intensive departure of carbon atoms from the α -solid solution takes place during steel tempering, and already within 1 hour during tempering into the α -solid solution the content of carbon does not exceed 0.005 wt.-% of the volume. It was also shown there that tempering does not change carbon concentration in the γ -crystalline lattice, and equals to the value of 0.5 wt.-% of the weight after quenching. But as the volume ratio of residual austenite in the tempered steel equals only to 3%, then concentration of carbon in the residual austenite of the studied steel turns out to be equal to 0.015 wt.-% of the weight. The volume ratio of the carbide phase in the studied steel equals to ~1%. It means that ~0.14 wt.-% of the carbon weight is accumulated in carbides. Thus, almost half of the carbon may be found on defects of the crystalline structure.

Conclusions

Analyzing the results obtained in the course of electronic microscopic research of the 30 CrMnSi steel structure after heat treatment we can draw the following conclusions:

- the main component (~96 %) of the tempered steel structure have become the α -phase which represents a mixture of lath and plate tempered martensite;
- concentration of carbon atoms in the α -solid solution during tempering does not exceed 0.005 wt.-% of the weight;
- residual austenite in the lath and plate low-temperature martensite is located on boundaries of martensite crystals in the form of long thin interlayers. The volume ratio of residual austenite equals to ~3 %;
- concentration of carbon atoms in the γ -phase (residual austenite) of the steel in question turns out to be equal to 0.015 wt.-% of the weight;
- the carbide phase is represented by M_6C -type primary carbides located in the material in random manner and have a spherical shape, the average particle diameter equals to 0.5 μm , the volume ratio is ~1%;
- ~0.14 wt.-% of the carbon volume is located in carbides;
- almost half of the carbon may be found on defects of the crystalline structure.

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Босатылған 30 ХГСА болаттың фазалық құрамы

Термиялық өңдеудің 30 ХГСА болаттың фазалық-құрылымдық жағдайына тигізетін әсері зерттелген. Болаттың негізгі морфологиялық құрамы α -фаза екені анықталған. Ол пакетті (0,7) және босатылған пластиналық мартенсит (0,3) қоспалары түрінде кездеседі. Пакетті мартенситтің жартысы фрагменттелген. Пластиналық мартенситте фрагментация құбылысы байқалмайды. Пакетті және пластиналық мартенситте қалдық аустенит мартенсит кристалдарының шекараларында ұзын жіңішке қабатша түрінде орналасқан. Қалдық аустениттің көлемдік үлесі $\sim 3\%$ құрайды. γ -фазаның негізгі бөлігі пластиналық мартенситте, аз бөлігі фрагменттелген пакетті мартенситте орналасқан. Материалдағы дислокацияның скалярлық тығыздығының орташа мәні $\rho = 7 \cdot 10^{10} \text{ см}^{-2}$ тең. Мұндағы дислокацияның басым бөлігі дислокациялық зарядтар түрінде орналасқан (дислокацияның қалдық тығыздығы $\rho \pm = 6.3 \cdot 10^{10} \text{ см}^{-2}$). Карбидтік фаза М6С типті алғашқы карбидтер түрінде кездеседі. Карбидтік бөлшектер сфералық пішінге ие және олардың орташа диаметрі 0,5 мкм құрайды, көлемдік үлесі $\sim 1\%$. Цементит пен екінші ретті арнайы карбидтер кездеспейді. Көміртегі атомдары α - қатты ерітіндісінде (0,005 салм.%) кездеседі. γ -қатты ерітіндісі (0,015 салм.%) көміртегі атомдарының шоғырланатын екінші орны. Олар карбидтік фазаларда да орналасқан (0,14 салм.%). Осыдан кристалдық торлардың ақауларында көміртегі атомдарының жартысы орналасқанын көруге болады.

Кілт сөздер: термиялық өңдеу, фазалық құрам, карбидтік фаза, көміртегі атомдары, орналасу, скалярлық тығыздық.

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Фазовый состав отпущенной стали 30 ХГСА

Было исследовано влияние термической обработки на фазово-структурное состояние стали 30 ХГСА. Установлено, что основной морфологической составляющей стали является α -фаза, которая представляет собой смесь пакетного (0.7) и пластинчатого отпущенного мартенсита (0.3). Половина пакетного мартенсита фрагментирована. В пластинчатом мартенсите фрагментация отсутствует. Остаточный аустенит в пакетном и пластинчатом низкотемпературном мартенсите располагается по границам мартенситных кристаллов в виде длинных тонких прослоек. Объемная доля остаточного аустенита составляет $\sim 3\%$. Большая часть γ -фазы находится в пластинчатом мартенсите, наименьшая — во фрагментированной пакетной составляющей мартенсита. Средняя скалярная плотность дислокаций в материале составляет величину $\rho = 7 \cdot 10^{10} \text{ см}^{-2}$, причем большая часть дислокаций расположена в виде дислокационных зарядов (избыточная плотность дислокаций $\rho \pm = 6.3 \cdot 10^{10} \text{ см}^{-2}$). Карбидная фаза представлена первичными карбидами типа М6С. Частицы карбида обладают сферической формой, средний диаметр частиц составляет 0.5 мкм, объемная доля — $\sim 1\%$. Цементит и вторичные специальные карбиды не обнаружены. Атомы углерода могут оказаться в α -твердом растворе (0.005 вес.%); γ -твердый раствор — это второе место локализации атомов углерода (0.015 вес.%); в частицах карбидных фаз (0.14 вес.%). По-видимому, на дефектах кристаллической решетки сосредоточена почти половина углерода.

Ключевые слова: термическая обработка, фазовый состав, карбидная фаза, атомы углерода, дислокация, скалярная плотность.