

PHASE TRANSFORMATIONS AND DEFECT STRUCTURE DURING MULTISTAGE QUENCHING OF TOOL CARBON STEELS

Begatov J. M.¹,
Mukhamedov A. A.²,
Platoshina M. M.³

¹ Joint Belarusian-Uzbek Intersectoral Institute of Applied Technical Qualifications, Tashkent, Uzbekistan

² Tashkent State Technical University, Tashkent, Uzbekistan

³ Kimyo International University in Tashkent, Uzbekistan

Abstract

This study investigates phase transformations and defect structure formation in tool carbon steels (U7 and U11) subjected to multistage quenching. It is established that high-temperature heating prior to the first quenching leads to the formation of a coarse-grained structure and an increased dislocation density, which is inherited during subsequent heat treatment stages. It is shown that re-quenching from standard recommended temperatures results in phase recrystallization and the formation of a fine-grained structure; however, a high level of defects is retained. The influence of the first quenching temperature and inter-quench tempering on dislocation density, grain size, hardness, and carbon distribution between martensite and retained austenite is analyzed. It is found that the increase in dislocation density is governed by two main factors: inheritance of the defect structure formed during high-temperature quenching and the formation of new grains during reheating, accompanied by microdistortions in the crystal lattice. Increasing the tempering temperature leads to a gradual relaxation of internal stresses. The results obtained provide deeper insight into the mechanisms of structure formation during multistage quenching and support the optimization of heat treatment regimes for tool steels.

Keywords: Multistage quenching; tool carbon steels; phase transformations; dislocation density; austenite; martensite; retained austenite; structural inheritance; heat treatment; hardness; grain size.

Introduction

During two-stage heat treatment, when steels are heated to high temperatures followed by rapid cooling, two effects occur. The first effect is the formation of a coarse-grained structure. The second effect manifests itself as an increased level of crystal lattice defects, expressed in terms of dislocation density.

At the second stage, which consists of re-quenching from temperatures recommended in reference literature, phase recrystallization occurs, resulting in the formation of a fine-grained structure during quenching.



It was previously established that high-temperature heating prior to quenching forms a defective crystal structure, which is inherited during subsequent heating. This defect structure, during the second quenching, leads to a high density of defects even in fine-grained steel [1–3].

A number of studies have been conducted on the mechanisms of grain and dislocation structure formation during cyclic quenching [2, 4–6]; however, these studies do not provide a complete understanding of structure formation. In the present work, the possible mechanisms of structure formation are examined in greater detail, particularly the manifestation of structural inheritance resulting from high-temperature heating during steel quenching.

Investigations of structural parameters (dislocation density and grain size) showed that U7 steel exhibits a significant change in dislocation density.

Table 1 Dislocation density $\rho \cdot 10^{11} \text{ 1/sm}^2$ after two-stage heat treatment

T ₁ quenching, °C	T ₂ quenching, °C	After first quenching (T ₁ + T ₁), °C	After inter-quench tempering, °C		
			300°C	400°C	500°C
Final tempering 160°C					
800	800	3,2	3,2	3,3	3,4
840	800	3,0	3,1	3,3	3,3
1000	800	3,4	3,2	3,25	3,6
1100	800	3,8	3,6	3,8	3,6
1230	800	3,6	3,5	3,6	3,4
$\frac{\rho_{max}}{\rho_1}$		$\frac{3,6}{3,2} = 1,125$	$\frac{3,5}{3,2} = 1,09$	$\frac{3,6}{3,3} = 1,09$	$\frac{3,4}{3,4} = 1$
Final tempering 200°C					
800	800	1,0	0,85	0,7	0,65
840	800	1,0	0,8	0,74	0,65
1000	800	1,04	1,0	0,8	0,7
1100	800	1,2	1,0	0,8	0,75
1200	800	1,1	0,9	0,75	0,7
$\frac{\rho_{max}}{\rho_1}$		$\frac{1,2}{1,0} = 1,2$	$\frac{1,0}{0,85} = 1,17$	$\frac{0,8}{0,7} = 1,14$	$\frac{0,75}{0,65} = 1,15$

The effectiveness of two-stage heat treatment can be considered significant when the ratio of dislocation density between the maximum and minimum quenching conditions exceeds unity and the effect reaches 50% or more [6].

Quenching from high temperatures leads to the growth of austenite grains; after the second quenching from standard temperatures, the austenite grain size strongly depends on the temperature of the first quenching (Table 2).

Table 2 Austenite grain parameter as a function of the first quenching temperature in U7 steel

First quenching temperature	Interquench tempering temperature °C			
	After first quenching	300°C	400°C	500°C
800	0,03	0,03	0,025	0,025
840	0,035	0,04	0,025	0,026
1000	0,04	0,045	0,035	0,03
1100	0,045	0,045	0,04	0,03
1200	0,05	0,045	0,045	0,035
Second quenching from a temperature of 800 °C in water, followed by a final tempering 160°C				

From Table 2 it can be seen that high heating temperatures have a direct influence on grain diameter; with an increase in tempering temperature, the grain diameter slightly decreases. This is associated with the precipitation of nitrogen- and oxygen-containing phases, which dissociate during heating to extreme temperatures, and during cooling precipitate in the form of dispersed particles of various sizes depending on the temperature of the first heating [6, 7]. During the final heat treatment of previously quenched steel, despite the complete double phase transformation α - γ - α , the state of the fine structure is determined by the structural state formed at the stage of billet production.

When quenching is carried out with heating to high temperatures of 1000–1230°C, dissociation of impurity phases occurs, which are present in any industrially produced steel, and the elements of these phases pass into the solid solution of the γ -phase [7]. The onset of this dissolution is characterized by the appearance of chemical microheterogeneity of the solid solution (austenite). As a result, during γ - α quenching, a large number of mismatch dislocations are generated in the α -phase (martensite). However, the grain becomes coarse with increasing heating temperature. Upon reheating to standard temperatures (for U7 steel this is 800 °C), due to orientation–size correspondence (the Konobeev–Dankov principle), new austenite grains (crystals) are crystallographically oriented relative to the previous coarse-grained structure. Even after completion, this orientation of the new grains is preserved. This fully corresponds to the works of Prof. S.S. Dyachenko, according to which the new phase (austenite) during heating nucleates from the old phase (martensite and tempering products of martensite) via a shear mechanism.

In this case, a large number of mismatch dislocations are formed, and in total the following picture is obtained. For example, in U7 steel, a high dislocation density inherited from the first quenching at 1000–1100°C is retained. To this is added an increased level of mismatch dislocations at the boundaries of the fine-grained portion after repeated quenching from 800°C. This circumstance already allows us to speak about the commonality of crystallographic orientation correspondence between the forming austenite and the initial structure.

During two-stage heat treatment accompanied by heating of steels, the formation of new grains occurs inside the austenite grains obtained during the first heating. These newly formed grains acquire the same crystallographic orientation, which leads to the development of microstresses in the crystal lattice.

Thus, an increase in dislocation density occurs due to two factors. The first factor is the influence of the first quenching temperature of 1230°C on the steel microstructure. The second factor is the formation of new grains, which leads to microdistortions in the crystal lattice that are retained during the final tempering at 200°C. With an increase in the tempering temperature, the initial microstresses in the crystal lattice are gradually relieved.

The structure formation during phase transformations in steels described in the works of Prof. S.S. Dyachenko is based on the conclusion that a phase work hardening (“phase strain hardening”) of the structure occurs due to the energy saturation of phase boundaries, accompanied by loss of phase coherency and the formation of dislocations [1].

The difference between U11 steel and the results obtained for U7 steel lies in the presence of secondary carbides in the structure. During high-temperature heating, their complete



dissolution in austenite occurs in the range of 1000–1100°C. The dissolution of impurity phases—carbonitrides and oxygen-containing phases—occurs approximately at similar temperatures (Table 3).

Table 3 Influence of two-stage heat treatment regimes on hardness (HRC) and dislocation density $\rho \cdot 10^{11}$ 1/sm² of U11, final tempering 200°C

T ₁ °C	T ₂ °C	After first quenching		Interquench tempering temperature °C					
				200°C		300°C		400°C	
		Dislocation density	Hardness	Dislocation density	Hardness	Dislocation density	Hardness	Dislocation density	Hardness
800	800	3,0	64	2,0	58-59	2,04	56-57	3,48	56-58
1000	800	4,17	64-65	3,27	59-60	3,06	57-58	3,48	56-58
1100	800	3,6	64-65	2,72	58-59	3,06	58-59	3,28	59-60
1230	800	3,71	63-64	3,01	59-60	2,5	59-60	3,4	58-59

During two-stage heat treatment, consisting of the first quenching from high temperatures and the second quenching from temperatures recommended in reference literature (standard quenching temperatures), carried out both with and without intermediate tempering, it was established that high-temperature heating prior to quenching leads to an increase in dislocation density. During the second heating for quenching, the process of carbon atom migration toward these dislocations begins (Table 4) [2].

Table 4 Influence of the first heating temperature for quenching on the carbon content in martensite and retained austenite in U11 steel

First quenching heating temperature, °C	Carbon content in tetragonal lattice %	Retained austenite %	Carbon content in austenite %
800	0,8	22	0,3
1000	0,75	21	0,25
1100	0,8	21	0,3
1230	0,8	21	0,3

Thus, it can be stated that in all cases the highest dislocation density is observed after high-temperature first quenching, both with different intermediate tempering regimes and without tempering. In all cases, the specimens exhibiting the maximum dislocation density after heat treatment show the minimum lattice parameter of the α -phase (martensite).

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