Proceedings of the International Symposium on Physics of Materials (ISPMA13)

Substructural Strengthening of Medium-Carbon Alloyed Steel with Preliminary Thermomechanical Processing

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Substructural strengthening result in preliminary thermomechanical processing, when applied cold deformation with the combination of post deformation annealing and induction hardening based on the of dislocation structure inheritance effect on the mechanical properties such as torsion static strength has been studied. Final heat treatment with the use of post deformation tempering followed by induction hardening and low temperature tempering demonstrated the highest static torsion strength in consequence of the inheritance of polygonal dislocation substructure of ferrite arised at the proper post deformation annealing temperature at preliminary thermomechanical processing by dislocation structure of austenite formed under followed induction hardening heating and then by dislocation substructure of martensite formed result in following quenching.

DOI: 10.12693/APhysPolA.128.527

PACS: 61.82.Bg, 62.20.–x, 62.20.Fe, 81.40.Gh

1. Introduction

One of the most advanced resource saving strengthening methods applied to metals and alloys is thermomechanical processing (TMP) based on the substructural changing result in inheritance effect of dislocation structure under heat and deformation action in different sequence [1]. Most utilized schemes of TMP such as thermomechanical control processing (TMCP), ausforming and etc. are based on the hot deformation realization [2–5].

At the same time there are many precision stocks and parts produced by cold rolling when metal utilization coefficient is on the level of 0.7–0.8, while the similar coefficient for conventional methods like forging is on the level of 0.25–0.45 [5, 6].

At present there are several varieties of this method, among them — longitudinal cold rolling in idle rolls as one of the most advanced method of producing parts of "axle" and "shaft" type [7]. The realization of the given methods under TMP base on the structural inheritance gives a substantial increase of their application efficiency [6, 7].

2. Experimental procedure

There was studied the effect of preliminary TMP (PTMP) on structure and cyclic durability of parts from medium carbon low alloyed structural steel 0.45CCrNiMV. The preliminary heat treatment was the following: annealing at 910 °C, cooling with the furnace to 550 °C for 7 h, heating to 650 °C, a hold for 4 h, and cooling in air (treatment for lamellar pearlite). The preliminarily heat-treated stocks — hot bars with 75 mm in diameter, were rolled in a longitudinal-rolling mill to provide deformation with a total strain degree, $\varepsilon_{\Sigma} \approx 50\%$. After rolling the stocks were annealed at 400–700 °C. The final heat treatment consisted of induction hardening with 1–2 °C/s heating rate up to 920 °C quenching temperature followed by tempering at 200 °C. Scheme of PTMP is shown in Fig. 1.

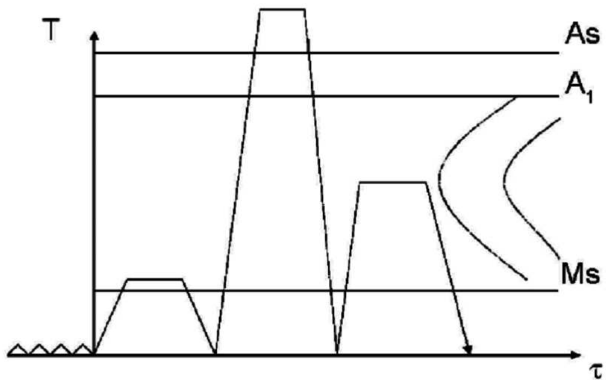

Fig. 1. The scheme of PTMP.

The rolled stocks were used to produce the torsion shafts of 40 mm in diameter. Structure was studied by transmission electron microscopy (TEM) technique with the use of JEM-200CX microscope at accelerating voltage of 200 kV.

The mechanical properties of axles produced by longitudinal-rolling were tested for static torsion strength after PTMP and after conventional heat treatment (CHT) of non-rolled stocks including 920 °C quenching temperature followed by tempering at 200 °C.

3. Structure and mechanical properties

After annealing, the structure of the steel consisted of lamellar pearlite represented by alternating lamellas of ferrite and cementite (≈70%), free ferrite (≈20%), and globular pearlite (≈10%). The dislocation density in the ferrite component in such condition was not high and did not exceed 5×10^8 cm^{-2}.

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Cold rolling with strain degree $\varepsilon_{\Sigma} \approx 50\%$ distorted the lamellar structure of the pearlite, which is manifested by bending of cementite lamellas, their crushing into parts, and rotation of individual lamellas. The matrix becomes fragmented, i.e., crystals of the α-phase break into regions less than 1 μm in size. A cellular structure forms in ferrite lamellas and pearlite colonies. Cementite lamellas are accompanied by accumulations of bent dislocations. A cellular structure forms in the regions of excess ferrite.

The effect of the post-deformation annealing temperature on the structure evolution was studied in the range 400–700 °C. The microstructures of steel 0.45CCrNiMV after cold rolling and annealing at 400–700 °C are presented in Fig. 2. Annealing of cold-deformed steel at the temperature of up to 400 °C causes regrouping and partial annihilation of dislocations and the beginning of formation of small-angle boundaries (Fig. 2a). The random distribution of dislocations in the ferrite is partially removed. The dislocations are formed a sub-boundaries in the ferrite layers of flaked pearlite.

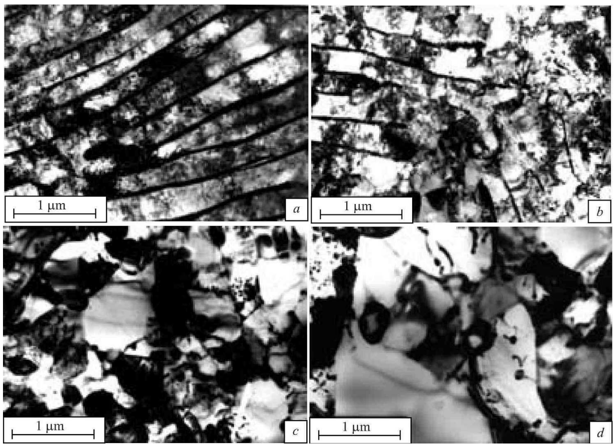

Fig. 2. Structure of steel after rolling with $\varepsilon_{\Sigma} \approx 50\%$ and annealing at 400 °C (a), 500 °C (b), 600 °C (c) and 400 °C (d) (TEM).

The increase of the annealing temperature up to 500 °C increases the volume fraction of polygonized ferrite and decreases the fraction of cellular structure, which promotes spheroidization of the carbide phase (Fig. 2b). The highest polygonization development and the beginning of recrystallization of ferrite were observed after annealing at 600 °C (Fig. 2c). Recrystallization nucleus (regions 0.5–1 μm in size free of dislocations and separated from the surrounding matrix by high-angle boundaries) are formed all over the volume. Individual recrystallized grains have a size of about 5 μm. Cementite undergoes coagulation; after such heating, flake particles are not observed. Annealing at 700 °C causes the development of recrystallization (Fig. 2d). New ferrite grains virtually free of dislocations arised and occupied the whole volume of the specimen. Their size do not exceed 10 μm. Spherical carbide particles are located on the boundaries and inside the grains of the α-phase.

The study of the post deformation annealing temperature effect on the dislocation structure showed that the treatment temperature ≈500 °C gave rise to polygonal dislocation structure in ferrite matrix (Fig. 2b). It is known that polygonal structure is one of the most thermodynamically stable dislocation configuration of substructure [8, 9]. One can suppose that such substructure results in heating with a high reheating rate up to quenching temperature allows to save the same dislocation configuration in the high temperature phase (austenite in our case) if the duration in austenitic zone will be short. Therefore, the evolution of polygonal substructure to the next stage of softening results in recombination of dislocation configuration — recrystallized structure will not take place. If such polygonal substructure in the high temperature austenite will undergo accelerate cooling with a rate exceeding the critical quenching rate, the formed martensite will inherit the dislocation substructure of high temperature austenite (in our case — polygonal). As a result, the substructure of martensite will be more stable. This allows to predict the increase of the strength and fracture resistance in the steel stocks treated by such procedure.

In this study the described effect of inheritance of dislocation structures at phase transformations: ferrite–austenite–martensite was detected in the investigated medium carbon low alloy steel under PTMP with induction hardening.

The inheritance of stable dislocation substructure of high temperature austenite by martensite as a result of quenching under ausforming process (modification of TMP) was found in [10] as well.

The tests for static torsion strength show (see Table) that studied steel treated by PTMP scheme has a better combination of mechanical properties. It should be noted that the values of the maximum residual shear are especially high.

TABLE

Mechanical properties of steel (static torsion).

Treatment	τ_{pr} [MPa]	$\tau_{0.3}$ [MPa]	γ_{max} [%]
PTMP	882 ± 19	1134 ± 19	18.9 ± 4.2
	921 ± 20	$1147 + 20$	27.3 ± 1.7
CHT	872 ± 19	1127 ± 20	17.4 ± 1.3

τ_{pr} — proportional limit, $\tau_{0.3}$ — yield strength at torsion, γ_{max} — maximum residual shear.

Functional characteristics (cyclic torsion tests), evaluated by laboratory testing, correspond 2–3 times to increase of requirements, imposed to similar parts treated CHT.

4. Conclusions

1. Post-deformation annealing of medium carbon low alloyed structural steel at 500 °C provides the formation of polygonal dislocation substructure in the preliminary cold deformed ferrite.

2. Induction hardening of medium carbon low alloyed steel with polygonal substructure of initial ferrite ensures the inheritance of martensite polygonal dislocation structure.

3. Preliminary thermomechanical processing is effective method of substructural strengthening and enables to increase appreciably cyclic torsion mechanical and functional properties of medium carbon low alloyed structural steel.

Acknowledgments

This work was supported by the Ministry of Education and Science of the Russian Federation (Project 14.z50.31.0018).

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