THEORY

MECHANISM OF STRAIN AGING OF MARTENSITE

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The combination of quenching and plastic deformation in a single technical process is one effective means of improving the strength of metals and alloys [1-3]. Plastic deformation results in an increase of the density of lattice defects and, consequently, the elastic energy of the material, which in turn acts as a thermodynamic stimulus to various physicochemical transformations and as the source of energy required for their occurrence.

In recent years a good deal of attention has been given to the method of strengthening steel based on a combination of the martensitic transformation and strain aging [4-12]. This treatment (marforming) is fairly practicable and permits the strength to be raised substantially.

The strengthening of martensite during deformation is usually judged from the effect of deformation on the aging of supersaturated solid solutions and on the character of the distribution and particle size of excess phase.

The intensification of aging resulting from cold deformation is due to a considerable extent to the effect of the large number of lattice defects occurring during plastic deformation. The density of linear defects increases greatly even after small deformation, and therefore impurity atoms can migrate by the shortest path to dislocations and cluster around them. The interaction of interstitial impurities with such defects leads (with diffusion to large distances) to the formation of Cottrell atmospheres, which reduce dislocation mobility and increase resistance to plastic deformation. The pinning of dislocations during strain aging was observed in a study of internal friction [13]. It is possible that the formation of ordered segregates of carbon atoms in the dislocation stress field is of importance in strain hardening of martensite [14].

Examination of the substructure of martensite by transmission electron microscopy has shown that deformation causes a reduction of the cross section and elongation of martensite platelets aligned in the direction of deformation. At the same time, they are divided into areas with substantial misorientation angles [15]. After deformation the dislocations do not form such a regular network as in the quenched and underformed steel. Twins are also observed in crystals of strained low-carbon martensite [16]. These are effective barriers to dislocation movements and therefore have a considerable influence on strain aging of martensite.

While acknowledging the decisive importance of strain aging in hardening martensite during cold plastic deformation, various authors disagree on the extent of the development of the process during deformation. Some have found only the early stages of strain aging – the interaction of dislocations with carbon atoms and the formation of extraneous zones (segregates) [13]. Others have observed the development of the late stages of this process – precipitation of carbide phase [11, 17, 18]. It was found in [18] that the amount of carbide residue increases after plastic deformation of martensite at room temperature. The aftereffects of such decomposition of martensite due to plastic deformation could not be observed on electron micrographs, which may be explained by the exceedingly small size of the carbide precipitates.

The results of our investigations lead to the conclusion that the effect of strain aging in terms of the late stages during deformation and during subsequent heating depends on the carbon content of the steel, the tempering of the martensite before deformation, and the degree of deformation.

Figure 1 shows the effect of rolling reduction on the mechanical properties of steel 26Kh2NGSM in relation to the degree of deformation of martensite with no preliminary tempering and with preliminary tempering.
 tempered before deformation. Deformation was conducted in several passes — 5% reduction in two passes, 10% reduction in three, 15% reduction in four, and 20% reduction in five passes. To obtain results characterizing the strengthening induced by processes that have time to occur during reduction the strained samples were not subjected to final tempering.

Without tempering before deformation, reduction of 5-10% results in a substantial increase of \( \sigma_{0,2} \) (from 136 to 165 kg/mm\(^2\)). Consequently, the result of cold deformation before the tensile tests is an increase of the stress at which dislocations surrounded by atmospheres of impurity atoms again acquire the ability to move. With 15% reduction there is little further effect on the increase of the yield strength and ultimate strength, while 20% reduction intensifies strain aging.

X-ray structural analysis showed that plastic deformation of untempered martensite reduces the width of (211) interference lines, especially the initial deformation (5% reduction). With greater reduction there is noticeable broadening of (211) (Fig. 1). The variation of the electrical resistivity \( \rho \) with the degree of deformation is different. At 5% reduction, where the width of (211) is smallest, \( \rho \) retains the same value as after standard quenching, and decreases only at 15-20% reduction (Fig. 1). These relationships are observed after the treatment without final tempering, and therefore it can be assumed that the processes affecting these relationships occur during deformation.

The narrowing of (211) at small reductions is due primarily to the redistribution of carbon as the result of migration to dislocations, which reduces the tetragonality of the martensite lattice. Small deformations without final tempering do not result in lowering the resistivity. This confirms the fact that no notable decomposition of the solid solution occurs in the process of such deformation.

The broadening of (211) with increasing reductions can be explained by the predominant influence of defects in the crystal structure under the given conditions.

The drop of the resistivity after 15-20% reduction is evidently due to the lower carbon concentration of the matrix. This is probably due to the development of strain aging to the stage where fine carbides are formed, which promotes a substantial increase of dislocation density. It is also possible that this phenomenon is due to some extent to the development of natural aging.

The increase of \( \sigma_{0,2} \) and \( \sigma_b \) at the beginning of deformation in the case where martensite is rolled after tempering at 200°C is smaller than in the case of deformation directly after quenching. This is explained by the lower carbon concentration of the solid solution after tempering and weakening of the effect of the interaction of carbon atoms with dislocations. The plasticity and fracture toughness decrease with