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The analysis of hardening of metal materials

Structural level of deformation and parameters of thermomechanical treatment

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Abstract There has been researched the interdependence of the process of microalloying, thermomechanical treatment and obtained mechanical characteristics of steel and AIMgSi alloys. There have been analyzed the hardening mechanisms of the mentioned alloys in correlation with grade, speed and temperature of strain. The achieved effects of alloys hardening are the consequences of combined operations of grain raffination, precipitation of dispersing particles of microalloying elements and increased density of dislocation.

Keywords Microalloying · Thermomechanical treatment · Hardening of alloys

Introduction

The need for materials having good combination of high mechanical characteristics caused the development and appearance of hardening procedures, as thermomechanical treatment (TMT). This procedure is applied, e.g. with rolling of small grained microalloyed steels, extruding of AlMgSi alloys etc.

The objective of this article is that on the basis of the results analysis of many years researches [1, 7, 8, 10], as well the researches of other authors [2, 3, 5, 6, 9], makes contributions to better understanding of the hardening of metal materials depending on TMT parameters, and with this also to more constructive designing of the technology for concrete alloys production, as steels and AlMgSi alloys.

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Structural levels of strain and types of hardening metal materials

From the standpoints of the structure assemblies of the given metal material, there are the following deformation levels [3, 9]: (a) the deformation of polycrystal sample; (b) grain deformation in polycrystal; (c) deformation of subgrain in grain and deformation of fragments and blocks in subgrain; (d) deformation on the level of basic cells and crystal twins, plain defects, respectively; (e) deformation at the level of dislocations, line defects, respectively; (f) deformation at the level of atoms, spot defects, respectively and (g) deformation of polycrystal specimen at the level of electrons, i.e. elementary particles.

Depending on complexity of metal material, there are the following types of deformation hardening [2–6, 9]:

1. Of monocrystal, that nucleates (forms) as the effect of heavy movement of dislocations, because of increasing their number and their mutual interaction.
2. Of metal, that nucleates (forms) on account of increasing of density of dislocations and their mutual interaction; microstructural barriers, i.e. interactions of dislocations with grain boundaries; subgrain barriers, i.e. interaction of dislocations and subgrain, as well interaction of dislocations and parts of subgrain (fragment, block, cell and twin).
3. Solid solutions, which—besides the mentioned effects—boost also on the account of: dislocation interaction and soluted atoms, dislocation interaction

and deformed, (strained), crystal lattice of basis, because of the soluted atoms of alloyed elements.

4. Complex heterogeneous alloys, that can boost, in other words strengthen also on account of: interaction of dislocation and dispersion particles, interaction of dislocations and inclusions, as oxides, nitrides, borides, carbides and intermetallic compounds.

According to the parameters of TMT there are the next sorts of reinforcement of metal materials [4, 7, 9, 10]: by grain refining, through the increasing of dislocation density, by precipitation of precipitating (temperature unstable) particles and dispersion (temperature stable) particles.

Analysis and discussion

Only complex studying of dependence of mechanical characteristics of alloys of their dislocation substructure, enables correct choice, selection, respectively, of parameters for TMT, in other words designing optimal technology of plastic deformation.

According to modern dislocation theory of plastic deformation, the obtained values of mechanical characteristics depend on the following parameters [2, 3, 5, 6]:

$$\sigma_T,\ K_{Ic} = f(\sigma_{PN}, \sigma_{GD}, \sigma_{RA}, \sigma_{DTC}, \sigma_{SB}) \qquad (1)$$

where σ_T—yield point of alloy; K_{Ic}—toughness of demolition, or stability against formation of cracks; σ_{PN}—Paierls–Nabaro constraint, or stress for overcoming friction in crystal lattice; σ_{GD}—reinforcement that appears on account of increasing of numbers (density) of dislocations, or stress necessary that dislocation overcomes resistance of other dislocations during its movement; σ_{RA}—reinforcement with dissolved atoms, or stress necessary to overcome resistance, which is put by dislocation atmospheres around the atoms of dissolved element; σ_{DTC}—reinforcement by dispersion (stable) and precipitation (metastable) particles; σ_{SB}—reinforcement with microstructural barriers which are on the way of moving dislocations.

The influence of dislocation density on the stress (σ_{GD}), indispensable for the appearance of plastic deformation, is determined by the equation [3, 9]:

$$\sigma_{GD} = \alpha \cdot G \cdot b \cdot \sqrt{\rho} \qquad (2)$$

where α—coefficient, depending on the metal nature; G—shearing modulus; b—Burgers vector and ρ—dislocation density.

With increasing the deformation degree, dislocation destiny is being actively raised:

$$\rho = \rho_0 + C \cdot \varepsilon^{\alpha} \qquad (3)$$

where ρ_0—starting density of dislocation; C and α—parameters depending of the type of crystal lattice and real conditions of deformation and ε—degree of deformation.

Typical values of these rates, magnitudes, respectively, for a number of metals are: $\rho_0 = 10^5$ to 10^7 cm^{-2}; $C = 10^{8\pm1}$; $\alpha = 1.0^{\pm0.5}$. At high degrees of deformation the ($\varepsilon \to 1$), quantity of dislocations rises to maximal densities, i.e. $\rho = 10^{12}$ to 10^{14} cm^{-2}.

The effect of microstructural barriers on reinforcement can be analytically expressed through the equation of Hall–Petch [3, 9]:

$$\sigma_T = \sigma_0 + K \cdot d^{-\frac{1}{2}} \qquad (4)$$

where σ_T—yield point of alloy; σ_0—stress, necessary to overcome the resistance to the movement of dislocations through grain, which has been caused by the presence of soluted atoms, dispersion particles and by dislocation interaction; d—average diameter of grain; K—a coefficient that takes into consideration stress necessary for dislocation formation in adjacent grains, in other words for deformation transmission from one grain into another one.

The effect of various dislocation configurations in microstructure onto deformation reinforcement can be defined by the equation:

$$\sigma_{OD} = \sigma_{ODP} + \sigma_{ODS} \qquad (5)$$

where σ_{OD}—general reinforcement of alloy at dislocation interaction; σ_{ODP}—reinforcement at chaotic overlapping of dislocations; σ_{ODS}—reinforcement at existing certain dislocation structures inside the grain.

The effect of dispersion and precipitation particles on the alloy reinforcement (σ_{DTC}) can be defined briefly by the equation:

$$\sigma_{DTC} = \sigma_{ODCMO} + \sigma_{OMH} + \sigma_{OMNM} \qquad (6)$$

where σ_{ODCMO}—reinforcement that originates on account of the interaction of movable dislocations and particles, in addition to the formation of dead-eyes, or curves according to Orowan's mechanism[5]; σ_{OMH}—reinforcement that appears because of increasing dislocation destiny, by formation prismatic and helical, spiral curves, or dead-eyes according to Hirsh's mechanism; σ_{OMNM}—reinforcement that originates through the intersection of particles by movable dislocations according to the mechanism of Nicolson and Mot [2].

The effect of substructural barriers on reinforcement can be, in general, expressed by the equation [2, 3, 5]:

$$\sigma_{SB} = \sigma_0 + \alpha \cdot K \cdot G \cdot b \cdot d^{-m} \qquad (7)$$

where σ_0—flow stress of base, without cell structure; α and K—coefficients; G—shearing modulus; b—Burgers vector; d—cell diameter and m—coefficient which has the value from 0.5 to 1.

From the standpoint of the effect of the parameters TMT on the structure and reinforcement alloy (the Eqs. 2, 4, and 7), it can be observed that, e.g. high strength and good resistance against brittle failure of the controlled rolled microalloyed steels (titanium, niobium, and vanadium) can be obtained by fine dispersion of titanium nitride, or niobium carbide, through combined operation: (a) refining of steel grain size, due to the capabilities of segregated particles to accelerate negatively, i.e. to retard austenite recrystallization; (b) by precipitation of dispersed carbides of microalloyed elements and (c) increasing the dislocation density by reducing the temperature of austenite transformation [7–9].

Grain refining is the consequence of combined effect of specific action of microalloyed elements (MAE) on the recrystallization process during the hpt deformation and controlled rolling which is distinguished by high degree of reduction at low temperatures. Such TMT regime of hot rolling provides the optimal grain refining and with it is simultaneously improved both strength and toughness.

Precipitation hardening of steel by fine particles of microalloying elements can be realized—selecting the appropriate technological parameters and designing of the adequate chemical composition—as in solid austenite solution, so in solid ferrite solution [7–9].

Precipitation hardening, i.e. enforcement in the solid γ-solution by carbonitrides, i.e. by carbonitriding of MAE-s is being performed during heating and rolling slabs, consequently in deformed and, still, uncrystallized austenite, segregating fine dispersolids, as on boundaries of grain and sub-grain (what retards, i.e. accelerates negatively recrystallization), so inside the grain (that traps their growth).

Precipitation hardening in solid ferrite solution can be realized if a certain quantity of MAE-s keeps in solid solution (by accelerated, i.e. forced cooling through γ/α-transformation area, i.e. between 800 and 500 °C), and then—by their precipitation in α-phase—by precipitation boosts ferrite [7, 8].

Similar hardening effects can, also, be done as well at the controlled extruding of microalloyed AlMgSi alloys [6, 10]. Hardening of the mentioned alloys on the basis of keeping unrecrystallized (polygonized) structure originates as the consequence of: (a) adding transitional elements, as Mn, Ti and Zr in micro quantity and (b) suitable speed of deformation (low) and deformation temperatures (high).

Namely, high temperature of deformation in combination with low speed of deformation and microalloying provides: (a) continuous process of recovery, when is being formed polygonal structure, very proof against recrystallization and (b) precipitation of intermetallides of transferring elements, which stabilize the obtained polygonal structure [6].

The polygonized structure of extruded semifinished articles (‘structural’ effect) in combination with the hardening effect by heat treatment precipitation, or ageing (‘precipitation’ effect) enable obtainment very high values of mechanical characteristics as well beside lower cooling at hardening [6, 10].

Conclusions

On the basis of the appointed objective and performed analysis and the discussion of results, it can be stated that the hardening of metal materials, during the designed TMT, is a very complex process.

In the concrete case, the booting of the controlled rolled microalloyed steels and extruded AlMgSi alloys is the consequence of: (a) combined operation of the refining of grain size, on account of the capability of particles to retard (accelerate negatively) recrystallization, (b) precipitation of intermetallides of microalloying elements, which stabilize the obtained polygonized structure and (c) increasing of dislocation density, by lowering the deformation temperature.

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