THE INFLUENCE OF THERMOMECHANICAL PROCESSING PARAMETERS ON THE MESOSTRUCTURE FORMATION AND MECHANICAL PROPERTIES

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Abstract

The influence of Temperature-Strain-Time parameters at the Thermomechanical Processing (TMP) of austenitic, duplex and pearlitic structural steels on the mesostructure formation has been studied based on the laboratory, industrial experiments and TEM analysis. The fragmented dislocation substructure observed in steels with a different carbon, nitrogen, titanium, niobium content as well as recrystallization gave evidence that TMP effects the work-hardening and softening behaviour. The problem of mesostructure appearing in various steels and alloys due to various modes of TMP used hot and hot-warm deformation is discussed. The role of plastic strain in the formation of mesostructure and the relation between the changes in the crystal structure due to TMP and the mechanical properties of the steels are considered.

Keywords: Thermomechanical Processing, fragmentation, mesostructure, recrystallization

1. INTRODUCTION

It is known that the Temperature-Strain-Time parameters at the Thermomechanical Processing are responsible for the generation of the different mechanical and functional properties of metallic materials. The crystal lattice defects such as dislocations and dislocations configurations: cells, polygons, disclinations, fragments, recrystallized grains, and fractions of this or that component of the structure arised in the total structure which differ not only in their kind but also in quantitative characteristics and in some cases TMP causes a change in the phase composition too result in TMP. The resulting set of mechanical, processing (deformability) and functional properties depends on the qualitative and quantitative proportion of these structural modes, and the effect of TMP can be used not only for strengthening which is described in quite a number of works [1-3], but also for softening, in particular, for realizing the effect of superplasticity [4, 5].

Taking into account the fact that the main contribution to the evolution of structure in TMP is made by Temperature-Strain-Time parameters [3,6], we will consider changes occurring at this or that structural level due to TMP from the standpoint of classification of structural levels described in [7, 8].

2. CLASSIFICATION OF STRUCTURAL LEVELS FROM THE STANDPOINT OF ADVANCED PHYSICS OF STRENGTH AND PLASTICITY

The physics of strength and plasticity differentiates two levels of crystal structure defects, i.e., an atomic level and a microlevel [9]. Defects of the atomic level have sizes little exceeding the interatomic spacing in all the three dimensions. These are point defects (vacancies, interstitial and substitutional atoms, their simplest complexes and combinations). The defects of the microlevel or microdefects have sizes close to interatomic ones in one or two dimensions and much greater sizes in the other two (one) dimensions and can attain the size of the single-crystal region where they reside. Accordingly, we differentiate planar and linear microdefects. Planar microdefects include packing imperfections, large-angle off-orientation boundaries, and phase boundaries. The microstructure is characterized by the dislocation density, the mean grain size, the size distribution of grains (subgrains), and their shape.

In the process of plastic deformation the microstructure evolves in a regular way. The dislocation density increases monotonically with growth in the degree of the deformation, and new slip systems come into play. The sizes and shapes of the grains change in accordance with the tensor of macroscopic plastic strain (the Polanyi - Taylor principle) [10]. This approach seems to be understandable. However, development of the methods of analytical transmission electron microscopy and intensification of research of defect structures in strongly deformed with a high strains (ε) crystals have shown that the classical dislocation approach is adequate, strictly speaking, only in the initial stages of deformation, specifically, in the stages that precede brittle fracture ($\varepsilon < 0.1$) [7,10]. At higher values of ε consideration of the microlevel of strain and of the processes occurring at this level have turned out to be insufficient for describing the effects of structure formation and macroscopic flow and fracture of loaded crystals. Experimental and theoretical computations have shown the absence of immediate transfer from the microlevel to the macrolevel of plastic flow. In order to explain the macro-properties of a solid body on the basis of the concepts of microdefects that are carriers of elementary acts of plastic displacement it became necessary to introduce into consideration the concepts of mesodefects, mesostructure, and mesolevel of plastic strain, which are principally new both for the physics and for the mechanics of plastic strain [7, 8]. At high ε collective modes of motion appear in an ensemble of interacting dislocations and cause self-organization of the ensemble in the process of plastic deformation. The formation of substructure in Thermomechanical Processing of metallic materials determines the level of their physical, mechanical, process, and functional properties. The main mode of structural transformations in most TMP variants is fragmentation of substructure. It causes formation of a substructure that belongs to the mesolevel in accordance with the modern approach to classification of structures. Thus, it is the mesostructure which is primarily responsible for this or that effect during and after the treatment. Collective modes of motion of dislocations cause the appearance of qualitatively new large-scale formations with ordered distribution of dislocations, which are stable in the field of applied stresses and in the process of continuing plastic deformation against the background of the evolving microstructure. Such formations have been termed mesodefects and the structure composed of them has been termed mesostructure [7, 8]. It follows from numerous experiments that noticeable effects of self-organization leading to the appearance of first mesodefects in an ensemble of strongly interacting dislocations start for many metals at $\varepsilon = \varepsilon 0$ and depends on the metal characteristic such as stacking fault energy and strain temperature. The most typical mesodefects are broken dislocation boundaries that, as will be shown below, appear in great number in the process of TMP plastic deformation and cause formation of fragmented structures due to implementation of a rotary mechanism of plastic strain [6-8, 13-16]. We will use this approach for study of the influence of TMP parameters on the mesostructure formation and mechanical properties.

3. STRUCTURAL TRANSFORMATIONS AT TMP WITH A DIFFERENT TEMPERATURE-STRAIN-TIME PARAMETERS AND THEIR ROLE IN THE FORMATION OF MECHANICAL PROPERTIES

At TMP the thermoplastic action makes the structure evolve. With growth of the strain all the levels mentioned above are involved progressively. The structural transformations occurring at the mesolevel are primarily responsible for formation of the final structure and hence for the properties of metals and alloys subjected to TMP.

At present a various variants of High-Temperature Thermomechanical Processing (HTMP) and controlled rolling (CR) have been developed primarily for sheets and, to a less degree, for rolled shapes. Tube strip performs are chiefly produced from low-carbon low-alloy steels including high-strength ones. Critical parts like track pins are fabricated from medium-carbon alloy steels. In the latter case the cyclic endurance of parts produced from such rolled billets is more than doubled with respect to conventional heat treatment. Corrosion-resistant austenitic and double-phase (duplex) steels are subjected to strengthening by TMP and this increases the yield strength by 70-100% and simultaneously raises the corrosion resistance and corrosion mechanical strength. The process of HTMP is comparatively easily adjustable to the working modes of pressure heat treatment of metals (rolling, drawing, forging, etc.). TMP variants are less used for the production of stocks and parts in the stage of machine-building conversion due to the more complex geometry of the cross section of the parts and hence due to the more difficult conditions for ensuring uniformity of structure and properties over the cross section (in some cases due to the necessity for creating special cooling devices). However, in the last decades, interest to the use of TMP for the production of machine parts has grown abruptly due to the unique possibilities of formation of an optimum structure and, consequently, of the required process, physical, mechanical, and functional properties at simultaneous decrease in the cost. New advanced methods of plastic forming are developed and the old methods are improved with the aim of lowering the cost of the products and elevating the combination of specified process and operating properties. TMP often helps in solving these problems simultaneously and efficiently [1-3, 6].

The efficiency of TMP depends primarily on such process factors as the temperature, degree, fractional nature, and rate of the deformation and (in the case of HTMP) on the post-deformation (before quenching) hold. In high-temperature TMP, deformation is performed in the hot and hot-warm temperature range [6]. It is known that in this case the rearrangement of the dislocation structure of the high-temperature phase (for steels this is austenite) is a consequence of competing and successively preparing each other process of mechanical hardening, dynamic recovery (or cell formation), and dynamic recrystallization. In the initial stages of the deformation the prevailing process is the first one. With growth in the degree and rate of the deformation the dislocation density increases [9]. In accordance with the advanced theory of high plastic deformation collective forms of motion arise in a dislocation ensemble and cause substantial restructuring, i.e., breakage of the body of grains first into somewhat off-oriented cells and then into fragments of substructure [6, 7, 10]. From the standpoint of the advanced physics of plastic deformation of crystals the appearance of collective forms of motion means the appearance of rotary modes of plasticity in the crystals. At a specific loading rate the deformed material becomes incapable of dissipating the mechanical energy supplied to it due to only plastic displacements. Therefore it breaks into a set of randomly oriented microregions (cells, fragments) each of which turns in a plastic manner in the deformation process and thus absorbs additional portions of energy. With growth in the loading rate (growth in the degree and rate of the deformation) the rotary modes and their structural feature (fragmentation) should intensify continuously. This goes on until the rate of supply of mechanical energy to the preform exceeds the next threshold value at which the fragmented structure becomes unsteady and dynamic recrystallization, which is the most powerful structural mechanism of energy dissipation, comes into play.

It is the change in the TMP parameters which is responsible for the kinetics of the processes of structure evolution, for the attainment of this or that state (often a heterogeneous structure consisting of regions of this or that structural mode in various proportions and distributed with different degrees of uniformity over the volume of the preform), and, correspondingly, for the attainment of a specific combination of properties.

For single-phase materials the concepts described above have been proved convincingly in our own works and in works of other authors for an example of HTMP of corrosion-resistant steels of austenitic and austenitic-ferritic classes [6, 11-13]. It was shown that the accumulation of strain upon growth in the number of passes (at one and the same total strain) produces qualitatively and quantitatively different effects on the changes in the structure and in the phase composition as compared to single increase in the degree of strain. For example, when the number of passes is increased in fractional deformation, the dislocation density starts to increase monotonically, especially after the first pass. After the third pass the dislocation density increases little and after the fifth one it increases insubstantially. The spatial distribution of the dislocations changes simultaneously and quite substantially. As the total degree of the deformation is increased, we first observe the appearance of a cellular structure with off-orientations not exceeding 0.1° (**Fig. 1a**). Then a fragmented structure with off-orientations on the order of θ =1-3° appear against this background (**Fig. 1b**). Broken boundaries are clearly seen in this case; the places of the breakage, i.e., the lines of imperfect disclinations [10], are sources of powerful stresses.

The fraction of the volume taken by fragmented structure after the first pass is only 5 - 10 %. Upon accumulation of strain the proportion of fragmented structure increases to 60 - 70% after the third pass and to 80 - 90% after the fifth pass. On the average, the fragments become smaller and the off-orientations between them increase noticeably. After five passes they attain several tens of degrees on individual boundaries, i.e.,$\theta_{1.4}$ = 20°, $\theta_{2.4}$ = 12°, etc. (**Fig. 1c**). In the case of more intense single reduction the evolution of the structure differs from the described one both qualitatively and quantitatively. For example, single reduction with θ = 30% yields regions of dynamic recrystallization (**Fig. 1d**), the volume of which increases from 30 to 90% upon growth in the reduction to ε = 50%. Note that it is especially important (and this reflects the continuity of structure evolution in the deformation process) that the dislocation density varies in a wide range depending on the deformation stage in which the recrystallized region has appeared, namely, from virtually full absence to about 10^{10} cm $^{-2}$. Fragmentation develops in nonrecrystallized grains but the angles of off-orientation of the fragments are smaller (up to 8.5° at ε = 50 %) than in fractional deformation with the same total strain (up to 20°). The proportion of the fragmented structure changes too; when the single reduction is increased from 10 to 30 %, the fraction of fragmented structure first increases from 5 - 10 % to 20 - 30 % and then decreases to 5 - 10 % again. The mechanical, corrosion, and corrosion-mechanical properties and the high-temperature strength change accordingly primarily as a function of the structural modes, of the sizes of the structural components, and of the off-orientation angles.

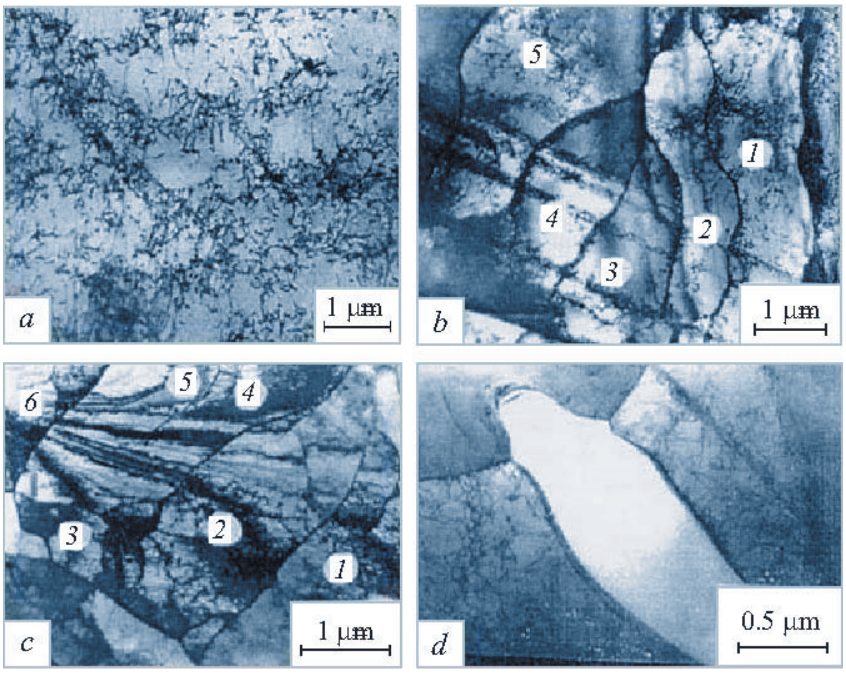


Fig. 1 Weakly off-oriented cellular (*a*), fragmented (*b*, *c*), and recrystallized (*d*) structures in austenitic steel Cr18-Ni10-Ti after fractional deformation (*c*) and after single-stage deformation (*a*, *b*, *d*): *a*) number of passes *n* =1, ε = 10%; *b*) *n* =1, ε = 10%; *c*) *n* =5, ε = 10%; *d*) *n* =1, ε = 30%; *1 - 6*) fragments on which crystallographic orientation (θ) has been determined

For example, the highest strength is observed in steel with nonrecrystallized structure and decreases with growth of recrystallized volumes. The high-temperature strength and the corrosion resistance change accordingly [2, 14]. Short-term high-temperature tests have shown that the highest strength level determined in thermomechanically strengthened rolled stock at room temperature is preserved at elevated temperatures too (**Fig. 2**).

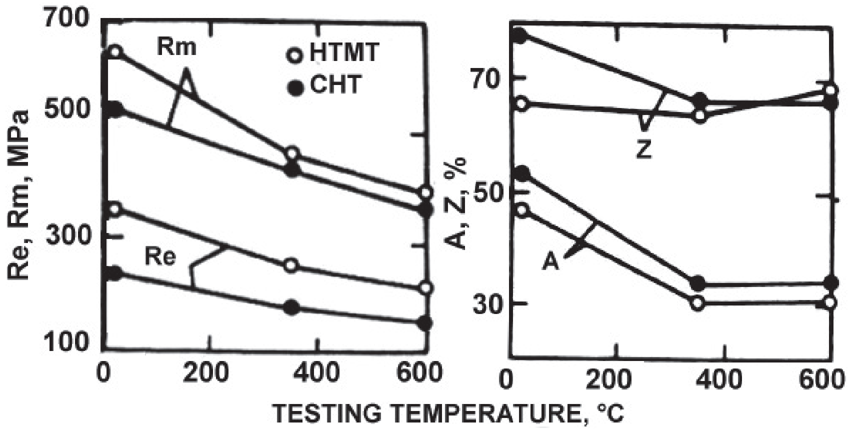
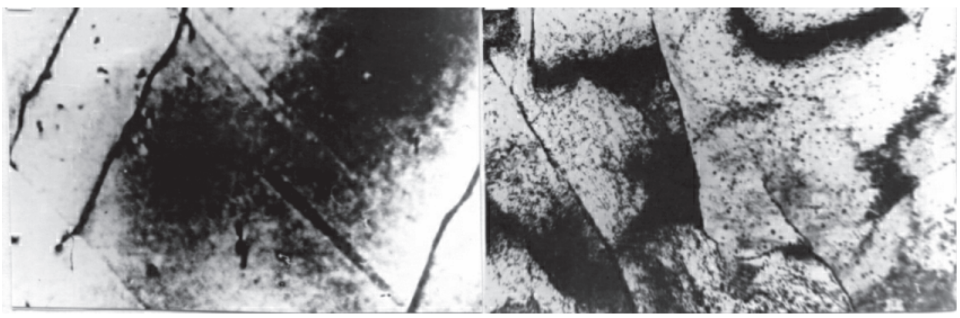


Fig. 2 Mechanical properties of Cr18Ni10Ti steel - after HTMP of bars produced in industrial rolling mill 350 and also conventionally heat-treated(CHT), with increasing testing temperature

Steels subjected to HTMP soften with growth in the temperature to a lesser degree than steels subjected to conventional heat treatment (quenching). In a long-term strength test the specimens of steel Cr18Ni10Ti subjected to HTMP did not fracture under higher loads and for a longer time than the specimens after conventional heat treatment. Such tests performed at a temperature of up to 800 °C also showed the advantage of preforms subjected to HTMP and the efficiency of the treatment depended on the substructure formed at the mesolevel.

In alloys undergoing phase transformations the kinetics of structure formation is more complex but its main feature is inheritance of the dislocation structure

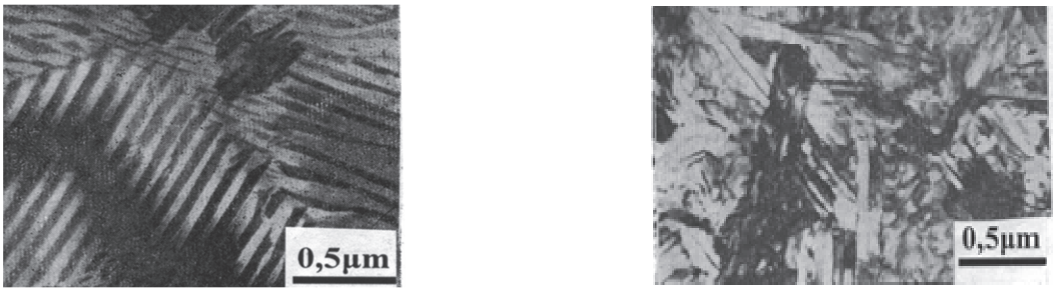
The effect of mesostructure formation in δ-ferrite of duplex austenitic-ferritic steel result in HTMP shown in **Fig. 3**.



a b

Fig. 3 Fine structure of δ ferrite in steel Cr18Ni12TiV result in CHT (quenching) and result in HTMP (b)

In alloys undergoing phase transformations the kinetics of structure formation is more complex but its main feature is inheritance of the dislocation mesostructure of the deformed alloy by the forming phase. For example, in alloys undergoing martensitic transformation the martensite formed as a result of accelerated cooling after TMP inherits the fine structure of hot-deformed austenite and the latter circumstance promotes suppression of brittleness [15]. In the case of TMP of pearlitic steels with the deformation in hot-warm temperature range accelerated cooling at a rate lower than the critical one the formed intermediate structures of pearlitic type have smaller sizes of pearlite colonies (**Fig. 4a**) than those ensured by cooling of nondeformed steel, which produces a positive effect on the mechanical properties (**Fig. 4**).



a b

Fig. 4 Pearlite structures in pearlitic steel 0.4 %C,Cr,Si: a - result in normalization at 900^{0}C; deformed at TMP in range 900-700 ^{0}C; a - multiple nucleation of pearlite colonies

Fragmentation of the material does cause substantial refinement of the structures, it has a much weaker effect on the strength properties of the steel. Its influence is mainly evidenced in an increase in crack- resistance of the material. The experimental results show that this parameter is actually always higher in structures formed after deformation that in similar structures obtained as the result of normal heat treatment

Studies performed not only on steels but also on heat-resistant nonferrous alloys (brass, copper, aluminum and titanium alloys, etc.) have shown that it is the mesostructural level which is responsible for the formation of the final set of physical, mechanical, process, and operating properties after this or that variant of TMP [16 - 18].

CONCLUSION

The Temperature-Strain-Time parameters are responsible for the generation of the mesostructure at Thermomechanical Processing. It is possible to obtain this or that combination of mechanical properties by controlling the mesostructure formation.

REFERENCES

[1] BERNSHTEIN M. L., ZAIMOVSKII V. A., KAPUTKINA L. M. Thermomechanical Treatment of Steel, Metallurgiya, Moscow. 1983. 480 p.

[2] GRIGOR'EV A. K. AND KODJASPIROV (KODZHASPIROV) G. E. Thermomechanical Hardening of Steel in the Blanking Production, Mashinostroenie, Leningrad, 1985. 143 p.

[3] KODJASPIROV (KODZHASPIROV) GEORGE, KIM INSOO., Thermomechanical Processing of Steels, St.Petersburg State Technical University,1998,.228 p.

[4] GRABSKII M. V., Structural Superplasticity of Metals, Metallurgiya, Moscow,1975. 280 p.

[5] KAIBYSHEV, O. A. Superplasticity of Commercial Alloys, Metallurgiya, Moscow,1984.279 p.

[6] KODJASPIROV(KODZHASPIROV) G. E., A. I. Rudskoy, and V. V. Rybin, Physical Foundations and Resource-Saving Technologies in the Production of Parts by Plastic Deformation , Nauka, St. Petersburg, (2006. 350 p.

[7] RYBIN V. V. “Regularities of mesostructures development in metals in the course of plastic deformation,” Vopr. Materialoved., 33(1), 2003, p. 9 - 28.

[8] PANIN V. E. (ed.), Physical Mesomechanics of Heterogeneous Media and Computer-Aided Design of Materials, Cambridge Interscience Publishing 1998.

[9] KELLY A. AND G. GROVES, Crystallography and Crystal Defects, Longman, Bristol (UK), 1970. p. 496.

[10] RYBIN V. V., High Plastic Deformations and Fracture of Metals [in Russian], Metallurgiya, Moscow,1986, 224 p.

[11] KODJASPIROV (KODZHASPIROV) G. E., SEMIBRATOV G. G., Thermomechanical Hardening of Parts with the Use of Drawing Processes, LDNTP, St. Petersburg, 1992, 22 p.

[12] RUBTSOV A. S., RYBIN V. V., “Structural features of plastic strain in the stage of localization of yielding,” Fiz. Met. M[etalloved., 44, Issue 3,1977, p. 611 - 622

[13] KODJASPIROV (KODZHASPIROV) G. E., RUDSKOY A. I., BOROWIKOW A. Thermomechanical processing of Ti and Nb alloyed stainless steels. Proc. Of the Int.conference ‘Rolling 2013”, Italy [CD-ROM], 2013. ISBN 9788885298958.

[14] KODJASPIROV G. E., VOL A. A., in: Proc. of the European Corrosion Congress (EUROCOR’97), Trondheim, Norway,1997, p. 353 - 356.

[15] SMIRNOV M. A., PETROVA S. N., AND SMIRNOV L. V., High-Temperature Thermomechanical Treatment and Brittleness of Steels and Alloys , Nauka, Moscow ,1991. 168 p.

[16] LAPINA I. V., SMIRNOV M. A, AND USHAKOV V. G., in: Proc. Int. Conf. “High Technologies in Modern Materials Science”, St. Petersburg, 1997, p. 11 - 12.

[17] ALIMOV V. I. AND FIN’KOI. A. V, in: Abs. Rep. Conf. “Bernshtein Perusal on Thermomechanical Treatment, MISiS, Moscow, 2001, p. 68.

[18] SUNDBERGAND R., SUNDBERG M., in: Thermomechanical Processing [TMP], Stockholm, 1996, p. 268 - 276.