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ADVANCED METALLIC MATERIALS AND PROCESSES

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Abstract. The following main tendencies in the evolution of metal science are described: development of new materials with predetermined mechanical, physical and functional properties as e.g. amorphous materials, ultra-fine-grained (including nanostructured) etc. Advanced resource-saving technologies applied to traditional and new materials as e.g. different schemes of thermomechanical processing, cyclic thermal treatment, cyclic deformation treatment etc. are presented. Application of advanced techniques: laser beam, high-energy electron-beam, plasma and simulation technique are described as well.

1. Introduction

The advanced directions in materials technology and processing of metallic materials are stipulated as all increasing technical requirements to materials in connection with generation of modern engineering, and with a becoming aggravated problem material and power resources.

In this connection it is possible to select the following base tendencies of the development: 1) generation of new materials with the predetermined physical and mechanical properties; 2) development of new resource-saving processes of treatment both traditional, and new materials; 3) application of new techniques of heating and cooling at heat treatment and plastic deformation (metal forming) treatments.

On the first section, it is necessary to mark the following directions: making ultrafine-grained (steels and alloys) and amorphous materials (metal glasses); development new save-alloyed steels and alloys (with a high damping, with a shape memory effect.); ceramics etc.

On the second section, it is possible to stand out the following directions:

- more and more active use of the different schemes of Thermomechanical Processing (TMP) not only with the purpose of strengthening, but also and as an expedient of both structure and phase composition of steels and alloys regulation, in particular, ensuring making not only high-strength, but superplasticity condition, creation of ultrafine-grained (including submicro- and nano-crystalline) structure and also as a resource-saving technology (owing to a heightening of constructive strengthening of the material and cancelling of necessity of special heat treatment application);
- thermocyclycal treatment (TCT), used for obtaining of a fine-grain structure ensuring a heightening of a complex of mechanical properties, cold resistance, and also in a series of cases as resource-saving technology;
- controlled thermal plastic treatment (CTPT), used at the rolling of carbon and low alloyed steel sheets;

- high-energy methods of metals and alloys treatment: laser, electron-beam, of a high- frequency currents etc.

In the field of a Thermo-Chemical heat treatment all more widely begin to apply a carbo-nitriding with the heightened contents of nitrogen at the expense of use of an injected method of input of ammonia, making of automatic regulating systems of carbon and nitric potentials, the interesting effects are obtained at use Chemical-Thermo-Cyclical Treatment (CTCT) of articles from powders.

As to the third units, here it is possible to speak about application of high-energy radiants of heat (laser, electron beam, plasma heat etc.).

Let us consider on some of the mentioned above directions.

2. Advanced materials

2.1. Amorphous materials.

1. There are two expedients of transition of crystalline systems in an amorphous state [1]: (a) at the hardening of the melt, for metals with cooling rates about 10^6-10^8 K/s; (b) as a result of a melting in a solid condition.

2. In homogeneous systems, when an increase of the free volume and free energies occurs equally on all volume of crystalline system, reaction the crystal - amorphous structure in a solid condition occurs suddenly in all volume of the material, as it is in smelting, without thermal activation at reaching a critical value of free volume.

3. In actual alloys with defects and precipitates of other phases the amorphousation process of structure occurs by formation of "nucleus" of amorphous structure on defects (and their congestions) of the lattice and is accompanied by processes of decomposition of the phases and diffusion of alloying elements. In this case the amorphousation process acquires the thermally activated character and depends on requirements of deformation and can develop at the annealing of the previously deformed alloy in the region of the temperatures below than crystallization point of an amorphous state.

4. The transition from crystalline to the amorphous state can realize through a series of intermediate structures with the not transmitting long-distance order. These materials have received the name quasi-crystals, which were discovered in 1984.

2.2. Ultrafine-grained materials with submicrocrystalline structure. The ultrafine-grained materials – nanocrystalline (NC) and submicrocrystalline (SMC) last years call major interest among the experts in the field of physical materials technology [2-4].

These materials have the small size of grains and, hence, huge extent of the grain boundaries (GB) in their structure, owing to what they have a lot of unusual physical and mechanical properties. For example, such fundamental parameters as Curie temperature, elastic moduluses vary, the diffusion constant is increased on some orders, in nanocrystallined condition the fragile ceramics becomes viscous. Nanocrytals with about 10 nm grain size most traditionally obtained by the use of special powder metallurgical techniques, but their serious deficiency is the presence of a porosity (up to 10 %) in the compacted sintered samples (Fig. 1).

At the same time, submicrocrystalline alloys with the about 100 nm (0.1 microns) grain size manage to be gained with the use of severe plastic deformations with consequent fixing of initial stages of recrystallization. This method of the SMC materials production has two important advantages: does not give in formation of a porosity, can be applied both to pure metals, and to alloys and to intermetallic compounds.

The base principle of thermoplastic (thermomechanical) treatment for the production of SMC materials consists in realization at the severe plastic deformations (true logarithmic deformations ($e = \ln h_0/h = 4$-7) of strongly fragmented structure with the attributes of an amorphous state with a consequent recrystallization. The study of physics of severe plastic deformations indicates that under these conditions the active role is played with rotation modes of a plastic deformation, result in the formation of strongly misoriented structure [5].

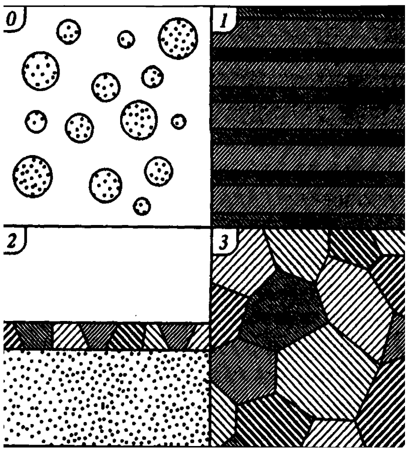


Fig. 1. Schematic introducing of the four types of nanostructured materials distinguishing in dimensionality of the structural unities: 0 – atomic clusters and particles; 1 – multilayers; 2 – ultrafine-grained coatings; 3 – volumetric nanocrystallined materials [2].

For the realization of severe plastic deformations the different methods of treatment – shear under pressure, special extrusion and rolling on multi-roll mills methods can be used, all-round forging etc. [2,4]. The fragile materials treat at the heightened temperature with its consequent lowering, more plastic – at the room temperature.

As the results of investigations testify, the metals and alloys in the SMC condition like nanocrystals have the much changed fundamental parameters – Curie temperature, elastic moduluses, diffusion constants. These differences are caused by not only of small grain size in structure, but also major extent and degree of non-equilibrium of the grain boundaries. The SMC materials are conceptually represent a new class of materials with unusual physical and mechanical properties – are anomalous by high strength and damping properties, concerning low temperature superplasticity, heightened viscosity, high magnetic properties.

Though these questions require more extending investigations, but taking into account technological effectiveness of the developed methods of the preparation of SMC structures, it is possible to expect perspectives of their industrial application.

3. Advanced processes

Let us consider some of the mentioned above advanced technologies in a physical metallurgy, plastic and heat treatments.

3.1. Thermomechanical Processing. It is known that TMP is one of the advanced resource– saving technologies of metallic stocks and parts of machine production [4-6]. As a result of TMP using rolling, forging, drawing and other metal forming processes it is possible to increase strength and toughness simultaneously applied to the different classes carbon and alloying austenitic and perlitic steels and alloys, and in the most of cases will not necessary to conduct heat treatment following by metal forming routinely. The recent ideas of the physics of high (severe) plastic deformation had been taken into account for interpretation of structure formation during (TMP).

According to advanced ideas the TMP is combination of plastic deformation, heating and cooling (in the different sequence) causing the formation of finished structure are occur in the high density of structural defects (dislocations, disclinations etc.) conditions induced by plastic deformation.

The main strengthening parameters under such type combine influence treatment are – increasing of dislocations density and its more uniform distribution in the volume of metal as compared with annealed condition; forming of dislocation barriers (grains, fragments, subgrains and twin boundaries), the dispersed secondaries phases, etc.; decreasing of the grain size, fragments and substructure with blockades dislocation boundaries; the forming of secondary dispersed phases, phase transformations in the material with preliminary induced substructure.

By now there are many schemes are developed up to days. The most important of them: High Temperature Thermomechanical Processing (HTMP), Low Temperature Thermomechanical Processing (Ausforming), Controlled Rolling, etc. (Fig. 2) [4, 6].

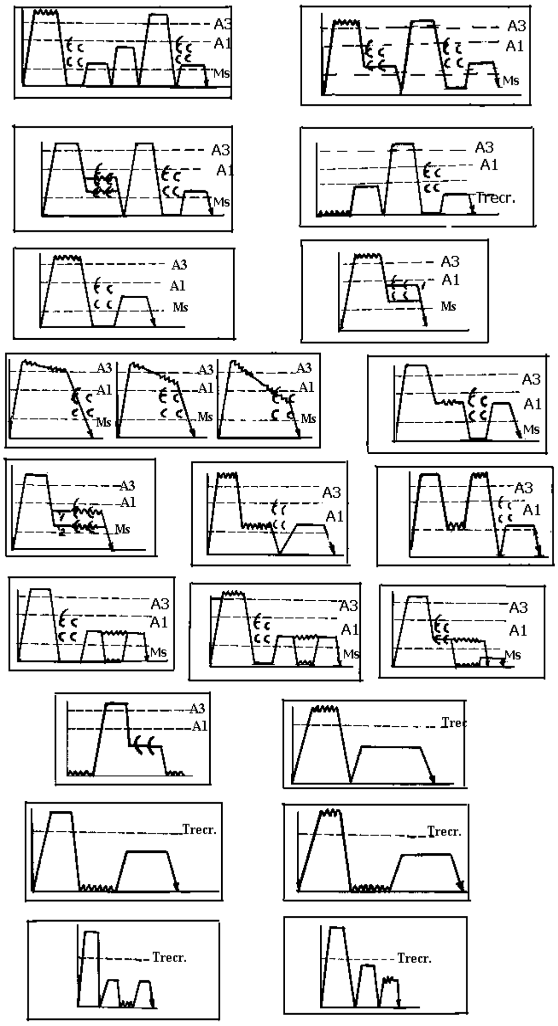


Fig. 2. The schemes of Thermomechanical Processing [4].

As a result of TMP realization it is possible to operate by structure and accordingly technological (for example, deformability, machining property etc.), mechanical and functional (fatigue limit, cyclic durability, corrosion-mechanical strength etc.) properties.

To the present time the different schemes of TMP - high-temperature (HTMP) and low-temperature (Ausforming), preliminary thermomechanical processing (PTMP) and Controlled Rolling (CR) and etc. are in detail enough investigated [4-6].

The mechanism of regulation of the structure and phase composition with the help of such processing consists in the forming of such dislocation structure, which simultaneously influences and change the phase composition and morphology of the generated phases.

It is known, that the rearrangrments of the dislocation structure originating at the deformation in austenitic zone, are a consequence three competing and sequentially of preparing each other processes: a mechanical hardening, dynamic recovery and dynamic recrystallization. In case of single-phase materials in accordance with lowering temperature at identical deformation parameters, there is a changing of the dissipative mechanism. If at the high temperatures of deformation the dynamic recrystallization – most powerful structural mechanism of a dissipation of energy takes place, at the lowering temperature begin to work other weaker dissipative mechanisms. So at the lower temperatures begins to develop fragmentation, and in accordance with lowering temperature there is a fine crushing of the fragments and decreasing of the high angle grain boundaries misorientation.

At the further lowering of the temperature in dislocation ensemble there is already forms the cellular structure. At the phenomenological level, last collective modes of the dislocations movement can be associated with the phenomenon of dynamic recovery.

According to contemporary ideas on the plastic deformation of crystals, they show that rotational plasticity modes have arisen in the crystal. A uniformly deformable material cannot further dissipate the mechanical energy supplied to it at a given load rate just by means of plastic shears. So it divides into a set of misoriented microregions (cells, fragments), each of which starts to swing round plastically during deformation, thereby absorbing additional portions of mechanical energy.

As the load rate increases, the rotational modes and their structural indication – fragmentation – will continue to intensify. This continues until the rate of mechanical energy supplied to the specimen exceeds the threshold value, at which a fragmented structure becomes unstable. As soon as that occurs under high temperature conditions the dynamic recrystallization develops – for a single-phase material the last and most powerful structural mechanism of energy dissipation [7].

In single-phase materials, a drop in deformation temperature results in enhanced strength and reduced ductility and toughness because the dynamic recovery processes are slowed down and more highly stressed structure states characterized by enhanced dislocation density are formed and the presence of strong sources of internal stresses are formed. The latter the increase to plastic shear and the propensity of the metal to the formation of microcracks.

With these general ideas in mind, it is simple to explain the pattern of structural transformations, which we have observed in these experiments dealing with TMP.

The marked features of structure formation are confirmed experimentally both on metals, and on steels [5, 6].

The strengthening kinetics is more complicated in materials, which experience phase transformations. The main is inheritance of the deformed structure peculiarities by the resulting structure. First, plastic deformation results in the formation of different structure states in the high- and low-temperature phases, distinguished from one another both by the temperature peculiarities of dynamic recovery of those phases and by different mechanisms of plastic deformation and work-hardening. Secondly, after deformation of the high-temperature phase a phase transformation takes place during subsequent cooling which results in additional precipitation hardening of the material.

The factors mentioned above have different influences on the strength and the ductility. In particular, they may simultaneously result in higher strength and ductility or while raising the strength, they may lower the ductility. So by varying the deformation temperature in the range of the phase transformations it is possible to form structure states which give different combinations of strength and ductility. This is especially important in the use of metal forming treatment for the metals in which the temperature at the end of deformation is lower of the phase transformation point.

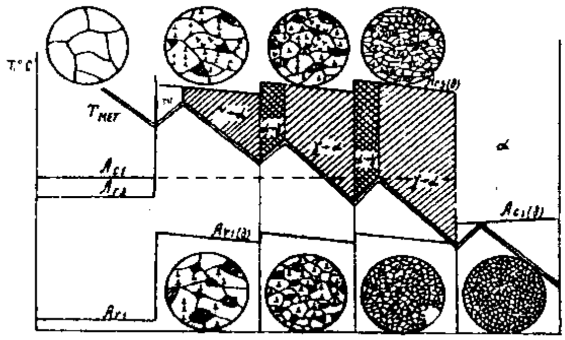
The numerous experimental data confirm a generality of the above described mechanisms for the steels with the different alloying. The resourse-saving technologies TMP-based successfully realiared in USA, Japan, Germany, UK, Russia, Korea etc.

3.2. Thermal plastic treatment with cyclic phase transformations. The processes of plastic deformation and thermal cycling treatment can be combined [8]. Plastic deformation is always accompanied by the alteration of sensible heat of the workpiece due to the generating heat of plastic deformation, surface friction in the contacting areas as well as heat abstraction to the deformation tool.

During the hot rolling of workpieces the temperature of the subsurface layers was observed to change most of all, the sharp reduction of temperature with the rate ~4000 °C/s occurring due to the contact with cold rolls. During the pause as a result of the effect of the heat flow from the within of the workpiece the subsurface layers are quickly heated. At the same time, its internal layers, at the moment of passing the deformation area gain temperature and later during the pauses between the passes cool, having warmed up the previously cooled peripheral layers. The temperature drop of the subsurface layers in the deformation area increases with the growth of the compression due to the growth of the deformation area extension and consequently, due to the contact period with the cold rolls. The higher the temperature gradient formed in the deformation area between the workpiece surface and center, the more intensive is further thermal exchange between them. Thus, during the multi-stage rolling it is possible to change the workpiece temperature from one pass to another according to the cycling law by varying the process parameters. Cyclic phase transformations are possible during multiple plastic deformation of metal in a temperature two-phase area.

As a result, in each consequent cycle crystallization will cover both new volumes and those undergone phase transformation before (Fig. 3).

Thus, periodic metal deformation in a certain inter-critical temperature range induces cyclic partial phase $\alpha \Leftrightarrow \gamma$ crystallization in the metal, which can be controlled by the selection of temperature-time and deformation rate treatment parameters. The complete course of partial cyclic phase transformations is controlled by co-arrangement of phase composition isolines of metastable system (during heating and cooling) and temperature alteration curve of certain metal volume on temperature-time diagrams of structural state of periodically deformed austenite-ferrite phase system plotted for certain steels.



1 CYCLE 2 CYCLE 3 CYCLE 4 CYCLE

Fig. 3. The scheme of the structure alteration during the $\alpha \rightarrow \gamma$ phase systems periodic deformation [8].

In the field of a Thermo-Chemical Treatment (TCT), to our mind, the investigations on steel workpieces carbonitriding with high nitric potential ensuring a heightening of the physical-mechanical and functional properties and intensification of the process are most interesting [9]. At the conventionally used processes of the contents of nitrogen in the carbonitrided layer is restricted 0.4 % because of danger of formation of defect as a "dark" component and lowering of the hardenability. At the same time, it was impossible to reach more than 0.5-0.6 % of nitrogen in a diffusive layer. However the application of an injector feeding of the ammonia expedient to the oven has allowed to generate high nitric potential and, thus, to realize qualitative layers with the 0.5-1.0 % nitrogen contents (at carbon 0.7-0.8 %). It was fixed that with the increasing of the nitrogen contents the structure containing coherent precipitations

GP zones and volume with quasi-amorphous ultrafine structure forms in the solid solution, heightened dislocation density and presence of substructure. Such structure ensures heightened plasticity (microplasticity), evaluated with a microhardness method. The toughness value at the room temperature evaluated by the mentioned above method is increases, and the degree of its lowering at the dipping in the region of negative temperatures drops, that is cold resistance is raises .

The application of the given process in an industry has allowed to produce carbonitrided layer by thickness up to 2.5 mm, to increase durability of the machine parts (gears), the instrument from constructional, tool and powder steels on 15-20 %.

In the field of the high power sources application it is possible to emphasize the good prospects of plasma technology application for heating before a plastic deformation as a local source, and at the arc-spray technology enables to production of coatings from the different materials. The laser heating is applied as well as a local source of heat to the surface hardening (Fig. 4), and at a so-called laser alloying.

The application of an electronic beam as a source of heating gives the formation on the steel surface of an amorphous layer and to change of physical-mechanical properties of the surface.

The microhardness of the electron-beam-irradiated metal is lower than a microhardness of the samples, irradiated by the laser (thus, undoubtedly, the treatment regimes render quantitative influence on this relation). At the analyses of the microstructure of a surface subjected electron-beam effect, it is not revealed of poorly etched light layers with heightened strength, which detect at the laser hardening. These distinctions can be connected as with different mechanisms of consumption by metal of the energy of electronic beam and laser radiation, as well as and other factors.

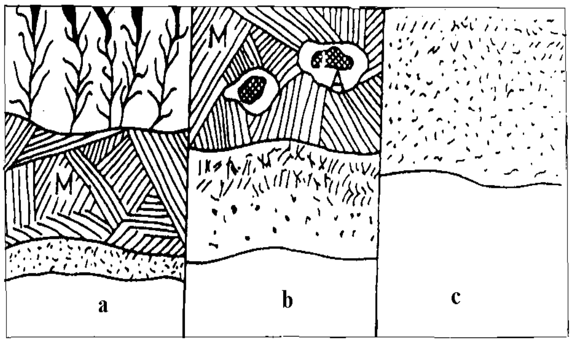


Fig. 4. The scheme of surface steels structure treated by laser beams:
a – hardening with melting zone on the surface (white layer);
b –hardening without melting zone on the surface; c – tempering zone on the surface.

As for simulation and modelling of the advanced processes it is effective the application of the experimental planning method, finite elements and finite difference methods [10].

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