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THERMOMECHANICAL PROCESSING OF STEELS AND ALLOYS PHYSICAL FOUNDATIONS, RESOURCE SAVING TECHNIQUE AND MODELLING

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Abstract. The physical fundamentals, resource-saving technique and modelling of Thermo-mechanical Processing (TMP) applied to steels and alloys are described. Structural and phase transformations under TMP and their role in formation of final structure and mechanical properties in the different steels and alloys are presented. The basic physical principles of TMP as a base for developing of new resource-saving technologies of metal products manu-facturing and examples of industrial application are presented. Different TMP schemes developed for producing of bar and sheet rolling products, annular billets cylindrical billets wi th variable sections of profile are demonstrated. Modelling, including Physical and Numerical simulation, Experimental Planning and FEM applied to control structure and mechanical properties of TMP treated products are presented.

Keywords: thermomechanical processing (TMP); physical foundations; steels; dynamic recrystallization.

1. Introduction

Steels and alloys, including ferritic-pearlitic, austenitic and duplex, TWIP and other steels and superalloys grades as well have been widely used in industry because of their good combination of mechanical and functional properties. Thermomechanically processed steels and alloys with a high strength, good toughness and weldability, cold and heat resistance, high corrosion resistance etc. have been a great commercial success as a structured materials for many years [1-3]. TMP applied to austenitic stainless steels could produce high-strength plates and stocks with yield strength of higher than 400 MPa, and 600 MPa for high nitrogen steels [4, 5]. It has been reported that TMP can give pearlitic low alloyed steels substructure hardening which rise strength without much reduction in ductility and toughness and functional properties such as cyclic torsion strength [6]. It is possible to obtain this or that combination of properties by controlling the structure evolution.

2. Physical Foundations

In Thermomechanical Processing thermo-deformation action makes the structure evolve. With growth in the strain degree all the structural levels (including atomic, micro- and meso-) involved progressively [7, 8]. 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. The efficiency of TMP depends primarily on process parameters

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such as temperature, strain, strain rate, divisibility, and time elapsed from the deformation to the start of quenching, in the case of High Temperature Thermomechanical Processing (HTMP). In last case (HTMP), deformation is realized in the hot and hot-warm temperature range. 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 and fragment substructure formation), and dynamic recrystallization. In the initial stages of the deformation the prevailing process is the first one. With growth in the strain and strain rate the dislocation density increases. In accordance with the modern 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[9, 10]. From the standpoint of the modern 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 the specific loading rate the deformed material becomes incapable of dissipating the mechanical energy supplied to it as a result of only plastic displacements. So it breaks into a set of randomly oriented micro-regions (cells, fragments) each of which turns in a plastic manner in the deformation process and thus absorbs additional portions of energy. With increasing of the loading rate (growth in the strain and strain rate) the rotary modes and their structural feature (fragmentation) should intensify continuously. This goes on until the rate of supply of mechanical energy to the billet exceeds the next threshold value at which the fragmented structure becomes unsteady and dynamic recrystallization, which is the most powerful energy dissipation structural mechanism, comes into play. It is the change in the thermomechanical temperature-strain parameters which is responsible for the kinetics 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 billet, and, correspondingly, for the attainment of a specific combination of properties.

The results of experimental studies applying single phase austenitic stainless steel alloyed by Ti and Nb the described above theory has been successfully confirmed [11]. In steel 18Cr10NiNb with a different deformation schedule fine structure evolved by different mechanisms. In case of fractional deformation, increase in total strain degree leads to increase the dislocation density. The greatest change is takes place after the first pass: from 10^8 to $2{,}5x10^{10}$ cm^{-2}. Subsequent increase in total strain degree has practically no effect on the dislocation density. After 5 passes it is remains at the level of 10% strain degree. The spatial distribution of dislocations after the first pass is characterized by the presence of sections with a weakly expressed cellular substructure as well as sections of fragmented substructure. In the similar corrosion-resistant austenitic Ti-bearing steel the sections where fragmentation is observed against the background of a deformational micro-twins are often encountered (Fig. 1a).

With fractional accumulation of the total deformation the fraction of the volume occupied by cellular substructure decreases monotonically, while the fraction of the volume occupied by fragmented substructure increases.. Thus after third pass, the fraction of volume with a fragmented substructure reached ~60% and after 5 passes ~90% for steel with Ti, and 80% - after 3 passes and 95% after 5 passes for Nb-bearing steel correspondingly (Fig. 1 b). No signs of dynamic recrystallization are seen even after 50% strain degree with a fractional accumulation of the strain (5 passes per 10% in each pass).The mentioned above takes place applied to both steels. Structure formation in one-time deformation also has distinctive features. In both steels the proportion of the volume occupied by cellular substructure decreases monotonically with increase of strain degree. The proportion of the volume occupied by fragmented substructure increases steadily. The most significant difference in the variation in structure in one time deformation in comparison with the fractional case is that sectioned of dynamic recrystallization appear in steel with increase in the strain degree on one time rolling reduction. They are first observed after 30% strain degree. The proportion of the volume covered by recrystallization structure increase in the both steels with increasing of single pass strain degree to 50% (Fig. 1 c,d). Similar structure transformation has been found in duplex austenitic–ferritic corrosion-resistance steel [10]. 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. For example, the highest strength is observed in steel with non-recrystallized structure and decreases with growth of recrystallized volumes.

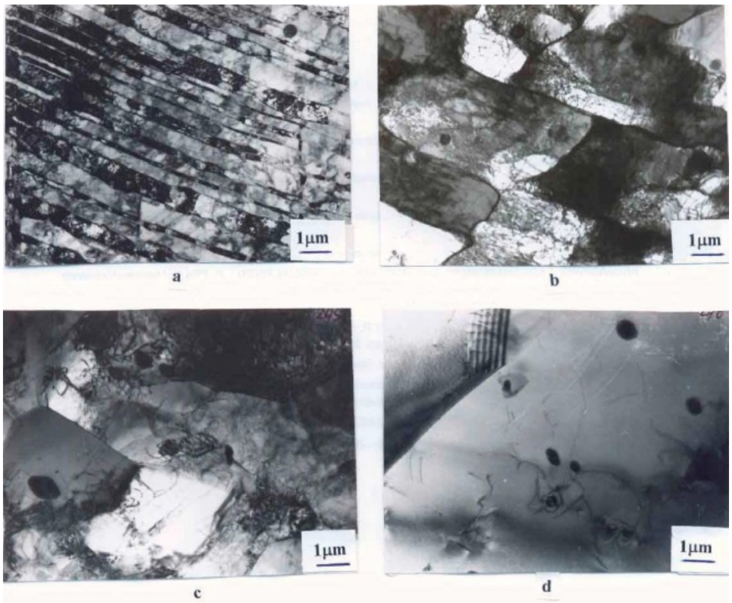

Fig. 1. Fine structure of austenitic stainless steels: Ti bearing steel, subjected to 10% strain for 1 pass (a); Nb bearing austenitic stainless steel subjected 50% strain for 5 passes (b); Nb bearing austenitic stainless steel subjected 50% strain degree for 1 passes (c, d) [7].

In alloys undergoing phase transformations the kinetics of structure formation is more complex but its main feature is inheritance of the dislocation structure 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 HTMP inherits the dislocation substructure including polygonal and fragmented ones of hot-deformed austenite. The latter circumstance promotes suppression of brittleness [2, 10]. In the case of HTMP with deformation in austenite-pearlite temperature range and accelerated cooling at a rate lower than the critical one the formed intermediate structures of pearlitic type have smaller sizes of pearlite grains than those ensured by cooling of non-deformed steel, which produces a positive effect on the mechanical properties [12].

3. Resource-saving technologies

Optimization of the TMP invites investigations of the structural-mechanical behavior and to develop resource-saving technology and proper equipment to manufacture different metal billets and parts. The mentioned above physical fundamentals based on the recent ideas of the physics of plastic deformation had been taken into account for the control of structure formation during thermomechanical processing (TMP) of steels and alloys [10]. By now there are many schemes of resource-saving TMP are developed up to days. The most important of which: HTMP, Ausforming, Controlled Rolling (CR), and etc. (Fig. 2) [1, 2, 10, 13, 14].

High Temperature Thermomechanical Processing. The High-Temperature Thermomechanical processing (HTMP) of steel, involving the hot deformation of austenite followed by accelerate cooling, is aimed at improving the mechanical properties of an austenite due to the formation of a well-developed substructure (for example in the austenitic heat-resistant and corrosion resistant steels and alloys) and also at improving the mechanical properties of the products of austenite transformation (martensite, bainite, pearlite) due to hereditary influences on their morphological and substructural characteristics [2, 10, 14, 15]. Of considerable interest is information about the features of formation of the austenite structure and of its change under the conditions of hot deformation within the HTMP cycle since the substructure is the primary factor that determines the structure and therefore the whole set of mechanical properties of the products of the austenite transformation.

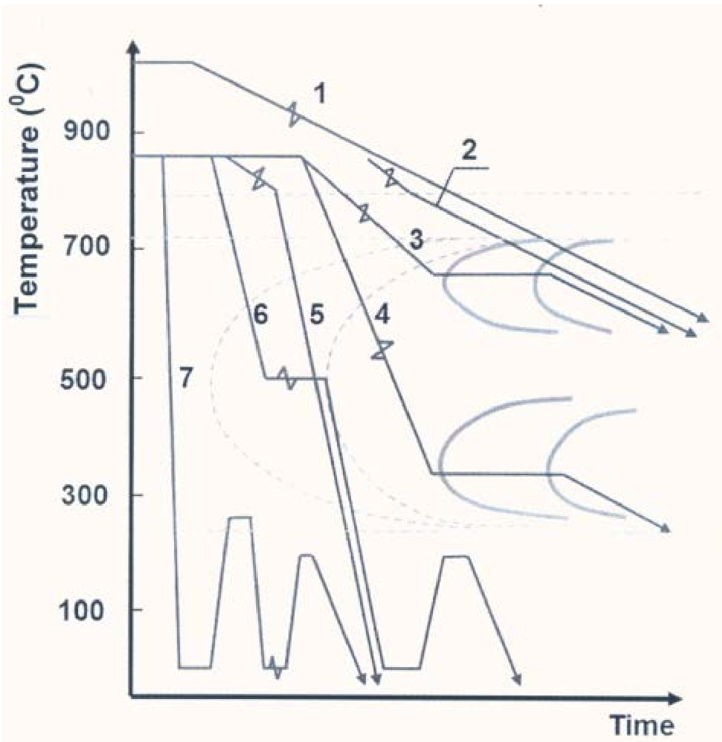

Fig. 2. The scheme of Thermomechanical Processing: 1 – hot rolling; 2 – Controlled Rolling; 3 – TMP with pearlitic transformation; 4 TMP with bainitic transformation; 5 – HTMP; 6 – Ausforming; 7 – Strain age-hardening of martensite.

Thermomechanical processing of steel plates. Most of the structural steel grades are flat products rolled on plate mills or hot strip mills. The application of microalloying elements since the 1960's mainly in combination with special rolling regimes developed first on plate mills enables a wide range of new economical, weldable, formable, tough and ductile high strength low alloy steel grades to be produced.

Last decades the considerable research efforts were directed toward the development of high strength low alloy (HSLA) steels [16-18]. The plates are used for structural applications such as buildings, bridges, ships, pressure vessels, tube and pipelines, and for automotive applications. In these cases the important mechanical properties are strength, ductility, and toughness at low temperatures, ductile-brittle transition temperature, and weldability. The basic difficulty is that these properties are often incompatible in HSLA steels. Later developed variants of CR with accelerated cooling make it possible to obtain a bainitic structure in some steels, which also inherits the mesostructure of hot-deformed austenite and, correspondingly, the positive effect due to this. Accelerated controlled cooling after hot rolling alters the microstructure of plate from ferrite-pearlite to fine grained ferrite-bainite and consequently increases the strength without a loss in low temperature toughness [19, 20]. The deleterious effect of precipitation hardening of Nb(C,N) or V(C,N) on impact toughness is counteracted by improved grain refinement.

The aims of recrystallization controlled rolling especially followed by accelerated cooling (RCR+ACC) are to produce hot rolled steel products having high strength, high toughness and good weldability. The concept of RCR+ACC is attractive in that it is a relatively uncomplicated and high productivity process and can be applied on conventional mills. This procedure is intrinsically more economical than controlled rolling at low finish rolling temperatures and also lends itself well to use in many mills which are not sufficiently strong for low temperature controlled rolling practice to produce heavy plates and long products. The key to success with recrystallization rolling is to define rolling schedules combining a maximum degree of microstructural refinement with acceptable low rolling loads, good shape control and high productivity.

Ausforming. Ausforming treatment is applied to the steel while it is in the metastable austenitic condition prior to quenching to martensite (Fig. 2). The principal benefit of this treatment is that it can produce significant improvements in strength without degrading toughness and ductility. In some steels, toughness is actually improved simultaneously with strength. The low temperature nature of this treatment produced very little thermal distortion, thus making it ideally suited for precision finishing operations. The Ausforming process can be directly substituted for groups of conventional finishing processes saving considerable cost while optimizing mechanical performance. The strengthening effect of Ausforming is attribute to the inheritance of the dislocation substructure and carbide distribution, generated in the metastable austenite during deformation, to the final martensite after quenching [13]. A fine dispersion of carbides is formed during the working of austenite, stabilization not only the grain size but the subgrain size as well [14]. Ausforming results in a very high dislocation density in the final martensite. The dislocation network produced is not the normal one where the dislocations are concentrated at the cell walls, rather they are more uniformly dispersed. Larger scale microstructure effects also play an important role in the strengthening process. The low temperature of working (in the range from room temperature to ~ 600°C depending on alloy composition tends to restrict austenite grain growth and hence, ultimately, the martensite plate size.

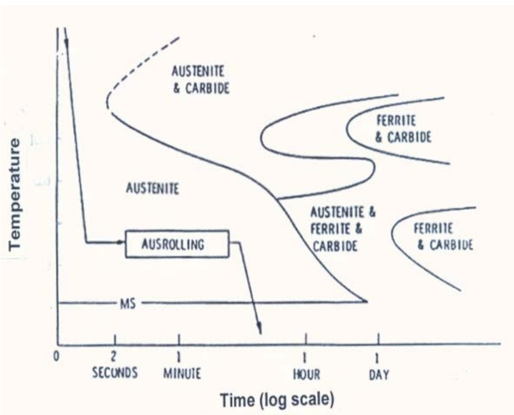

Fig. 3. Schematic illustration depicting ausrolling time-temperature regime quench from austenitizing temperature.

Ausforming steels can eliminate stage tempering which would have occurred during the tempering of conventionally quenched martensite. Thus, autotempering appears to be promote by ausforming. For surface ausforming, optimum tempering treatments are most likely not those used for conventionally developed martensite. The principal features of the apparatus for precision ausforming of gears are interactive forming utilizing closed-loop control and high accuracy forming die. Low temperature thermomechanical processing has considerable potential for the finishing of precision machine elements to net shape. In this process, the final dimensions and finish quality are achieved by thermomechanically working the carburized case of gear teeth while they are still in the metastable austenitic condition prior to quenching to martensite. The results of such processing methods are (1) the elimination of several manufacturing steps including grinding and hard finishing, (2) the generation and retention of surface compressive residual stresses, and (3) the achievement of strengthening in the surface layers subjected to the high operating stresses. The following benefits are derived from these effects: significantly lower manufacturing costs, greater yield strength, improved fracture resistance, greater pitting and bending fatigue strength, and greater product reliability and as a result resource-saving effect. The encouraging results from previous studies justifies additional research and development to refine and implement the technology and to extend it to be other machine elements such as bearings, splines, cams, roller, clutch surfaces and shafts.

Resource-saving technologies for TMP of rings, shafts and axles. One of the most advanced methods of producing precision billets is rolling that ensures the metal utilization coefficient on the level of 0,7-0,8, while the similar coefficient for conventional methods is on the level of 0,25-0,45. At present there are several varieties of this method, among them - radial rolling, face rolling and longitudinal rolling in idle rollers.

The realization of the given methods for plastic deformation under the conditions of the thermomechanical processing (TMP) gives a substantial increase of their application efficiency. In this case the parameter level increase of mechanical and functional properties is possible and it is determined as a result of the inheritance of the dislocation structure elements formed during the deformation process on the products transformation formed to the end of the TMP. The different TMP schemes developed for application to two rolling methods - radial- face rolling for producing annular billets including billets with Z-shaped profile. The rotating treatment taking place during the radial-face rolling provides reduction of the deformation stress due to local loading which in turn allows to apply deformation in rather a wide temperature interval and to receive high-precision billets. The possibility of temperature lowering till the warm temperature deformation creates preconditions for realization of special TMP due to the regulation of structure formation by the control of temperature-strain regime of the hot-warm deformation taking place very often without application the subsequent special cooling. On the basis of studies carried out for the rings, diameter from 150 to 700 mm, made of low alloyed steels with 0,4% C and others it were developed the basic principles of non-isothermal TMP of annular billets and realized as new resource-saving technologies. The regulation of cooling velocity was carried out by means of variation of water consumption or by water-air mixture prepared in special spraying device that provided cooling of rings of different profile sections according to predetermined regime (Fig. 4).

The deformation of middle-carbon steels in the temperature interval 1000-600°C under continuous air cooling with velocity from 10 to 1°C/s causes processes of partial cementite coagulation in the pearlite component, the formation of cellular and fragmented structure in ferrite with dislocation density inside of cells and fragments in the interval 10^9-10^{10} cm^{-2}. The temperature lowering in the end of the deformation causes gradual increase of defects of both structure components with some growth perlite portion component. Due to such type TMP it is possible to adjust mechanical and technological properties in the wide range.

The cold longitudinal rolling is one of the most advanced methods of producing parts of "axle" and "shaft" type. With the help of this method it is possible to produce parts from carbon steels as well as from alloyed steels, and besides quite recently the rolling of parts from heat resistant dispersion-hardened alloys of type 1%Cr, 65%Ni, 1%Mo, 1%Ti, 1%Al, 1%W was also applied. The list of parts includes parts beginning from force studs, whose diameter is 23,5 mm before treatment and length 322 mm to the waggon axles with diameter 200 mm and length - 1800 mm. The realization of producing steel parts according to scheme of Preliminary Thermomechanical Processing (PTMP) makes possible along with shaping to provide an increase of this or that property complex due to structure regulation by means of its level change of parameters with simultaneous reduction of product cost price (Fig. 5).

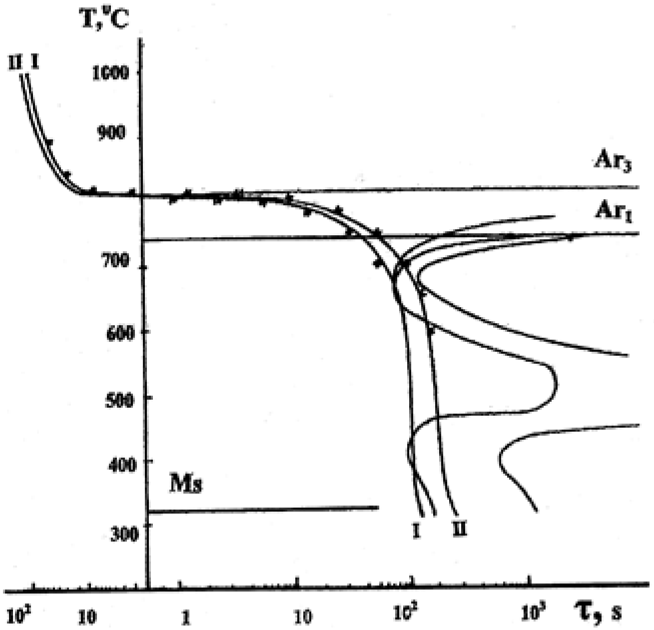

Fig. 4. Cooling and rolling curves of steel (0,38CCrSi) rings under the non-isothermal regimes with deformation in the range 900 - 700°C (I) and 800-600°C [12].

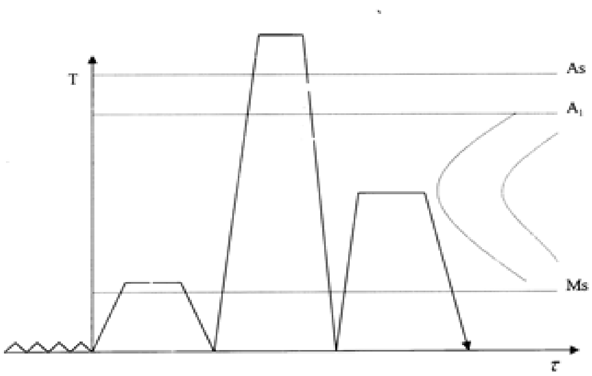

Fig. 5. The scheme of Prereliminary Thermomechanical Processing (PTMP).

Substructural strengthening result in PTMP, 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 in [6]. There were carried studies of the value influence of particular and total reductions, of the deformation fractionality and of the post-deformation heating temperature on structure, mechanical properties and cyclic durability of parts from steels 0,6%C, 2%Si, 1%Cr; and 0,45%C, 1%Cr, 2%Ni, 1%Mo, 1%V.

The rolling of initial billets with pretreatment annealing was applied on the mill "PR-100" with capacity 100t. The deformation was carried out for different number of particular reduction (ε_i=4-12%) under total degree ε_Σ=50%, ensuring the required technological plasticity and a given profile of the finished billet. As a result of studies carried out with the use of optic and electron microscopy it was established that the initial ferrite-perlite structure changes substantially under the influence of the plastic deformation. Ferrite locations prolong along the deformation direction, and electron microscopic studies shows ferrite fragmentation. In this case the cementite plates are breaked and bended (sometimes), but the main deformation taken place in the more mild and plastic ferrite matrix. The further studies were carried out on the cold-deformed billets with the following heating in the temperature interval 300-700°C. The temperature increase till 500°C causes the polygonization in the ferrite matrix before induction hardening followed by low temperature tempering and allows to realize the positive effect of TMP. The results of mechanical tests shows an increase of the level of plasticity characteristic and impact strength by 30-40% in comparison with non-deformed condition. Functional characteristics, evaluated by laboratory testing, correspond to 3-4 fold increase of requirements, imposed to similar parts.

4. Modelling of thermomechanical processing of steels and alloys

In the development of TMP mathematical, physical and numerical simulations have important roles to play. By using best current knowledge and modern facilities, these modelling techniques can enable the rapid and economic evaluation and prediction of TMP processes and applications. There are different techniques are used for the creation of the models described effect of the main process parameters to the structure and mechanical and functional properties. The most popular are: physical simulation based on the torsion (or compression), Experiment planning method (EPM); Finite element method (FEM) based model of structure development in metal forming processes. As for physical simulation of TMP there are different testing systems are developed including Setaram and Gleeble systems. As for advanced Gleeble 3800 there are four mobile convert units (MCU) that could be connected to main load unit: universal Pocket Jaw MCU for tension/compression uniaxis tests, torsion MCU for torsion tests; Hydrawedge MCU for high speed compression uniaxis tests; MaxStrain MCU for multiaxis deformation tests. All MCUs mentioned above could be used for multistage plastic deformation physical simulation. The development of the optimum TMP technology, which could provide the required structure including proper substructure and recrystallization ratio as well as dynamic recrystallization grain size, requires preliminary investigations by physical and numerical simulation. The properties of metals and alloys after TMP are determined by the special feature of the structure formed of two processes: strengthening and softening. The kinetics of these processes depends on the temperature-strain parameters of TMP. The kinetics are determines by the combined effect of parameters, i.e. multifactoral process. The conventional methods of the effect of TMP parameters examination, the main of which are deformation temperature (T_d, °C), the degree (ε, %), or the rate (ε, s^{-1}) of deformation, and the time elapsed from the end of deformation to the start of quenching (τ, s) are based on the variation of the factor with the remaining process parameters being constant. This greatly complicated the search for the optimum conditions. For this reason, EPM has been used on an increasing scale for the examination of the combined effect of the HTMP parameters on the structure and properties. The main problem in the development of TMP is the construction of the model which could be used to control the process, moreover to create mathematical model, which may be foundation for computer modelling. In the first stage, this includes the construction of polynomial models for various steels, alloys, and possibility, also of their typical groups. The second stage may consist of optimization in respect of the main optimization parameter. To achieve precise prediction control of product quality, the details of microstructural evolution occurring during to deformation and accelerate cooling and relationship between the TMP parameters, structure and mechanical properties is still somewhat complicated. In its present state it is not an everyday tool for the engineer. With a more user-friendly EPM and FEM will make a great important compared existing design method. Experiment planning method has proved to be a good tool for the definite relationship between TMP parameters and mechanical properties. Simulation of TMP for the definite cross-section of profile by FEM on the base of the data obtained by experiment planning method allowed to predict structure and mechanical properties and to develop computer modelling for the different cross-section of rolling profile [21]. Using the physical simulation of dynamic recrystallization it' possible estimate the microstructure evolution under TMP and to predict final properties as demonstrated in Ni-based super alloy [22]. The results of modelling of dynamic recrystallization in the manufacture of workpieces of complicated profile cross-section based on the physical and numerical simulation allow to optimize the technological process of plastic forming and reduce the development of technology costs. Simulation of HTMT for the definite cross-section of profile by Finite Element Method (FEM) on the base of the data obtained by physical simulation and EPM allowed to predict structure and mechanical properties and to develop computer modelling for the different cross-section of rolling profile.

5. Conclusions

Thermomechanical Processing using a variety of plastic forming methods based on the understanding of physical fundamentals is a progressive resource-saving technique to produce metal billets and parts with the high level of structural strength and functional properties applying to different type steels and alloys. By using best current knowledge and modern facilities, numerical and physical simulation techniques can enable the rapid and economic evaluation prediction and control of TMP processes.

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