THERMOMECHANICAL PROCESSING OF STEELS & ALLOYS AS AN ADVANCED RESOURCE SAVING TECHNIQUE

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Abstract

The different schemes of resource-saving Thermomechanical Processing (TMP) based on the hot, hot-warm and cold deformation applied to various steels and alloys including sheets, bars and parts production are described. Structural and phase transformations in the course of TMP and their role in formation of structure and mechanical properties in the different cross section shape of billets and parts are presented. The basic physical principles of non-isothermal TMP as a base for developing of new resource-saving technologies of metal products manufacturing and examples of industrial application are demonstrated. Different TMP schemes developed for application to two rolling methods - radial face rolling for producing annular billets including billets with Z-shaped profile and longitudinal rolling for producing cylindrical billets with variable sections of profile, for stepped shafts. Physical simulation to control structure and mechanical properties of TMP treated products are presented.

Keywords: Thermomechanical Processing, steels, resource-saving technologies

1. INTRODUCTION

Improvement of the quality of metal goods is one of the most important problems of each industrially developed country. The ways of solving this problem are the creation and the use of effective technological processes based upon the recent achievements of science. When applied to metals and alloys, such effective processes are realized in different schemes of combined treatment enabling to improve operating capacities of these materials using deliberate change of their structure and phase composition. At the present stage of development of the physics of metals, all this permits to look upon deformation not only as a process of changing the shape, but also as a powerful method of influencing the fine structure, the phase composition and, consequently, the structural-sensitive properties of metals and alloys determined their functional properties.

Last time, the modern metal forming methods are using not only as a shaping billets geometry method, but for provide the definite structure and phase composition of the billets and finished parts. This is especially true in regard to the Thermomechanical Processing (TMP) such as controlled rolling (forging), high temperature thermomechanical processing and others [1-3]. Improvements of mechanical and functional properties, simultaneously strength and toughness, plasticity, and low cost processing of the different types of steels are the most important subjects for TMP. The majority of industrial plastic deformation formation processes (rolling, forging and etc.) use non-isothermal methods with continuous cooling by the accumulation of deformation and post deformation time to room temperature. Optimization of the TMP invites investigations of the structural-mechanical behavior under non-isothermal conditions and to develop resource-saving technology and proper equipment to manufacture different metal billets and parts. This paper concerned with result of such investigations, applied to the different classes carbon and alloying austenitic and pearlitic steels and the application of the non-isothermal processing especially in industry. The recent ideas of the physics of plastic deformation had been taken into account for interpretation of structure formation during thermomechanical processing (TMP) of steels [4, 5].

2. CLASSIFICATION OF TMP METHODS

By now there are many schemes of TMP are developed up to days. The most important of which: High Temperature Thermomechanical Processing (HTMP), Low Temperature Thermomechanical Processing (Ausforming), Controlled Rolling and etc. (**Figure 1**) [1-3, 6].

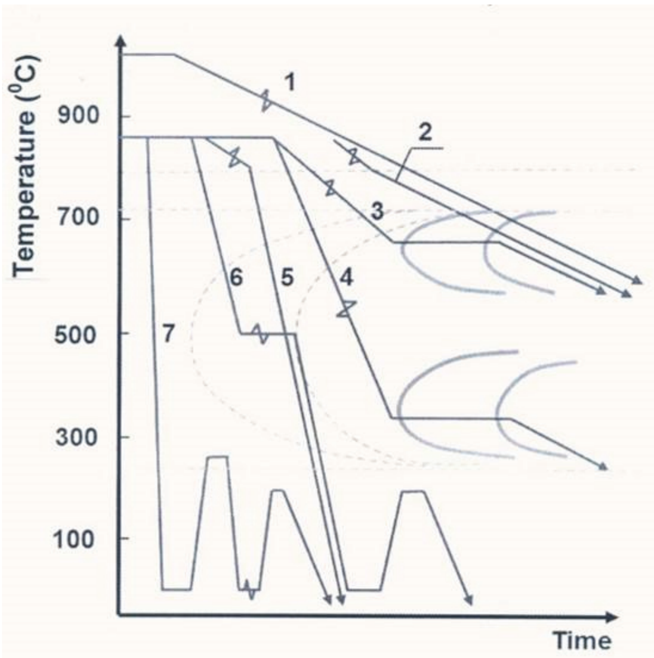

Figure 1 The scheme of Thermomechanical Processing: 1 - hot rolling; 2 - Controlled Rolling; 3 - TMP with pearlitic transformation; 4 TMP with bainitic transformation; 5 - HTMP; 6 - Ausforming; 7 - strain age-hardening of martensite

2.1. High Temperature Thermomechanical Processing

The High-Temperature Thermomechanical processing (HTMP) of steel, involving the hot deformation of austenite and its subsequent cooling, is aimed at improving the mechanical properties of an austenite due to the formation of a well-developed substructure (for example in heat-resistant and corrosion resistant steels) 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, 5, 6]. 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.

One of the most important processes in structure formation as a result of HTMP is recrystallization, which includes dynamic recrystallization occurring during plastic deformation and static recrystallization which takes place in the holding period (elapsed time) prior to quenching.

In developing HTMP schedules it is important to obtain a quantitative estimate of the development of recrystallization for various values of the main treatment parameters. In view of the fact that HTMP schedules are in many respects dependent on the characteristics of a given rolling mill (permissible loading of the plant, distance from the rolling mill to the quenching installation, etc.). In the author's view it would be most useful for the development of HTMP technology to have a special recrystallization diagram type which takes account of the fraction of recrystallized structure (%) vs major HTMP parameters. **Figure 2** shows proposed recrystallization diagram which can be used to determine the fraction of recrystallization, *R* depending on deformation temperature, strain degree (rolling reduction), and elapsed time between the end of rolling and start of quenching. Comparison of the experimental results with those of earlier investigations shows that the recrystallization of austenite follows a similar general pattern during HTMP of various steels [1-3]. Both pearlitic and austenitic steels have a temperature-deformation-time zone where no visible recrystallization occurs, a second zone where recrystallization starts to develop, and a third in which the structure is fully recrystallized.

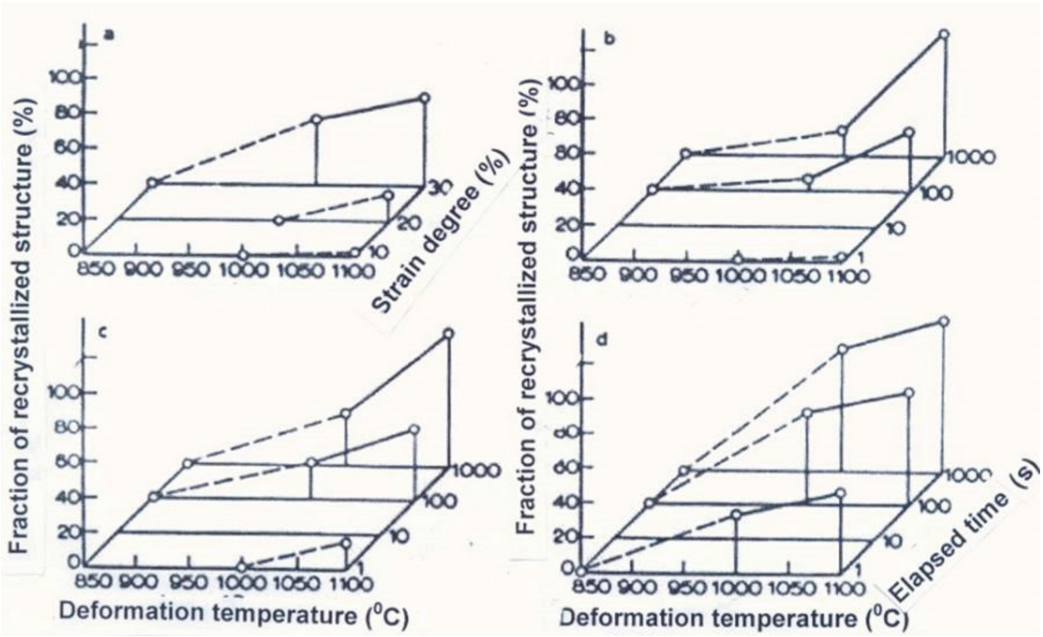

Figure 2 Recrystallization diagrams for AISI 321 type steel during rolling in HTMP conditions

The boundaries of these zones in austenitic steels are, however, displaced considerably towards longer elapsed times. As the temperature and strain degree increases, these zone shift, in both types of steel, towards shorter elapsed times. Tensile test result showed that the kinetics of change in the mechanical properties correspond generally to the recrystallization kinetics. A softening process was, however, observed during HTMP in the case. There is a continuous decrease in yield strength (without an incubation period) with increasing deformation temperature and post-deformation holding time. At 850 °C, with a strain (reduction) of 30 % in particular, the tensile properties were found to decrease with increasing post-deformation holding and no recrystallization was observed in this instance (**Figure 2**), thereby indicating the onset of recovery phenomena in the pre-recrystallization stage of softening. This is also confirmed by the temperature dependence of the yield strength from which it is clear that, in HTMP with immediate quenching, there is a continuous decrease in the yield strength with increasing deformation temperature. The rate of softening increases with the shift towards higher rolling reductions, which corresponds to a shift towards the stage of developing recrystallization processes and shows that they have a greater influence on mechanical properties than recovery.

With the aid of the recrystallization diagram described here, it is therefore possible to control the structural state of the steel during deformation in HTMP conditions.

2.2. Low Temperature Thermomechanical Processing (Ausforming)

Ausforming treatment is applied to the steel while it is in the metastable austenitic condition prior to quenching to martensite (**Figure 3**). 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 [8, 9]. A fine dispersion of carbides is formed during the working of austenite, stabilization not only the grain size but the subgrain size as well. 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.

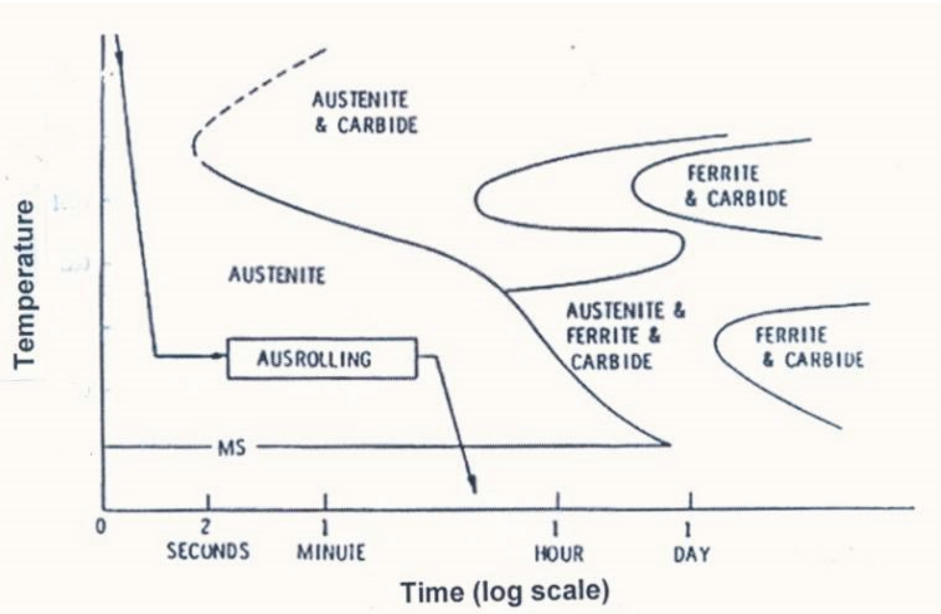

Figure 3 Schematic illustration depicting ausrolling time-temperature regime quench from austenitizing temperature [9]

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 ausform 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.

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.

2.3. Advanced methods of TMP

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 the inheritance of elements formed during the deformation process of the dislocation structure and by their influence on the product transformation formed to the end of the TMP [7].

Different TMP schemes developed for application to two rolling methods - radial face rolling for producing annular billets including billets with Z-shaped profile, and longitudinal rolling for producing cylindrical billets with variable sections of profile, for stepped shafts.

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 created preconditions for realization of the TMP effect, not only according to the high temperature thermomechanical processing (HTMP) but due to the regulation of structure formation in the regime of the hot-warm deformation taking place very often without application the subsequent special cooling.

As a result, the basic principles of non-isothermal TMP of annular billets were formulated and they were assumed as a base for developing of new resource-saving technologies. The regulation of cooling rate 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.

By means of transmission electron microscopy and X-rayed structural analysis it was established that the perlite and martensite structure of constructional steels forming during the non-isothermic TMP reveals distinctive signs of hot-deformed austenite with the finishing of deformation in the perlite transformation interval. It was discovered that the carbon content redistribution has great influence on strength of thermo-strengthened steels, and structure fragmentation has influence on resistance to cracking. 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 type “axle” and “shaft”. 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 was also applied. The list of parts includes parts beginning from force studs, whose diameter is 23 mm before treatment and length 322 mm to the wagon axles with diameter 200 mm and length - 188 mm. The realization of producing steel parts according to scheme of the 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.

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 0.4 % C, 1 % Cr, 2 % Ni, 1 % Mo, 1 % V .

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 TEM studies shows ferrite fragmentation. In this case the cementite plates are banded, but the main deformation takes 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. In case of post-deformation heating in the temperature interval 300 - 400 °C substantial structure changes were not discovered.

The temperature increase till 500 °C causes the polygonization in the ferrite matrix. The next operation of Preliminary Thermomechanical Processing (PTMP), the high-frequency current hardening (HFCH) was applied to the billets deformed with ε_i = 4 % and with the post-deformation heating at 500 °C, as the most suitable heating for realization of PTMP effect - to polygonized state. The result 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 [7].

The advanced resource-saving TMP technologies and specialized equipment, i.e. robotic complex and flexible manufacturing systems (FMS) for producing annular billets, parts of type “axle” and “shaft” by means of TMP with the use of rolling processes were developed and put into practice on the basis of the above described studies. The TMP schemes developed for application to 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 TMP, but due to the regulation of structure formation in the 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. As a result, the basic principles of non-isothermal TMP of annular billets were formulated and they were assumed as a base for developing of new resource-saving technologies.

Using the physical simulation of dynamic recrystallization, estimate the microstructure evolution under TMP and to predict final properties [10, 11].

The results of modeling of dynamic recrystallization in the manufacture of workpieces of complicated profile cross-section allow to optimize the technological process of plastic forming and drastically reduce the development of technology costs.

3. CONCLUSION

Thermomechanical Processing using a variety of plastic forming methods is a progressive resource-saving technique to produce metal billets and parts and has a great potential to improve structural strength and functional properties.

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