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PHYSICAL SIMULATION OF PRECIPITATION HARDENED FERRITE-PEARLITE STEELS DURING HOT DEFORMATION PROCESSING

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Abstract. Simulation processes of static and dynamic recrystallisation were carried out with Gleeble 3800 System. The resulting data form the basis of a statistical database, linking chemical composition - processing parameters – structure – mechanical properties, which will form the base of the mathematical models of the evolution of the microstructure of the steels subjected to the experiment.

1. Introduction

The companies of the bulk metal forming industry are facing a high competition from other companies of alternative processes industry. Thereby the excellence of metal bulk forming industry is the production of reliable highly stressed parts, which are essential to the automotive Industry in particular.

Under the aspect of economic and ecologic optimization of processes, lightweight is an important factor in a process designed to reduce costs. Here on the one hand, parts are optimized in terms of their structure, so material can be saved without a loss of quality or structural stability of the produced parts. On the other hand, the development of new materials plays a vital role in reducing costs or optimizing parts in terms of their load capacity. While the development of completely new materials, for example carbon fibre reinforced materials, can be successfully integrated in some applications, the classic steel is still essential, especially to bulk metal formed parts like in example for the automotive industry. For many technical applications steel is the most important material, which is well known with his characteristics and object of many studies. Moreover, the steel material properties can be changed by adding alloying elements, changing their composition or even by a heat treatment. The important advantages of steel in comparison with other materials are the cost efficient production and the recyclability, which make it a sustainable material [2-6].

As steel is the most important material in the forging industry, it has a big spectrum of different groups. For example, dependent on its different applications, the material is subdivided in groups like case-hardening steels, quenched and tempered steels or stainless steels (Fig. 1).

One of the important groups, which is developed and investigated in the early 70´s are precipitation-hardening ferrite-pearlite steels. This group of steels was developed as a counterpart to the quenched and tempered steels in terms of more cost-efficient production. It has characteristically an alloying amount of 0.1-0.4 % vanadium, which is responsible for the excellent mechanical properties of this steel. Within a hot forging process and by temperature over the austenitic transformation temperature, the vanadium is completely dissolved in the austenitic structure of the steel. After the forging cycle, this steel is typically cooled in air, where its changes into the ferritic or temperature depended into the ferritic-pearlitic microstructure. With this microstructure the vanadium has significantly lower solubility. This effect is used in the precipitation-hardening ferritic-pearlitic steels to achieve the excellent mechanical strengths. While cooling and changing the microstructure from austenite into ferrite-pearlite, a precipitation-hardening occurs, in which the vanadium connects with carbon and thus carbides are created. These carbides, which have sizes of just a few nanometers, are homogeneously distributed within the material and increase its hardening. Due to this effect, Steel with high mechanical strength can be produced without the need for expensive hardening and tempering processes. Furthermore the typical quenching process is also substituted to avoid undesired material failures like micro-cracks, which saves costs of expensive component testing.

One of the common used precipitation-hardening steels, which was in focus of many investigations in the recent years, is the 38MnVS6 (1.5231) with an alloying amount of 0.1 % vanadium. Within the group of precipitation-hardening steels, this material with its different versions has the highest hardness, a good nitridability with a high notched bar impact work, which decreases its lower strength. In the lower strength area, within this group of steels, the StE 460 (1.8824) is a commonly used steel which is developed to ensure a good weldability [1-4, 7].

The group of the precipitation-hardening steels is still in focus of actual investigations and shows a high potential for improvements. Different studies investigate further micro-alloying elements, like nobium and titanium, and their influence on the microstructure and the mechanical properties of the steel.

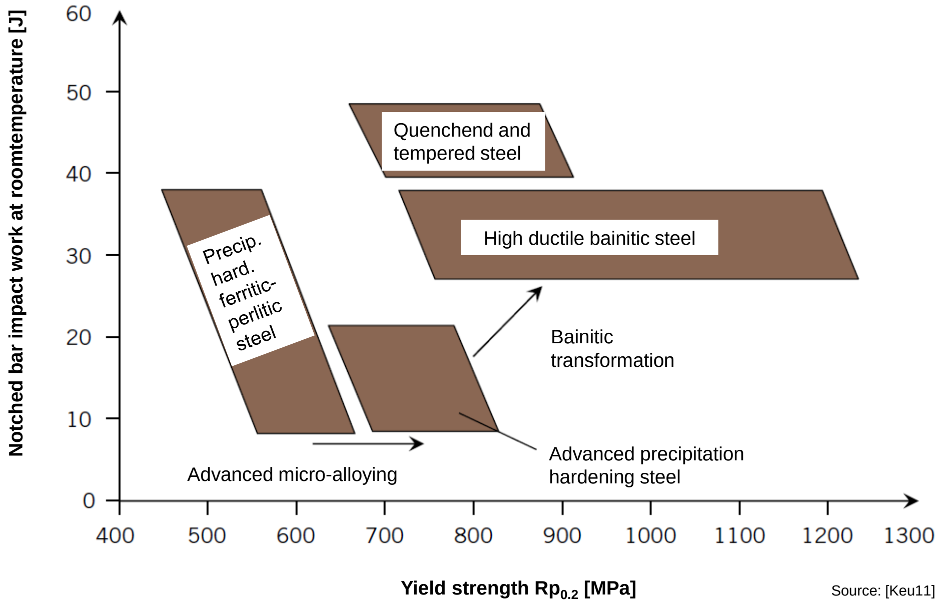

Fig. 1. Ratio of strength and toughness for some steels.

The calculations of economists show that the use of processing modes, eliminating the need for heat treatment would provide significant energy savings, equipment and human resources. In addition to reducing the energy intensity of the use of these materials will reduce warped parts, surface decarbonisation and improve environmental production standards. However, development of the technology of controlled forging or rolling of steel to provide the desired level of mechanical properties in the resulting product requires mathematical models to predict the properties of materials, depending on the mode of treatment.

The last 20 years in the advanced industrial countries have been developing and put into practice large-scale production technology of prediction and control of the structure and mechanical properties of materials in the processes of plastic and heat treatment. These technologies are based on the use of integrated mathematical models that include a set of models for quantitative changes in temperature of the material deformation, the evolution of the microstructure of austenite, the austenite decomposition during continuous cooling to form a variety of products, as well as a model for the calculation of mechanical properties. The development of such models and their implementing computer programs is a challenge that can be successfully solved only through close cooperation of various specialists – Metall-physicists, metallurgists, engineers, programmers, and others. Development of a set of physically-based mathematical models of the evolution of the microstructure of steel is an important step in creating a modern "through" model of steel production.

Creation of a quantitative model to describe the formation of the structure of these steels in the practically significant temperature range of deformation of austenite requires development of three sub-models of interacting processes. The first of these processes is actually austenite recrystallisation, which modeling suggests the description of the nucleation and growth of the recrystallised grains. The second important task is a return which will result insignificant changes of the average density of dislocations created by plastic deformation and, accordingly, the force of recrystallisation. The third important process is the selection of particles of carbonitrides of microalloying elements induced by plastic deformation, as the process in these steels has a significant impact on the kinetics of the return, and recrystallisation.

Isolation of carbonitrides at deformed austenite dislocations is one of the important processes which controls the formation of the structure of micro-alloyed steels in the process of hot rolling. This process occurs when the temperature drops below the rental solvus temperature of the corresponding carbonitride and its isolation becomes energetically favourable. Usually the formation of particles of this kind has a strong influence on the static recrystallisation of the deformed austenite due to the deceleration of growth of recrystallised grains (until it stops), which is caused by the interaction of the particles and moving boundaries (pinning borders).As a result of practical importance of the isolation induced by the deformation of carbonitrides, a great number of scientific works are devoted to its experimental studies and mathematical modelling [8-16].

The isolation of carbonitrid particles induced by the deformation occurs in the resulting dislocational network points. Moving boundaries of there crystallised grains absorb dislocations as a result reducing the number of places of origin of the particles. Consequently, the resulting particles inhibit the movement of the new grain boundaries and reduce the rate of recrystallisation. In addition, there is a mechanism for acceleration of boundary movement connected with a decrease in their solid-inhibition with decreasing concentration of atoms of alloying elements in solid solution.

The aim of this work is the improvement and development of new technologies of hot plastic processing precipitation-hardened ferrite-pearlite steels based on the physically justified models of the evolution of the microstructure.

2. Physical Modelling

All experimental studies on physical modelling of static and dynamic recrystallisation were performed on a testing complex Gleeble-3800 System, which is able to carry out physical modelling of most processes of thermomechanical processing of materials. In this paper, for the experiments a circuit module Hydrawedge deformation “Flow Stress” was used (Fig. 2). This experiment presents a deformation of a uniaxial compressive strain between two flat dies. The experimental procedure involves using cylindrical samples with a ratio of height to diameter of the sample 1.5.

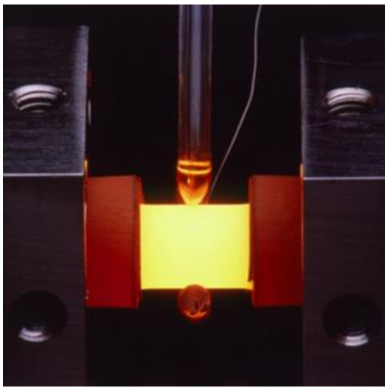

Fig. 2. Sample during the test under the scheme “Flow Stress”.

To protect the samples heated to high temperatures from surface oxidation tests were carried out in a vacuum, and to eliminate the samples welding to strikers during the deformation there were used molybdenum foil gaskets.

Tests were conducted at temperatures of 1200 °C, 1100 °C, 1000 °C and 900 °C. More detailed studies at low temperatures are connected with the complex shape of the respective curves which, in turn, is connected with the effect of inhibition of the static recrystallization of particles by the emitted carbonitrides of micro-alloying elements (strain-induced precipitation of carbonitrides).

The study was carried out in dynamic recrystallization deformation speeds range from 0.5 to 10 s^{-1}. Theexample of the plastic flow curve obtained for the steel at 1200 °C and at different strain rates is shown in Fig. 3.

Fig. 4 illustrates the method of calculating the share of dynamically recrystallized metal. In the technique the resulting flow stress (depending on the temperature, the value of plastic deformation, its velocity and chemical composition of the steel) is represented as:

$$\sigma = \sigma_e - \Delta\sigma, \quad (1)$$

where σ_e – hardening of the material, with the contribution of dynamic recovery taken into account; $\Delta\sigma$ – contribution to the relaxation of stresses caused by dynamic recrystallization.

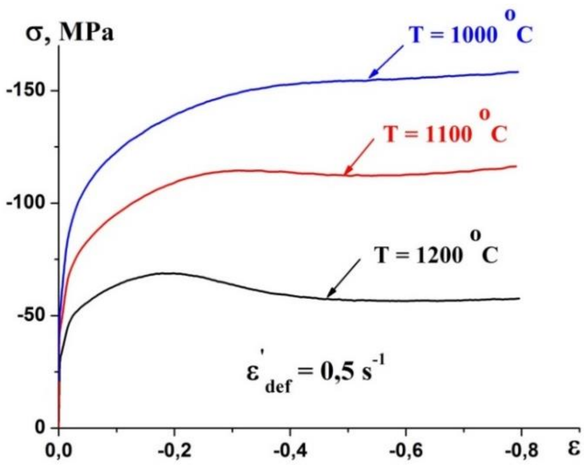

Fig. 3. Theexample of plastic flow curves obtained in experiments on dynamic recrystallization.

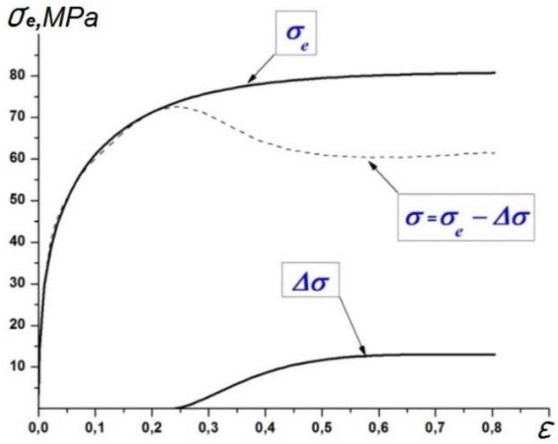

Fig. 4. Illustration of the changes of simulated deposits into the voltage of the plastic flow with increasing strain.

Formula used to calculate the share of dynamically recrystallized material:

$$F_{DRX} = 1 - \exp\left[-k\left(\frac{\varepsilon - \alpha\varepsilon_p}{\varepsilon_p} \right)^{m'} \right], \tag{2}$$

where α; k; m' – the parameters of the model.

The example of the curve of the plastic flow resulting from tests on a double loading of the steel at a temperature of 1200 ° C and a strain rate of 1 s-1 is shown in Fig. 5, where it is possible to trace how the induced strain hardening is reduced due to the processes of return and recrystallization due to a 20 c pause between strains.

The proportion of the relaxed (or statically recrystallized) material F_x can be quantitatively calculated using the formula:

$$F_x = \frac{\sigma_m - \sigma_2}{\sigma_m - \sigma_1}, \tag{3}$$

where σ_m – the pressure of the deformation of a material before its first loading directly before unloading; σ_1 and σ_2 – the voltage corresponding to the full (yield limit at the first loading) and partial recrystallization of the material.

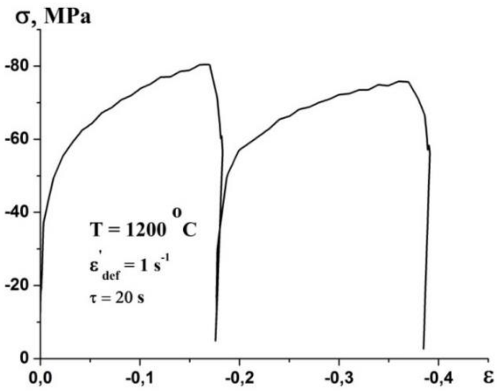

Fig. 5. Theexample of the plastic flow curve obtained for the steel in the experiments with double loading.

Figure 6 illustrates a procedure of calculating the proportion of the relaxed material with the help of formula (3).

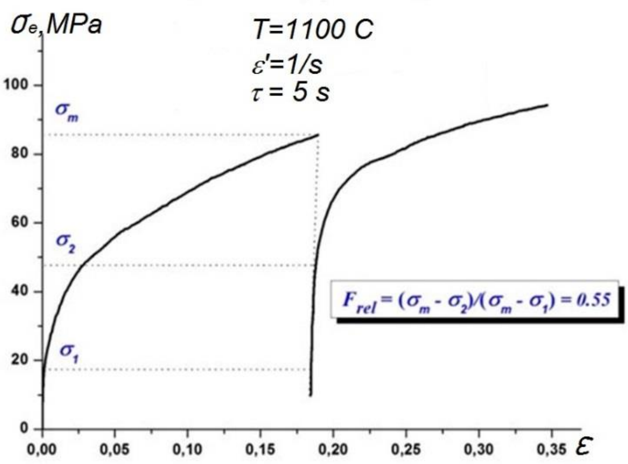

Fig. 6. Illustration of the procedure of calculating the proportion of the relaxed material for one of the experiments on double loading.

Relaxation during the pause between the deformation occurs due to the processes of the return and static recrystallization. To determine the proportion of relaxation, taking place during each of these processes, a method for calculating the share of the recrystallized material, based on the method of "backward extrapolation" was used. In this method, it is assumed that after a small deformation (about 3÷5 %) a plastic flow curve after unloading coincides with the curve of fully annealed material. The value of the voltage is determined by the intersection of the line of the unloading with the curve obtained by the superposition of the curve in the current preliminary flow on the curve after the discharge (Fig. 7).

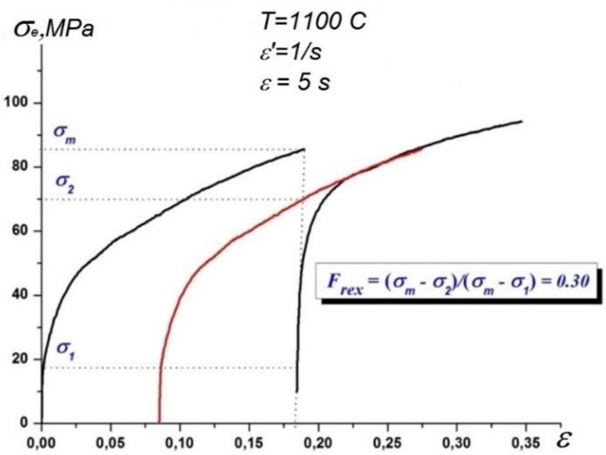

Fig. 7. Illustration of the procedure of calculating the share of statically recrystallized material using the method of the "backward extrapolation" in one of the experiments on double loading of the steel.

3. Conclusions

Simulation processes of static and dynamic recrystallization were carried out with Gleeble 3800 System. The resulting data form the basis of a statistical database, linking chemical composition – processing parameters – structure – mechanical properties, which will form the base of the mathematical models of the evolution of the microstructure of the steels subjected to the experiment.

References

[1] G. Akerstrom, H. Ravenshorst, S. Gunnarson // *Materials & Design* **12 (1)** (1991) 33.
[2] B.-A. Behrens, W. Bleck, Fr.-W. Bach, E. Brinksmeier, U. Fritsching, M. Liewald, H.-W. Zoch // *Key Engineering Materials* **504-506** (2012) 151.
[3] Industrieverband Massivumformung, Info Extra, New steels for bulk metal forming, Info Reihe Massivumformung, March 2012.
[4] E. Hajyheydari, M. Liewald, A. Felde // *Schmiede Journal* **9** (2012) 105.
[5] C. Keul, L. Mosecker, W. Bleck, T. Rekersdrees, A. Stüber, H. Schliephake, C. Beyer, H.-W. Raedt, In: *Proceeding of the 3rd International SCT Conference Steels for Cars and Trucks* (Austria, Salzburg, June 5-9, 2011).
[6] H.-W. Raedt // *Konstruktion* **4** (2005).
[7] N. Exel, H. Kaufmann // In: *Proceeding of the 3rd International SCT Conference Steels for Cars and Trucks* (Austria, Salzburg, June 5-9, 2011).
[8] H.J. Kestenbach // *Mater. Sci. Technol.* **13** (1997) 731.
[9] R. Kampmann, R. Wagner, In: *Decomposition of Alloys: The Early Stages* (Pergamon Press., Oxford, 1994), p. 91.
[10] R. Kampmann // *Physica Status Solidi A* **172** (1992) 295.
[11] A. Deschamps, Y. Brechet // *Acta Materialia* **47** (1999) 293.
[12] B. Dutta, E.J. Palmiere, C.M. Sellars // *Acta Materialia* **49** (2001) 785.
[13] M. Volmer, A. Weber // *Zeitschrift für Physikalische Chemie* **119** (1926) 277.
[14] H.S. Zurob, Y. Brechet, G. Purdy // *Acta Materialia* **49** (2001) 4183.
[15] H.S. Zurob, C.R. Hutchison, Y. Brechet, G. Purdy // *Acta Materialia* **50** (2002) 3075.
[16] H.S. Zurob, S.V. Subramanian, G. Purdy, C.R. Hutchison, Y. Brechet // *ISIJ Internationsl* **45 (5)** (2005) 713.