SIMULATION OF DYNAMIC RECRYSTALLIZATION OF STEELS AND ALLOYS DURING ROLLING AND FORGING THROUGH THE USE OF FEM AND EXPERIMENTAL PLANNING METHODS

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Abstract

The evolution of the new microstructures produced under hot deformation conditions is reviewed. The Finite Element Method (FEM) and Experimental Planning Method (EPM) has been used for the examination of the combined effect of the temperature-strain-time parameters of structural and stainless steels during rolling and forging metal forming technique. It is shown that simulation of recrystallization for the definite cross-section of profile by FEM on the base of the data obtained by EPM allowed to predict structure and mechanical properties and to develop computer modelling for the different cross-section of finished profile.

Keywords: Simulation, recrystallization, rolling, forging, steels, experimental planning method (EPM), finite element method (FEM), mechanical properties

1. INTRODUCTION

The main aim of computer modelling and simulation is to contribute to making better products cheaper and/or faster. The hot metal forming processes, including High Temperature Thermomechanical Processing (HTMP), are aimed at shape formation and also at improving the mechanical properties. The last ones result in the formation of the products of hot deformed austenite transformation to martensite, bainite or pearlite due to hereditary influences on their morphological and substructural characteristics [1-3]. As for industrial conditions of hot deformation it is difficult to prevent start of recrystallization processes because of different reasons (temperature and strain rate changing, layout of deformation and cooling equipment and etc.).The mechanical and some functional properties of metals and alloys result in hot deformation and HTMP are determined by the special feature of the structure formed of two competitive processes: strengthening (work hardening) and softening (dynamic and meta-dynamic recrystallization) [1,2,4]. The kinetics of these processes depends on the temperature-strain parameters and determined by the combined effect of the last ones, i.e. HTMP is a multiple-factor process. To achieve precise prediction control of product quality, the details of microstructural evolution occurring during hot deformation and cooling should be illustrated in the model. The past decade has involved a number of investigators developing mathematical models to predict the final structure and mechanical properties of hot deformed steels. Most of these are based on models proposed by Sellars and cowokers [5]. The physical models developed by different groups, e.g. Corus, VAI, differ in detail in the form of relationships used in each physical sub-model, but essentially they operate in the same way to compute the evolution of microstructure [6-8]. The conventional methods of the effect of hot deformation and HTMP parameters examination, the main of which are deformation temperature (T_d,^{0}C), strain (e), strain rate($\dot{e}$, s^{-1}), 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 optimal conditions. EPM has proved to be a good tool for the definite relationship between hot deformation (including HTMP) parameters and mechanical properties [9]. For this reason, EPM has been used for the examination of the combined effect of the mentioned above parameters on the structure and mechanical properties. The main problem in the development of HTMP is the construction of the regression model which could be used to control the process, moreover to create mathematical model, which may be foundation for computer modelling. It is important to obtain a quantitative estimation of the development of recrystallization (dynamic and meta-dynamic) for various values of the main processing parameters. In view of the fact that hot deformation and HTMP schedules are many respects dependent on the characteristics of a given rolling mill (permissible loading of the mill stand, distance from the rolling mill to the quenching installation, etc.), it seems necessary to use diagrams enabling a quantitative evaluation of the development of recrystallization to be made in relation to major process parameters. Simulation of hot deformation and HTMP 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.

2. EXPERIMENTAL PLANNING METHOD

The experiments has been realized into the above mentioned hot deformation parameters during continuously air cooling applied austenitic stainless steel AISI321. The optimization parameters (target functions) were represented by the fraction of recrystallized structure (R, %) and yield strength (YS, MPa). The level of the factors variations were selected on the basis of the actual possibilities of the process realization. Experiment of type 3^3 was realized. All the 22x22 mm section billets were heated in electric furnace prior to rolling to 1100°C. Some of samples had been deformed at 1100°C and the remainder had been rolled after air cooling to 1000 and 850°C. The rolling reductions used were 10, 20, and 30% and times between the end of rolling and start of quenching were 1, 100, and 1000 s. Curves plotting the distribution of the fraction (%) of recrystallized grains were derived for each specimen and had been used to estimate the average size of the fraction. **Figure 1** shows recrystallization diagram which can be used to determine the fraction of recrystallization, R in relation to rolling temperature (**t** roll), strain (rolling reduction,ε,%), and time between the end of rolling and start of the accelerate cooling (τ, s).

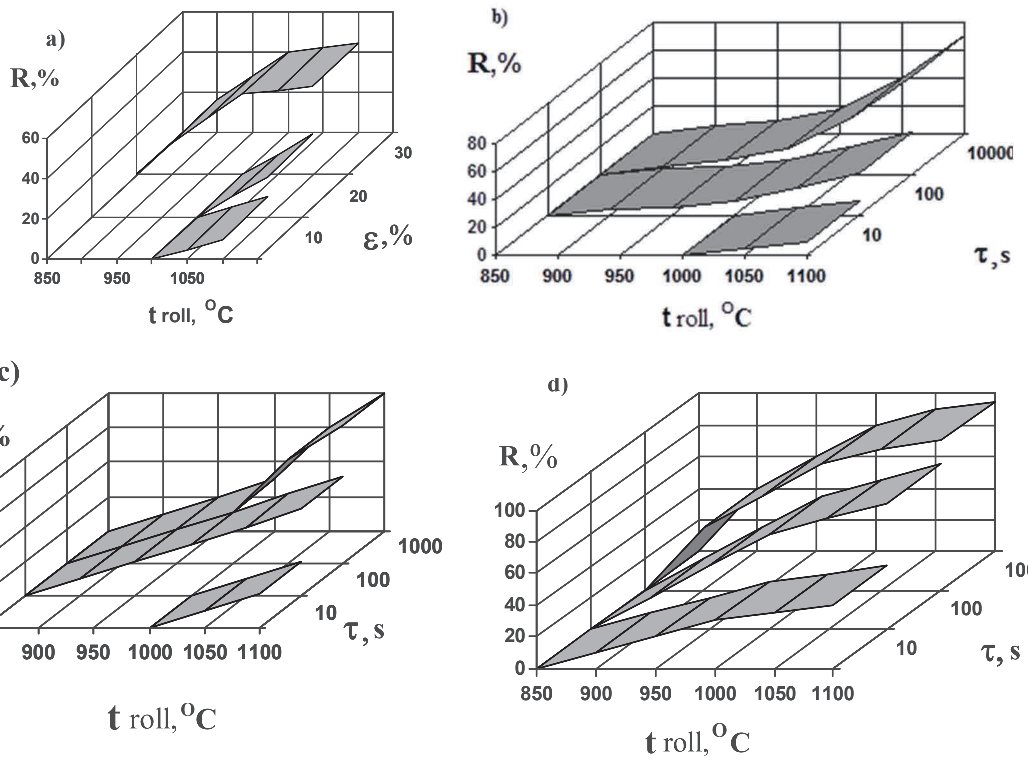


Figure 1 Recrystallization diagrams for AISI321 steel under hot deformation conditions:
a) τ=1s; b) ε=10%; c) ε=20%; d) ε=30%

It can be seen from **Figure 1** that dynamic recrystallization (τ=1 s) occurs only at the deformation temperatures > 1000 °C with the reduction >20 %. During the deformation temperature of 850°C, no recrystallized grains were observed in any of the specimens studied. As a result of the data processing regression equations describing the dependence of the yield strength (YS) and R on the hot deformation parameters were obtained for the experimental material and given region of the factorial space. The recrystallization's degree and yield strength - Td, ε, τ relationship were obtained by accounting of experimental planning method.

$$R = 24.3 + 14.3X + 24.0Y + 13.3Z + 15.2XY + 8.4YZ - 5.25Y^2 - 4.0XYZ - 3.75XY^2Z + 2.6Z^2 \quad (1)$$

$$YS = 319 - 22.0X - 47Y + 20.0Z + 6.0XY - 15YZ - 6.0YZ^2 + 4.0Y^2Z, \quad (2)$$

where $X = 2/3\lg\tau$; $Y = 0.01Td - 10$; $Y^2 = 293 - 0.6Td + 0.0003Td^2$;

$Z = 0.01\varepsilon - 2$; $Z^2 = 10 - 1.2\varepsilon + 0.003\varepsilon^2$.

From (1), and (2) we notice that the regression equations which describe the effect of HTMP parameters on the R and YS are quadratic. Besides the regression equations also contain several significant terms which take into account the paired interactions. The statistical models (1), and (2) give possibility to fit such relationship between parameters Td, ε and τ in the solution of the problem of quality control that will be provide required level of R and respectively mechanical properties, in particular YS= f (R). In order to use the performed laboratory experiment results which were carried out with the 22x22 mm prior to deformation section billets for the plates or profiles of other cross-section shape with various thickness of the same steels type it is required to complement the (1), and (2) statistic models which describe the thermal operations conditions of required steel plates thickness. As is evident from the equation (1), in the examined range of the factorial space, corresponded to the real industrial conditions, the most significant factor is deformation temperature and cooling time until quenching paired interaction. From physical point of view this interaction is determine by the quenched temperature. It is necessary to follow conditions of physical similarity of laboratory and industrial processes for applying results of laboratory investigations of the dependences of recrystallizations fraction, yield strength and other characteristics from deformation temperature, reduction, quenched temperature applying to the kind of hot deformation and HTMP. Physical simulation has been provided by corresponding thermo-physical and deformation characteristics of processes. Thermo-physical process modelling has been achieved by solving of unsteady heat transfer differential equation with boundary conditions of the third mode with given heat change surface condition of the sample or workpiece (metal sheet or other profile). When the heat transfer task is solved and temperature in every point of cross-section of the profile at every required moments of time is known we transfer the results of laboratory studies to industrial workpiece. For transferring of the results of laboratory investigations to real object it is necessary to simulate process of deformation. It has been achieved by solving of plastic flow task for definite cross-section of profile or forge piece. The form changing process from initial to final profile is followed during solvation. In every spot (in each node of finite element) at every moment the components of deformation, stresses and movements is being counted. Thus, the degree and rate of deformation are known in each point of cross-section. If it`s known we can refer to the results of corresponding laboratory experiments. To be use the recrystallization diagrams, which were constructed on the basis of experimental data (**Figure 1**) in order that to predict properties of rolled plates of the AISI 321 type steel with various thickness it is necessary to go over from the combination of Td - ε - τ - factors to the combination of Td - ε - Tq - factors (where Tq - quenching temperature), simultaneously to retain invariable heat exchange conditions. Mathematical models of $YS = f_1(Td, \varepsilon, Tq)$ dependences can be obtained by accounting cooling curves of 22x22 mm rolled in the 210 mill with the air cooling after deformation. Under three factors (3^3) experimental planning data treatment instead of time factor it will take part other one, conforming to the start of rapid cooling billet temperature which in actually is quenching temperature. As a result, the models according to the Td - ε - Tq factor system will stand up as follows.

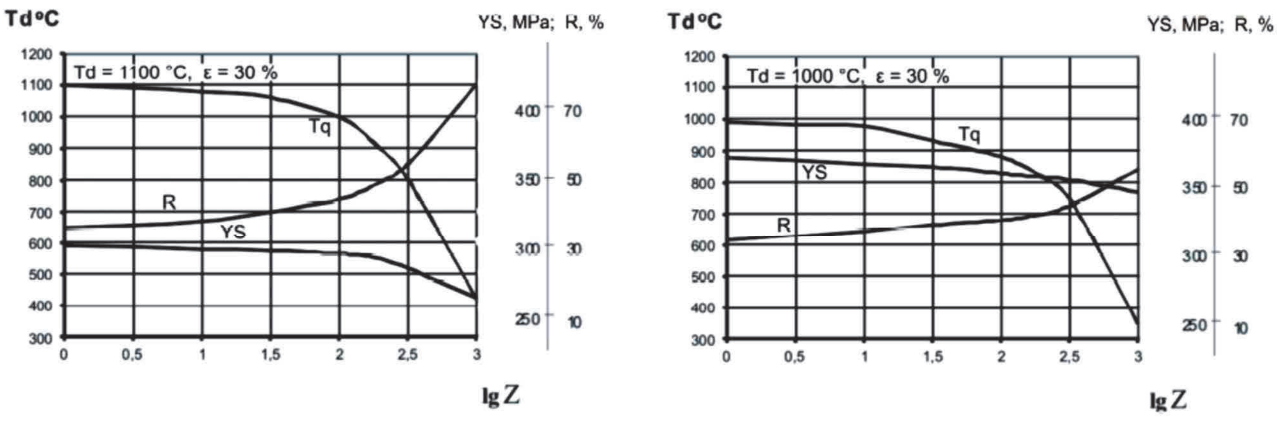
$$YS = 322 + 18X - 59Y + 24Z - 22YZ \qquad (3)$$

$$R = 25 - 11.4X + 24.2Y + 14.2Z - 11.9XY + 9.5YZ - 4.4ZY^2 + 4.1XYZ \qquad (4)$$

where $X = Tq/300 - 2$, $Y = 0.001Td - 10$, $Z = 0.1\varepsilon - 2$

$Y^2 = 298 - 0.6Td + 0.0003Td^2$.

For the calculation of the yield strength and recrystallization fraction in case of the required thickness (h) plate rolling with the designated reduction and temperature it is necessary to simulate cooling process for the concrete plate billet under deformation in the rolling stand and following air cooling. As this take place the time when the billet between the rolls from start to the end of the rolling will be result from the linear rolling speed - $\upsilon = \omega$ x r and length of arc of the roll contact - $l = \sqrt{rx\Delta h}$ corresponding to rolling in the rolls with the r - radius, ω - angular roll rotation speed, where Δh - draught. Heat changes conditions are similar to the experimental ones with the 22 x 22 mm cross-section billets. If we will follow to the deformed plate cooling conditions it is possible to definite the time when the plate temperature will reach the quenching temperature. This quenching temperature in combination with the set preliminary rolling temperature (Td) and reduction (ε) will give the required properties level which are calculated according to the (3), and (4) equations. Thermo-physical processes modelling of rolling with the following cooling are realized by means of numerical solution of unsteady heat transfer equation by the finite elements with the time various third mode boundary conditions. As an example of graphic illustration the designed cooling and properties in the centre of the rolled plates with the initial thickness h_o = 50 mm and rolling with reduction ε_i = 10, 20 and 30 % and Td=1100^{0}C and 1000^{0}C, (a) and (b) respectively to the plates with the finite thickness h_i = 35 mm are shown in **Figure 2**. But it is necessary to take into account that cooling in water is realized in designated time with the plate temperature corresponding to this time. Thus, mathematical simulation of thermo-deformation processes of real object allows to set up the temperature, time and deformation in each point of profile cross-section. As a result, knowing this combination of parameters we can find the properties of workpiece from the same material which are known at base on laboratory experiment with samples.



a b

Figure 2 Nomograms for defining of the recrystallization fraction, R and yield strength, YS in the billet with final thickness 35 mm: Td=1100^{0}C (a) and 1000^{0}C (b)

3. FINITE ELEMENT METHOD

Using the technique of studying a dynamically recrystallized grain with computer simulation [10, 11], we can analyze the structure that forms in a part during deformation and to optimize the process of production of the part in order to ensure its required properties. In this work, we consider an axisymmetric non-isothermal problem of stamping. It was took into account the rheological properties of the steel that were obtained during physical modeling; Young's modulus; the thermal conductivity; the emissivity; the convection coefficient; and the blank, punch, and die sizes. The die temperature was chosen to be 100°C, which took into account the contact heating of the die as a result of heading of the previous blanks. The results of computer simulation of the temperature-deformation fields in a part were compared with the structure studied upon physical modeling of the process performed at similar deformation - temperature parameters. Some of the results of this comparison are presented in **Figure 3**. Note that the high temperatures and strains at the edge and the center of the bolt head (**Figure 3**; zones 1, 2) cause higher development of recrystallization as compared to other regions but to relatively low values, R = 8-11% at T = 850-1050°C and e = 0.9-1.8. The zone where the neck joins the bolt head contains the boundary that separates deformed and under-formed regions (in real practice, fullering is performed in this zone to decrease the heterogeneity in this zone). In the near-surface regions (zone 3), the degree of recrystallization is low (R = 1-2%) because of a low temperature and insignificant deformation. As follows from the flow stresses, the deformation conditions at T= 850°C, è = 1 s^{-1}, and e = 0.9 do not relieve the internal stresses in the deformed region (zone 4). This is also indicated by the data of microstructural analysis, which exhibit no signs of recrystallization. According to the simulation data, recrystallization does not occur at e = 0.4, è = 1 s^{-1}, and T = 950°C. After the end of stamping, a predominantly deformed structure with a low fraction of recrystallized grains (mainly coarse elongated grains exist) is observed in the zones that are adjacent to the punch and the die and the strain in these zones is 0.3-0.6. The temperature was found to decrease gradually from the edge to the center of the head. Moreover, the surface layer temperature decreases significantly down to a temperature below the end of recrystallization, which is related to the low die temperature (100°C). However, a high strain rate provides heating at the center of the blank and a gradual heat flow to the cooled surface.

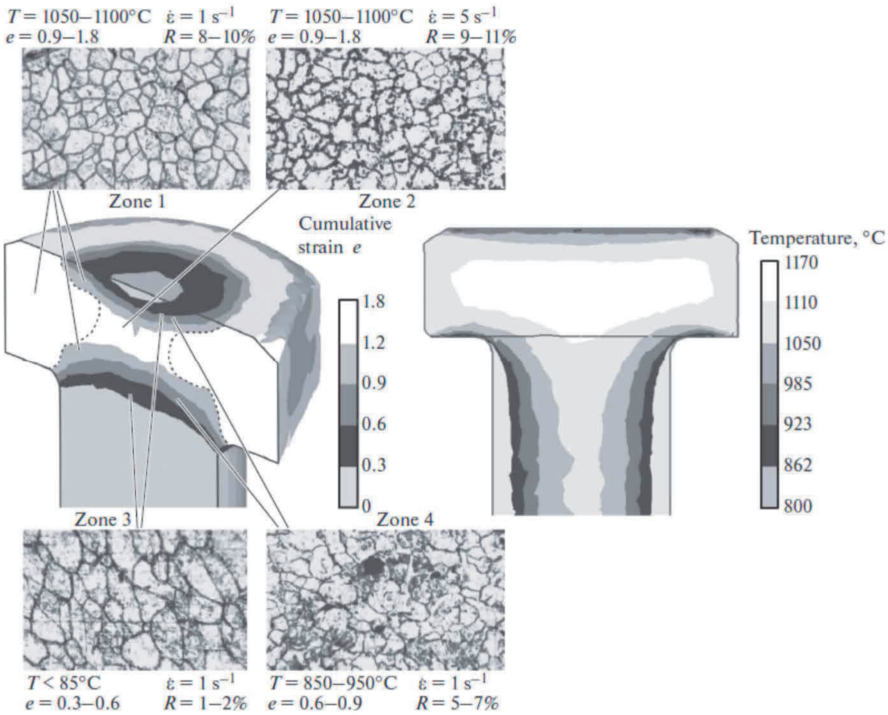


Figure 3 Strain, temperature and recrystallized structure fields in the section of a bolt head at stamping

The example of FEM calculation applying to hot rolling of steel AISI321 shown in **Figure 4**. Thus, mathematical simulation of thermo-deformation processes of real object allows to set up the temperature, time and deformation in each point of profile cross-section. The same approach has been used applying to superalloys.As a result is to be known this combination of parameters we can find the properties of workpiece from the same material which are known at base on laboratory experiment with samples.

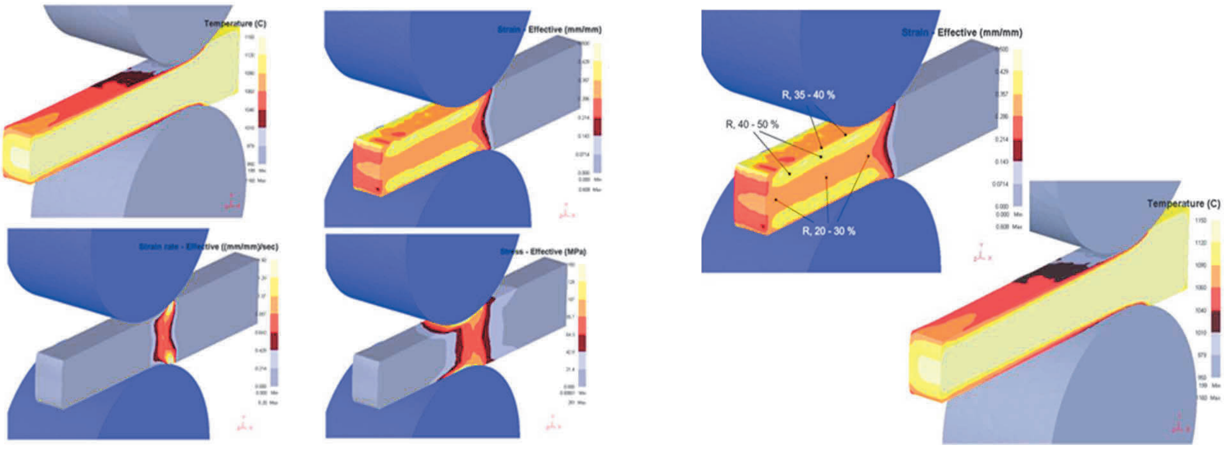


Figure 4 Strain and temperature fields in the section of AISI 321 rolled strip

4. CONCLUSION

Experiment planning method has proved to be a good tool for the modeling relationship between temperature-strain-time-time hot deformation parameters and fraction recrystallized and mechanical properties determination.

The proposed simulation of recrystallization for the definite cross-section of the billets by Finite Element Method technique on the base of the data obtained by experimental planning method is promising to predict fraction recrystallized and mechanical properties for the different cross-section of rolled or forged profile.

REFERENCES

[1] DEARDO A.J. New Challenges in the Thermomechanical Processing of HSLA Steels, *Materials Science Forum*, 2003, Vols.426-432, pp. 49-56.

[2] JONAS J.J., BARNETT M.R. AND HODGSON P.D. Thermomechanical Processing; *Materials Processing Handbook*, CRC (Chemical Rubber Corp.) Handbook series, Taylor & Francis; eds. J.R. Groza, J.F. Shackelford, E.J. Lavernia and M.T. Powers,2007, 29, p.1.

[3] G.E.KODZHASPIROV ,A.I.RUDSKOY, Substructural strengthening of medium-carbon alloyed steel with preliminary thermomechanical processing. *Acta Physica Polonica* A, 2015, Vol.128, No.4, pp.527-529.

[4] KODZHASPIROV G.E., RYBIN V.V., APOSTOLOPOULOS H. Role of mesostructured in thermomechanical treatment of metallic materials. *Metal Science and Heat Treatment*, 2007, Vol.1-2, pp.24-28.

[5] C M SELLARS 50th Hatfield Memorial Lecture: *The University of Sheffield,* 2002.

[6] J.H.BEYNON AND C.M.SELLARS, *ISIJ International*, 1992, 32, p.359.

[7] A.J.Trowsdale, J.P.Tunstall, K.Randerson, P.F.Morris and Z.Hussain, *Proc. Conf. on*

[8] J.H.BEYNON et al. Modelling of Metal Rolling Processes, London,.1999, *3rd ed*,

IOM Communications Ltd, London, 1999, p 12.

[9] G. E. KODZHASPIROV, A. I. RUDSKOY, V. V. RYBIN, Physical Fundamentals and Resource-Saving Technologies in the Production of Parts by Plastic Deformation [in Russian], *Nauka*, St. Petersburg , 2007, 350 p.

[10] G. KODZHASPIROV, A. BOROWIKOW, and M. TERENTYEV, Modeling the hot deformation stress-strain curve of a Ni-based superalloy, *Materials Scince Forum* 2013,762, pp. 753-756.

[11] A. I. RUDSKOI, G. E. KODZHASPIROV, AND E. I. KAMELIN, Dynamic recrystallization during the hot stamping of complex-profile parts made of an Ni-Cr-Fe alloy, *Forging and stamping production*, [in Russian] 2014, No. 6, pp. 16-19.