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THE APPLICATION OF THE PROGRAM QFORM 2D IN THE STAMPING OF WHEELS FOR RAILWAY VEHICLES

UPORABA PROGRAMA QFORM 2D PRI KOVANJU KOLES ZA ŽELEZNIŠKA VOZILA

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Computers allow us to obtain and process data to improve and accelerate the analysis of the information required to optimize the processes of metal forming and to minimize production costs. The computer program Qform 2D, adapted to wheel forming, has been used for several years in the company "Interpipe – Nikopolski tube rolling plants" for solving problems related to the selection of the optimal schemes for the hot plastic deformation of wheel blanks, the analysis of existing shapes and the development of new shapes for the die-forging tool.

Key words: stamping, railway wheels, computer simulation, distribution and rate of deformation

Računalniki omogočajo, da pridobimo in procesiramo podatke za izboljšanje in pospešenje analize podatkov za optimizacijo procesa oblikovanja kovin in zmanjšanje stroškov izdelave. Računalniški program Qform, prilagojen za kovanje koles, se uporablja že več let v podjetju "Interpipe- Nikopolski tube rolling plant" za reševanje problemov, povezanih z izbiro optimalne sheme za vroče kovanje surovcev za kolesa, analizo uporabljenih oblik in za razvoj novih oblik orodij za utopno kovanje.

Ključne besede: kovanje, železniška kolesa, računalniška simulacija, porazdelitev in hitrost deformacije

1 INTRODUCTION

Railway transport and the manufacturers of wheels for railway transport are constantly facing more and more complex problems related to the reliability and durability of the rolling stock under conditions that are becoming increasingly strict.

From an analysis of the development of the technology for manufacturing the wheels for railway vehicles of major producers it is clear that it is necessary to increase the exploitation properties of wheels and to optimize the hot forming of wheel blanks. The use of modern computer facilities and methods for obtaining and processing data allows us to improve and accelerate the analysis of the data necessary to optimize the processes of metal forming and, at the same time, to minimize the costs of production.

The computer program Qform 2D, adapted to the conditions of wheel manufacturing, has been used for several years in the company "Interpipe – Nikopolski tube rolling works" for solving problems connected with the choice of the optimal schemes for the hot plastic forming of wheel blanks as well as the analysis of existing, and the development of new, grooves for the die-forging tool.

2 EFFECT OF THE PARAMETERS OF HOT PLASTIC DEFORMATION ON THE WHEEL RIM'S MECHANICAL PROPERTIES

The effect of deformation on the mechanical properties of the wheel's steel was determined with laboratory specimens and from stamped wheels. It is related to the steel's macrostructure and microstructure[1]. In addition, the degree of deformation, the temperature and the rate of deformation significantly affect the mechanical properties as well as the "hardening-softening" processes occurring during the deformation, including the time of the inter-deformation pauses. During the hot plastic deformation at a temperature above the temperature of recrystallization, the processes of metal hardening and softening occur in parallel and compete with each other. As a rule, during the hot deformation, softening prevails over hardening.

A distinctive feature of the hot-forming process is the stage of stable flow, when above a critical level the deformation resistance becomes independent of the increasing plastic deformation. The critical deformation depends on the rate and the temperature of deformation that affect the mechanism and the kinetics of the hardening and softening processes.

The strain resistance increases with the increase of the extent of hot deformation and the rate, which may even hinder the softening processes and increase the deformation hardening, while the rate of deformation also increases the temperature that then increases the rate of metal softening.

Therefore, it is possible to regulate the steel's microstructure, its homogeneity and stability with changes of the deformation schemes' schedules and temperature and to affect, in this way, the mechanical properties of the metal. In the company "Interpipe – Nikopolski tube rolling works" the optimizing of the schedules of the wheel blanks' hot deformation was solved on the basis of the results of a series of laboratory and industrial experiments in cooperation with scientists from the Iron and Steel Institute of the National Academy of Sciences of Ukraine and the National Metallurgical Academy of Ukraine using the computer program Qform.

In the investigations the effects of the degree, rate and temperature of deformation on steel hardening were determined with a Type 805 A/D[2]-dilatometer. The investigations were performed on samples of steel cut out from the ingot zone intended for the wheel rim. In the process of plant forming the maximum steel hardening is achieved during the initial stages of the wheel blank's deformation, while the deformation in the last stages of forming must be sufficient to compensate for the steel softening during inter-deformation pauses with a decreasing time-length or with increasing the rate of deformation in the following stages. The influence of deformation pauses on the steel softening was studied with dilatometry and the deformation of specimens at different temperatures with various degrees of deformation and different inter-deformation pauses[2].

Various versions of the wheel blanks' hot-deformation schemes were suggested and investigated with simulation by applying the program Qform 2D. The computer model used in the present work is based on the plastic-flow theory. In this theory, the deformed metal is assumed to be an incompressible and rigid plastic body. The model describing the plastic deforming includes:

– the differential equation of motion:

$$\sigma_{ij,j} = 0 \tag{1}$$

– the kinematic correlation:

$$\omega_{ij} = \frac{1}{2}(\nu_{i,j} + \nu_{j,i}) \tag{2}$$

– the state equation:

$$\sigma_{ij} = \sigma_0 \delta_{ij} + \frac{2\overline{\sigma}}{3\overline{\omega}}\omega_{ij}) \tag{3}$$

– the expression for incompressibility:

$$\nu_{i,i} = 0 \tag{4}$$

– the heat-balance equation:

$$c(T)\rho(T)\frac{\mathrm{d}T}{\mathrm{d}\tau} = \mathrm{div}(k(T)\mathrm{grad}(T)) + \beta\overline{\sigma}\overline{\omega} \tag{5}$$

– the model of material flow stress in dependence on the deformation parameters:

$$\sigma = f(\overline{\varepsilon}, \overline{\omega}, T) \tag{6}$$

With σ_{ij}, ε_{ij}, ν_i being the components of the tensors of the stress and the rate of deformation and the vector of the flow rate; $\overline{\sigma}, \overline{\varepsilon}, \overline{\omega}$ being the intensities of the stresses, deformations and rates of deformation; σ_0 the average normal stress; δ_{ij} the Kronecker symbol; T the temperature; β the coefficient of transition of mechanical energy into heat (β = 0.9–0.95); ρ the density; c the thermal capacity and k the thermal conductivity.

In equations (1)–(4) the rule of summation with repeating indexes is used. The indexes i, j change from 1 to 2 for two-dimensional calculations and from 1 to 3 for three-dimensional calculations.

The cooling of the blank during the transport from the furnace to the press, as well as between the presses and the rolling mill, is described with the equation of thermal conductivity (5).

The heat boundary conditions on the free surface include the heat exchange by convection and radiation. The heat exchange on the contact surface is considered with a heat-transfer coefficient, while the friction on the contact surface is determined by applying Levanov's relation:

$$\tau = K_\mathrm{s}(1 - \mathrm{e}^{1,25\sigma_\mathrm{n}/\sigma_\mathrm{s}}) \tag{7}$$

with K_s being surface constant; σ_n the pressure constant; σ_s the yield stress.

The equations (1)–(4) are transformed into a system of algebraic equations on the basis of virtual speed principles and a FEM, where the components of the rate vector and the average stress are nodes of unknown values. The rate and the average stress are approximated with square and linear functions of the form on triangular elements. The generation and rebuilding of the FE of the network are automated.

The heat-balance equation (5) is transformed by means of Galerkin's method into a system of differential equations that are numerically integrated with respect to time.

The thermomechanical problem is solved by applying the method of successive approximations of the mechanical and heat problem by entering the boundary values.

In the strength calculation the tool is assumed to be an elastic-plastic body with linear strain hardening and submitted to the blank contact forces that depend on the boundary conditions.

The results of the calculation of the deformation parameters in the central zone of the wheel rim with a mass of 400 kg according to the different schedules are shown in **Figure 1**.

With the options of the program the deformation parameters influencing the mechanical properties in different zones of the wheel are investigated, e.g., the

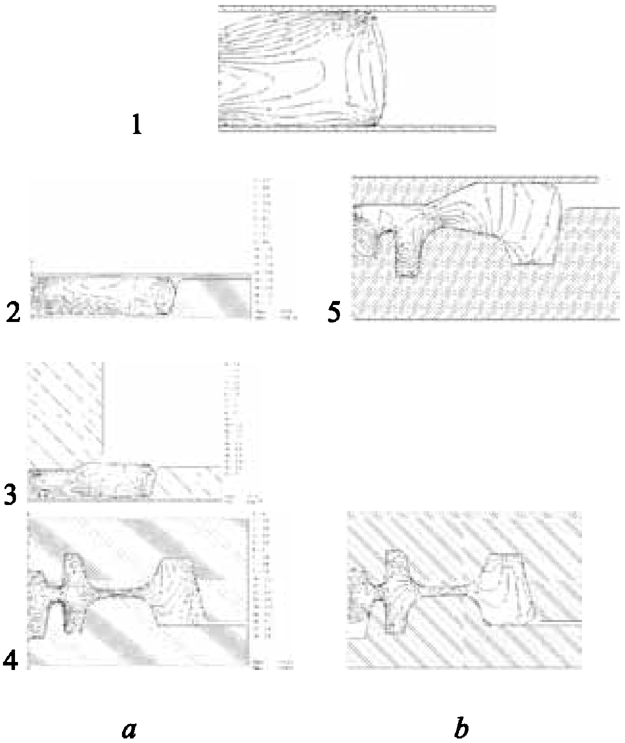

Figure 1: Results of the calculation of the wheel-blank shape change at different stages of the existing (a) and the experimental (b) technology: 1 – upsetting in the 20-MN press; 2 – upsetting to a ring in the 50-MN press; 3 – ring expansion (dilatation) with a punch on the 50-MN press; 4 – stamping in the 100-MN press; 5 – stamping in the 50-MN press

Slika 1: Rezultati izračunov spremembe oblike surovca pri različnih stopnjah sedanje (a) in poskusne (b) tehnologije. 1 – krčenje v 20 MN-preši, 2 – krčenje v obroč v 50 MN-preši, 3 – širjenje obroča, s trnom v 50 MN-preši, oblikovanje v 100 MN preši, oblikovanje v 50 Mn preši

rate and degree of deformation and the rate of accumulation of the deformation can be determined. For the presented case, the rate and degree of deformation calculated by applying the program Qform are shown in **Figure 2**.

The comparison of the experimental data on the rheological properties of the wheel steel with the results of the computer simulation allowed us to determine, and afterwards to realize in the stamping process also, the most suitable scheme of the distribution of rate and the degree of deformation by passes for the multistage stamping of the wheel blank and to obtain improved mechanical properties in the central wheel-rim zone[3].

3 INFLUENCE OF DEFORMATION SCHEME ON THE HARDNESS OF THE WHEEL-HUB METAL

The practice of manufacturing wheel pairs with increased wheel hardness (HB = 320) in the train car buildings plant revealed a substantial spread in the metal hardness values (above HB = 20) around the opening

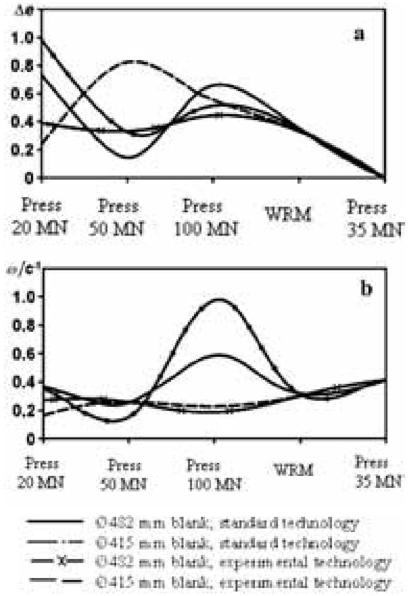

Figure 2: Distribution of deformation (a) and of deformation rate (b) in the central wheel-rim zone for the stages of the blanks' forming using different schemes of stamping

Slika 2: Porazdelitev deformacije (a) in hitrosti deformacije (b) v središčni zoni oboda kolesa pri fazah oblikovanja surovca in pri uporabi različnih shem oblikovanja

(bore) for the wheel hub on the internal and external sides of the wheel. An irregular hardness distribution over the length of the wheel hub bore generatrix affects the accuracy of the geometrical parameters of the bore turning before the wheel is pressed on the axis. The irregular hardness distribution is often connected with the coning of the bore of more than 50 μm, which is a reason for rejecting the wheel.

The hardness (HB) of carbon steels is related to the flow stress characterizing the plastic strain resistance of steel (σ_f) by a linear dependence through the factor of proportionality (C):

$$\sigma_f = C \times HB$$

The steel's plastic strain resistance depends on its microstructure. In the present case, besides the microstructure, it includes the changes to the intra-grain and dislocation structure, too.

The various mechanisms hindering the dislocations slip that are widely used for increasing the plastic strain resistance and hardness are related to the interaction of dislocations with the presence of effective and uniformly distributed obstacles, as well as grain boundaries.

The parameters of the hot plastic steel deformation, such as the rate and degree of deformation, the degree of total deformation, the temperature of deformation including the length of inter-deformation pauses, significantly affect the grain size of the wheel steel [2].

The influence of the these parameters on the distribution of hardness along the generatrix of the wheel-hub bore was investigated in the plant in the frame of the production of wheels with D = 957 mm

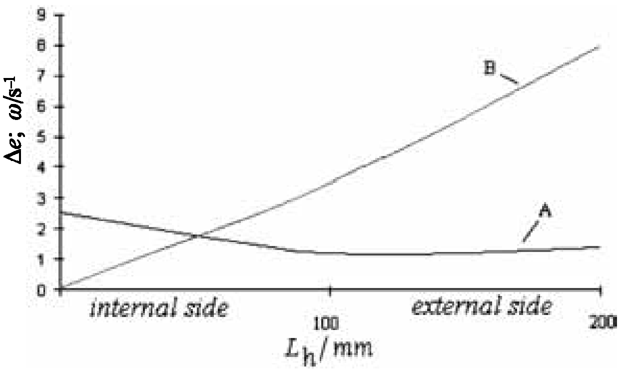

Figure 3: Distribution of the degree (A) and the rate (B) of steel deformation along the generatrix of the wheel-hub bore for stamping the blank in the 100-MN press

Slika 3: Porazdelitev stopnje (a) in hitrosti (b) deformacije po obodu izvrtine pest kolesa za oblikovanje surovca v 100 MN preši

according to the standard GOST 10791-2004 as well as wheels with increased hardness according to the technical conditions TU V 35.2-23365425-600; 2006. The parameters of the deformation of the internal, central and external zones in the wheel hub were determined with a computer simulation of the wheel-stamping process applying the program Qform 2 (**Figure 3**).

As shown in **Figure 3**, the true (logarithmic) deformation of steel (Δe) on the hub internal side during stamping the blank in the 100-MN press achieves a value of 2.4; it decreases in the central zone and on the external hub side to values of 1.2–1.4. At the same time, the deformation rate (ω) increases from the internal to external side of hub from 0.1 s^{-1} to 8 s^{-1}.

Earlier investigations of the rheological particularities of the wheel's steel have shown a softening of the metal, while deforming it with a rate of deformation of 0.1 s^{-1} and values of the logarithmic deformation of above 0.15 at a temperature of 1100 °C (the temperature of the wheel blank stamping in the 100-MN press). At the same temperature, steel hardening still takes place, while deforming with a rate 10s^{-1} and a logarithmic deformation of 1.2[2]. Thus, applying the existing scheme of deformation for the wheel blank in the 100-MN press, steel softening will take place on the internal side of the wheel hub, while hardening will take place on the hub's external side. Metallographic studies of the changes in the microstructure of steel for different wheel-hub parts confirmed that under these conditions a different steel hardness on the opposite ends of the wheel hub is obtained[4].

4 DETERMINATION OF THE POSITION OF THE NEUTRAL PLANE BY STAMPING WHEEL BLANKS

The stamping process must ensure a precise mass distribution of the initial blank for the part of the disc and the wheel hub as well as other parts of the wheel. An erroneous balance of the masses of different parts of the blanks leads to the formation of defects in the wheel's geometry, e.g., rim shrinkage, non-filling of the hub, and a "thick disc". For this reason, when calculating groovings it is of great importance to know the position of the plane relative to which the metal flows to both sides during the wheel forming in the press. The position of this plane changes in the process of blank forming; however, it is not clear how the change occurs. When calculating the groovings for wheels with a flat disc it is assumed that the neutral plane corresponds to the middle of the wheel disc length. No recommendations have been given about how to determine the neutral plane position in the calculation of the groovings for the wheel with a disc of curvilinear form.

With the program Qform it is possible to determine the value and the direction of the rate of deformation at any point of the wheel during the whole cycle of the blank's deformation[5]. From the vectors of the directions of deformation rate it is possible to establish the position of the neutral section of the wheel as the plane relative to which the metal flows to both sides (**Figure 4.1–4.2**). The program Qform was used to study the position of the neutral radius (R_n) and the metal flow rate at any point during the cycle of forming the blank to various shapes of the disc.

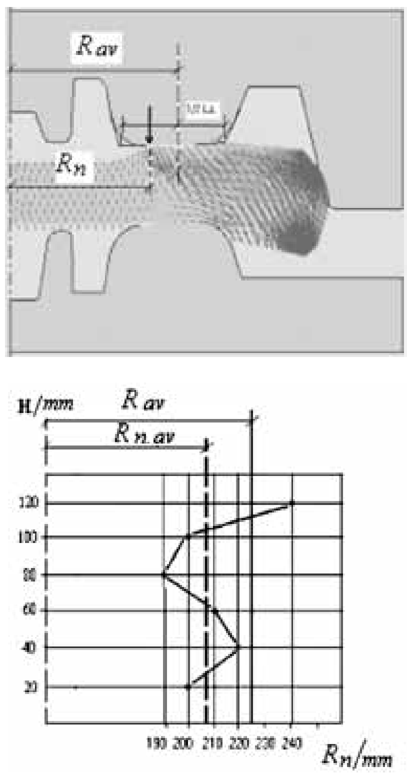

Figure 4.1: Variation of the position of the neutral plane (R_n) relative to the middle of the disc (R_{av}) in the process of forming the wheel blank with D = 957 mm in the 100-MN press

Slika 4.1: Sprememba položaja nevtralne ravnine (R_n) glede na sredino diska (R_{av}) pri oblikovanju surovca za kolo z D = 957 mm v 100 MN-preši

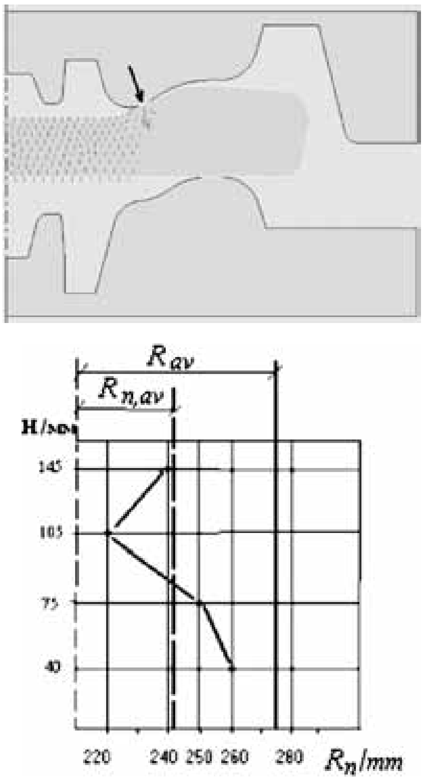

Figure 4.2: Change of the neutral plane position (R_n) relative to the middle of the disc (R_{av}) in the process of forming the wheel blank with D = 932 mm in the 100-MN press

Slika 4.2: Sprememba položaja nevtralne ravnine (R_n) glede na sredino diska (R_{av}) pri oblikovanju surovca za kolo z D = 932 mm v 100 MN-preši

Two types of wheels were chosen as the object of investigation: a wheel with a flat-conical disc and a wheel with a curvilinear disc. The process of stage-by-stage deformation of the blanks in the 100-MN press was simulated considering the groovings of the deforming tool for stamping both wheels. The value of the "neutral" radius (R_n) was determined for each stage of the blank deformation and the results of these investigations served as a basis for building the curves of the change of the position of the neutral plane (R_n) relative to the middle of the disc (R_{av}).

As shown in **Figure 4.1**, during deforming the blank for the wheel with a flat-conical disc, the neutral plane, defined with the parameter R_n, constantly changes its position (place) relative to the middle of the wheel disc defined with the parameter R_{av}. The average of all the values of R_n ($R_{n.av}$) is displaced toward the side of the wheel axis by 8 % for wheel blanks with a mass of 500 kg and by 11 % for wheel blanks with a mass of 700 kg.

A different picture is obtained for the stamping of wheels with a curvilinear disc shape (**Figure 4.2**). In this case the character of metal flow in the deformation process is determined by the surface of the upper die forming the wheel disc with the greatest angle to the horizontal. The neutral plane then passes through the point close to its middle and not to the middle of the disc, as in the previous case. In this connection, R_n is displaced along the horizontal relative to R_{av} for a much greater value, equal to 16 %.

Investigations of the influence of different factors on the position of the neutral plane showed that while calculating the groovings of the press tool for manufacturing wheels for various disc shapes, one should be initially guided by the disc geometry and consider the findings in[6].

5 CONCLUSIONS

- The program QForm 2D can be successfully used for the computer simulation of the deformation process for stamping railway wheels with different shapes and sizes.
- The program allows us to determine the intensity of deformation and the rate of metal flow at any point of the wheel and to determine the position of the neutral plane of metal flow.
- The program was tested with calculations of the shape of forming tools and verified with the industrial production of wheels of different shapes and sizes.
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