The influence of initial blank parameters on railway wheels manufacture with hot plastic deformation process

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Abstract
The current article aims at simulation of hot plastic deformation process with the objective to determine the influence of initial blank H / D ratio on the cumulative deformation distribution within the wheel blank and position of its axial zone with its macrostructure improper quality. The methods of mathematical simulation have been applied for metal yield at the main stages of wheel blank hot plastic deformation (upset forging, spread and die forging) and simulation is carried out with program "Forge 3".
The research results are in the assessment performed for the deformed metal within the wheel volume and the research has been made with computer simulation of the hot plastic deformation for the wheel blanks with Ø 360 – 520 mm and shape form of H/D = 0.5– 1.6. The research has determined that the optimal initial blank for production of Ø 957-mm-railway wheels is the wheel blank of Ø 450 mm (H / D = 0.84) and its application enables fine workability of the wheel rim (the value of the cumulative degree of deformation is 85%) and that of the wheel disk is 92 %, this practice also excludes occasional defects of macrostructure to be present in the wheel. The scientific novelty of the current paper is in featuring the influence of initial blank geometry on the distribution of cumulative deformation and position of axial low-quality zone of the macrostructure in wheel blanks after hot plastic deformation. It has been found that on condition when wheel blank shape (H / D) is 0.73, 0.84 or 1.11, cumulative degree of deformation in wheel rim change insignificantly and is of 85 %. The practical value of the paper we see in determining the best possible or optimal initial blank for production of railway wheels with Ø 957 mm in diameter (a blank of Ø 450 mm and its H / D = 0.84), application of which provides good industrial results stated above.
Key words: WHEEL BLANK, SHAPE FACTOR, COMPUTER SIMULATION, HOT PLASTIC DEFORMATION, MACROSTRUCTURE

Background

At the present time, in order to meet the increasingly restrictive requirements to the railway wheels operational and service properties, there is a need in optimization for the railway wheels production technology not only at the stage of steelmaking and heat treatment, but also in the process of hot plastic deformation of wheel blank [1, 2].

The production process for solid-rolled railway wheels includes several stages of blank deformation, which has a specific character, combining in itself the elements of forging and rolling.

The main stages of forming the cast billet in wheels production are as follows:

1) production of a flat round blank (sometimes with a center-hole pierced);

2) forming a wheel blank, close to the configuration of the finished wheel (this blank differs from the rolled wheel only by the shape and dimensions of the rim);

3) rolling the wheel blank;

4) bending of the disk and calibration of the rim in width.

This scheme of deformation is the most rational or suitable one [3]. The further improvements on the technology are possible only if a detailed study of the metal flow under deformation takes place, it will allow us to determine the ways to improve the quality of wheels.

It is well known that stress-strain properties of the product metal determine its service properties and depend on the structure formed during its manufacture. One of the main factors influencing them is the deformation degree [4]. Moreover, the deformation degree can be enhanced by a change in the geometric parameters of the initial ingot – H / D shape factor (where H is the height of the billet, and D - its diameter [5]).

The earlier publication [2] demonstrates that in hot plastic deformation, the increase in the degree of deformation work performed on a wheel rim (increase in the value of the cumulative degree of deformation) by means of the decrease in the blank diameter leads to forming more dense dendritic structure. Furthermore, this hot plastic deformation decreases austenite stability in the pearlite zone and increases pearlite transformation rate resulting in fine recrystallized perlite grain formation. The higher is the reduction, the more intensifying impact of hot deformation on perlite transformation is [6]. It influences positively the static strength and ductility properties as well as the service performance of railway wheels (impact ductility and fracture toughness K_1c).

Currently, along with conventional methods of the deformed state evaluation, the finite-element method (FME) is used, in particular, “Forge 3” program by “Transvalor” company (France).

With its help, a number of problems related to the peculiarities of the upset forging process and die forging has been successfully solved for the samples of cylindrical shape [7 – 10].

The aim of this research is to apply the computer simulation for the objective to determine how the H/D shape factor (the ratio of the initial diameter of the blank to its height) of a primary blank influences the cumulative deformation distribution within the volume of wheel blanks and the position of the macrostructure low-quality axial zone.

Material and the research methods

For computer simulation, we chose the production process for railway wheels of Ø 957 mm in diameter with flat-cone disk (GOST 10791 – 2011).

Mathematical modeling of metal flow at the main stages of the wheel blanks hot plastic deformation (upset forging, spread and die forging) has been carried out with the help of “Forge 3” software. The initial data for simulation of the production transitions of the wheel blanks forming are given in Table 1.

Table 1. The parameters of the initial wheel blanks for mathematical modeling of hot plastic deformation

Sample number	Diameter (D), mm	Height (H), mm	Mass, kg	H / D Ratio	Wheel Diameter Ø, mm	Axial Porosity Distribution (1 point – 10 % $D_{initial\ blank}$)*, mm
1	520	295	465	0.57	957	52.0
2	485	320		0.66		48.5
3	470	345		0.73		47.0
4	450	380		0.84		45.0
5	410	454		1,11		41.0
6	360	588		1.63		36.0

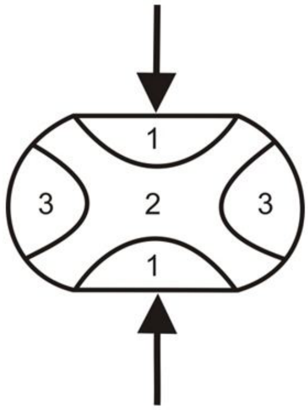
Research results

When developing the production technology for railway wheels, one of the most urgent tasks is to select the optimal diameter of the initial blank with simultaneous consideration of the features of its solidification and subsequent deformation.

The technological schemes of hot deformation for producing wheels are used in various plants, they differ, as a rule, by a number of features, related to specific conditions appropriate for each of these plants. However, the scheme of billets deformation includes a preliminary upset forging, scale removal from the side surface; upset forging in the ring; metal spread by for its desired distribution between the wheel elements; final forming of the wheel hub and the adjacent part of the disk, preliminary forming of the rim and other part of the disk, rolling the rim and the adjacent part of the disk on the rolling mill; disk bending and wheel size calibration; piercing within the wheel hub.

Analyzing the various kinds of metal forming methods, the combination of which is used in the manufacture of solid-rolled wheels, it is very important to define the degree of metal working (the amount of deformation) at this or that stage of processing. Having an idea how the deformation spreads, one can estimate the degree of participation of a certain tool in the named process as well as strive to ensure the best possible work on the metal in all the elements of wheels.

Upset fording for a cylindrical body or a body close to the cylindrical outlines is sufficiently well studied by the researches [3]. It has been determined that the presence of friction forces on the contact surfaces leads to an uneven distribution of deformation along the body volume during its upset forging. The volume being deformed falls into three areas (Fig. 1). In area 1, the deformation is complicated due to friction forces impact. Area 2, represents the area of the most intense deformation. The flow lines in this area are located in the most efficient way to the direction of the compressing forces action, i.e. at the angle of 45° or close to it. Finally, the extent of deformation in area 3 is less than in area 2.



1 – the area of complicated deformation during upset forging; 2 – the area of the most intensive deformation; 3 – the area of less intensive deformation than in area 2.

Figure 1. The deformability of the metal upon upset forging

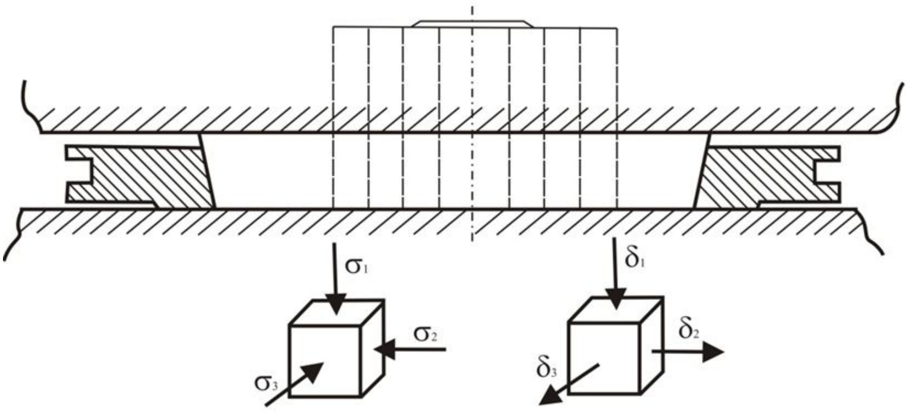


Figure 2. The scheme of deformation and stress during blank upset forging

The upset forging is characterized by heteronymous deformation scheme. Along one of the main axes (the vertical one) compression takes place, and along the other two (the radial and tangential ones) extension occurs. During upset forging, the presence of friction forces evokes three-dimensional stress state which can be characterized by the scheme of all-round non-uniform compression (Fig. 2). The height of a disk obtained, when a blank undergoes the upset forging, is determined, on the one hand, by the size of the calibration ring diameter, which is chosen on the basis of the conventionally permissible height of deformation and is limited by the dimensions of the dies used to form the wheel blank, on the other hand.

The character of metal flow, i.e. the distribution of separate zones of the initial blanks throughout the elements (disk, hub, and rim) of a wheel, is generally related to the ratio of the initial blank height to its diameter (H/D). In upset forging for cylindrical blanks, stress-strain behavior depends to the shape factor as follows:

1) $H / D < 0.3 \div 0.4$ – there is a single barrel distortion on the lateral surface, the considerable part of the contact surface develops sliding, and practically the entire volume of the forging is under conditions of all-round compression;

2) $0.3 \div 0.4 < H / D < 1.5 \div 2.0$ – there is also a single barrel distortion on the lateral surface but almost all the contact surface is the sticking region, and the scheme of volume non-uniform compression is expressed less acutely;

3) $H / D > 1.5 \div 2.0$ – is featured with the double barrel distortion on the lateral surface, sticking regions are on the contact surfaces and three-dimensional non-uniform compression occurs not within the whole blank – in the middle portion of its height, the metal is under conditions of linear stressed compression. Depending on the shape factor value, the blanks are commonly classified as low, moderate and high [5].

Earlier, for example, under conditions of PJSC "Interpipe NTZ" facilities, railway wheels of Ø 957 mm in diameter were made from ingots with the diameter of 520 mm, cast in ingot molds. After cutting the ingot onto blanks, their shape factors were in the range 0.4-0.6, that is, the blanks used in the production were on the border between low and moderate. The usual practice was that the blank after the upset forging was assumed as 105-110 mm high. Based on these data, it can be determined that the value of the vertical deformation in the upset forging was in the range of 63 - 65% for wheels of Ø 957 mm.

The subsequent forming of the workpiece was the most difficult of the forging operations and was carried out in the press-rolling department. The complexity of this operation was determined by the need to obtain the final dimensions of the hub and disk in the figured dies. Molding press formed two annular conical cavities, located concentrically at the center and along the periphery of the dies. In this case, the hub was formed by filling the central conical cavity, and the rim – by filling the outer cavity. As a result of the reduction of the disk in the dies of the molding press, a complex configuration was produced, resembling a wheel in shape.

We applied the computer simulation of the hot plastic deformation process for wheel blanks in order to study the influence of the parameters of the initial continuous cast billet (the ratio of the blank size H/D) on the features of its hot plastic deformation, namely the degree of workability of the wheel rim, which is formed from billet zone 3 (see Figure 1).

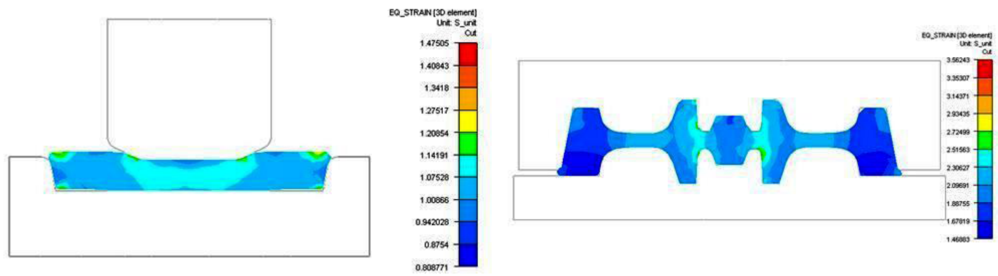
Figure 3 shows the results of this process simulation for wheel blanks after upset fogging in the ring and spread of the central part with a punch on a press with a force of 5,000 tons and subsequent forming the workpiece on a press with the force of 10,000 tons, where the maximum degree of cumulative deformation in the railway wheel elements is reached. These very operations have a major influence on work performed on the structure of the middle layers of the blank. Rolling, disk bending, calibrating the rim along the width give the wheel only the final shape and geometric dimensions, and do not lead to a significant accumulation of deformation.

As the analysis of the obtained data shows (Figures 4-5) the maximal work on the blank peripheral zone, from which the rim of the railway wheel will be subsequently formed, occurs at the stage of upset forging and metal spread on the press of 5,000 tons. The cumulative degree of deformation in this zone is in the range of 57% for a blank with the size of 520 × 295 mm (D × H) and reaches up to 72% for a blank of 360 × 588 mm (Figure 5). Obviously, as the H/D ratio decreases, the degree of the wheel elements workability decreases as well. However, this dependence is not linear in nature and its intensity decreases as the H/D ratio decreases and it practically does not change when the ratio of the height to the diameter is less than 0.73.

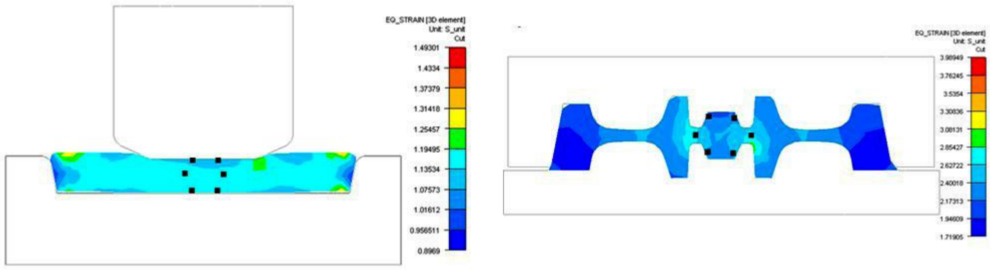
After forming on a press with a force capacity of 10,000 tons, the degrees of deformation of the parts of the wheel blank are different (Figure 3). Nevertheless, despite of the difference in the shape factor (H/D) of the blanks under research, the distribution of the accumulated deformation between the wheel elements has a general tendency - the metal of the rim undergoes the least deformation, unlike the hub metal and, especially, that of the the disk. At this stage, the cumulative deformation increases, on average, by 20%, and mainly this occurs due to the redistribution of the metal during filling the die with the metal coming from the area of the wheel disk (Figure 5).

After the press of 5 000 tons **After the press of 10 000 tons**

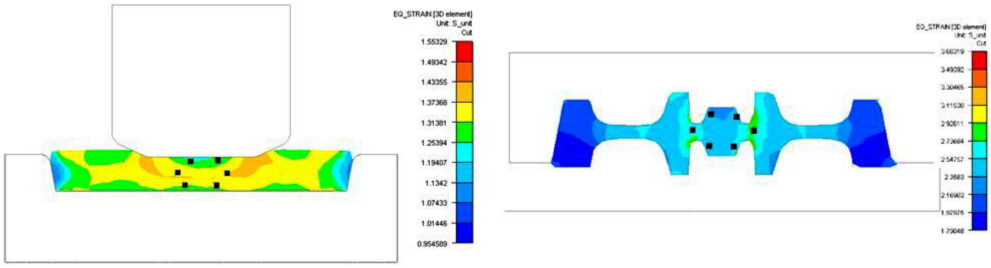
Workpiece of 520 × 295 mm (H/D = 0.57)



Workpiece of 485 × 320 mm (H/D = 0.66)



Workpiece of 450 × 380 mm (H/D = 0.84)



Workpiece of 360 × 588 mm (H/D = 1.63)

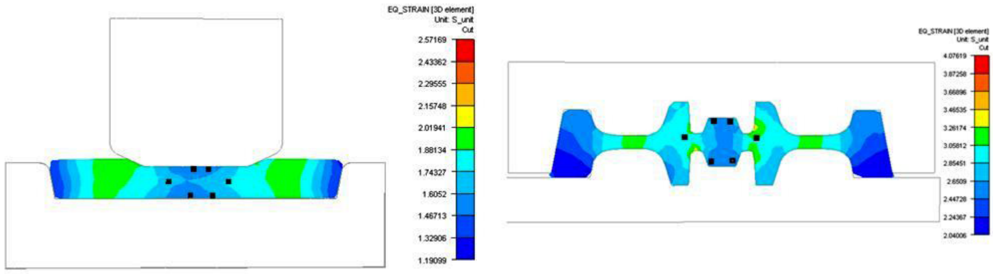


Figure 3. Distribution of the cumulative degree of deformation for wheel blanks of various diameters after upset forging in the ring and metal spread of the central part by a punch on a press with a force capacity of 5,000 tons and further forming on a press with 10,000 tons of capacity.

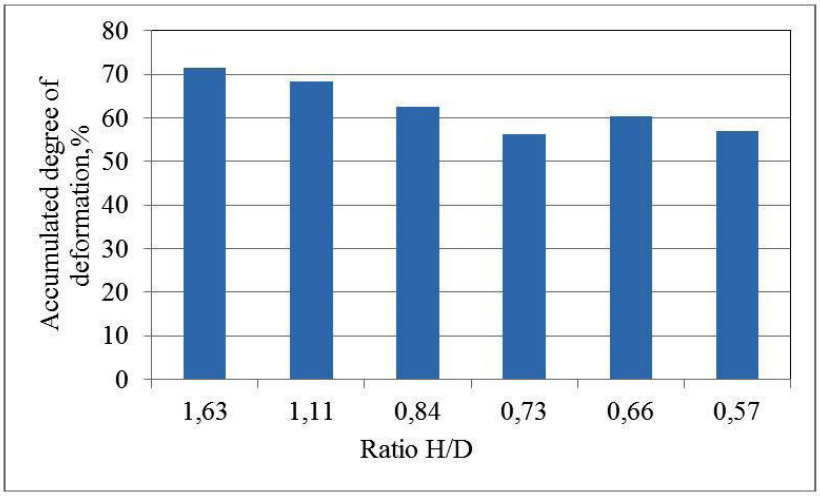


Figure 4. Cumulative degree of blank deformation. The peripheral zone (rim zone) after the press of 5 000 tons

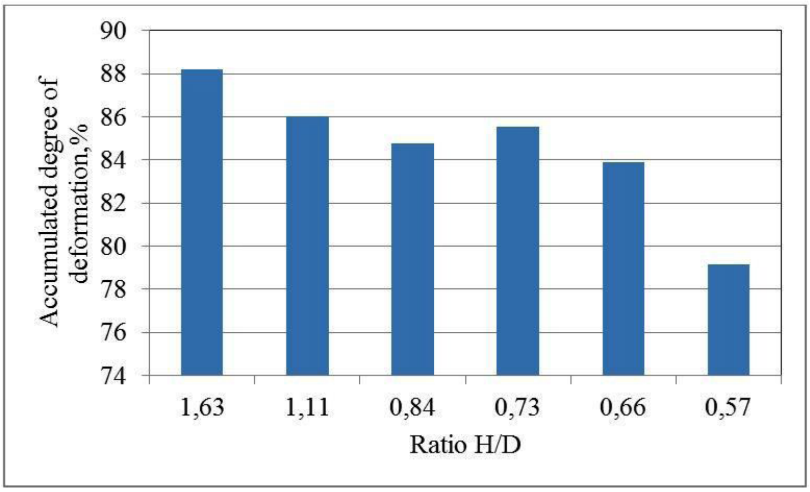


Figure 5. Cumulative degree of billet deformation in the rim zone after the press of 10 000 tons

Naturally, with an increase in the shape factor (H/D> 1.5) of the initial workpiece, the cumulative degree of deformation reaches the maximum values in all elements of the wheel. However, the production practice with blanks of 360 × 588 mm under real industrial conditions is accompanied by a number of difficulties. For example, in connection with the longitudinal instability of blanks with a diameter of 360 mm, their upset forging should be carried out in a special container [5]. Therefore, the use of high blanks for mass scale production of railway wheels is non-technological and cannot be accepted for industrial implementation.

Thus, taking into account the peculiarities of the hot deformation process, it is explained that the initial blanks with the shape factor within the range of 0.3 ÷ 0.4 <H/D <1.5 ÷ 2.0 provide normal conditions of deformation and the good workability not only of the central, but also of the peripheral zone and are optimal for the production of railway wheels.

Additionally, along with ensuring the maximum possible workability of the metal of all wheel elements, there is another important factor related to the peculiarities of the blank macrostructure and influencing the choice of the wheel blank optimal diameter. That is the necessary to eliminate the parts of the cast billet central poor-quality zone coming into the wheel during the process of hot plastic deformation due to the metal flow into the wheel hub and it is especially crucial with the wheel disk [11, 12].

In the requirements of the regulatory and technical documentation for the wheels manufacture (TU U 27.1 - 23365425 - 663: 2011 "Continuous Cast Round Billets for the Manufacture of Wheeled Products"), it is stated that the axial porosity and axial segregation should not exceed 2 points in MPG MPP 77.040 - 191: 2007 "Continuous Cast Billet for the Production of Long Products and Tube Billets. Method of Macrostructure Control" or 15% and 25% of the diameter of the initial billet respectively.

For the reported research, the boundary of axial porosity and axial segregation zones with 1 point rate (according to SSU MPP 77.040 - 191: 2007) were outlined with the marker when simulating the process of blanks deformation with different H/D ratios in the blank models (Table 1). We have estimated the pro- bability of axial defects coming into the finished product by movements of the markers during deformation of the wheel blanks (Figure 3).

Based on the results of computer simulation of the deformation process with various H/D shape factors, it can be concluded that an insufficient axial zone in the cast billets macrostructure with a shape factor of 0.5 <H/D <1.0 is completely concentrated in the extrusion and removed during hole piercing of the hub while the items with the shape factor of H/D ≥ 1.0, even possessing the minimum axial zone diameter (0.1 $D_{initial\ billet}$) have the axial poor-quality traces in the wheel hub. The latter is unacceptable without any doubt.

Thus, the optimal initial billet for the production of railway wheels of Ø 957 mm in diameter is a continuous casting of Ø 450 mm (H / D = 0.84), the use of which will increase the degree of metal working during the process of hot plastic deformation and exclude the entry of occasional macrostructure defects into the wheel elements.

Conclusions

1. By means of the computer simulation, the estimation have been carried out on the hot plastic deformation process for the wheel blanks of Ø 360 - 520 mm in the diameter range and the shape factor of H/D = 0.5 – 1.6.

2. The research results have shown that the de-

crease in the billet diameter from 520 mm to 360 mm when the railway wheels production leads to the increase in the workability degree of the metal in all the wheel elements.

3. It has been determined that the poor-quality of axial zone macrostructure in the cast billets is completely concentrated in the extrusion and removed with the hole piercing in the hub provided that the initial billet shape factor is 0.5 <H/D <1.0 while the billets with the shape factor of H/D ≥ 1.0 possess the axial zone traces within the hub even if the diameter of this zone is minimum (0.1 $D_{\text{initial billet}}$).

4. The optimum initial blank for the production of railway wheels of Ø 957 mm is the billet of Ø 450 mm (H/D = 0.84), the use of which will ensure a good workability of the rim metal (the value of the cumulative deformation is of 85%) and that of the disk (the cumulative deformation amount is of 92 %) and will exclude the ingress of occasional macrostructure defects of the billet central zone into the elements of the wheels.

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