

Finite Element Modelling of Combined Process of Plate Rolling and Stamping

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Abstract. This article presents the results of finite element modelling of a fundamentally new combined process of plate rolling and stamping. This process was first used to produce large-sized bodies of revolution, such as the bottom of a vacuum vessel, bottom of a ladle furnace, and others. Traditionally, such products (with the wall thickness exceeding 40 mm and the diameter width of up to 4000 mm) are produced in machine-building enterprises using stamping processes. Various schemes of implementing this combined process are investigated in the article.

1 Introduction

In such energy-intensive industries as metallurgy and heavy engineering, technologies of manufacturing and processing thick-plated metal products with wall thickness exceeding 40 mm and diameter up to 4000 mm are especially important. Such products are large-sized bodies of revolution (e.g. bottom of a vacuum vessel) formed by hot stamping. They are used in metallurgical, petrochemical, atomic, and gas industries in construction of storage tanks, vessels, high-pressure machinery, and other industrial machines. Current methods of manufacturing these metal products have several technological flaws, such as: 1) high energy intensity of manufacturing processes; 2) low efficiency; 3) operating conditions of large-sized products demand a high degree of resistance to stress, yet thick-plate metal parts are susceptible to stress and have a high degree of variation in their width, which increases the probability of eventual cracks, folds and other defects, lowering the reliability of the resulting metal structures. All these issues decrease the economic efficiency of manufacturing high-duty large-sized metal parts.

Plate stamping process is described in the works [1-2]. The basic principles of combined process of asymmetric rolling and plastic bending are studied and presented extensively in academic literature [2-11]. This article is directed towards developing the theory and technology of new, efficient and productive, deformation methods that are based on combining the processes of thick-plate rolling and stamping [12-13]. These new methods will allow us to produce large-sized metal parts with curvilinear surfaces (with wall thickness lying between 40 and 120 mm and diameter up to 4000 mm), from metallic materials of enhanced physical properties, under the conditions of a rolling mill without the use of

pressure equipment. The article cites the FE modelling results of a drastically new combined process of rolling and stamping. Various methods of implementing this combined process are investigated.

2 Numerical study

FE modelling of the combined rolling-and-stamping process was given with the help of DEFORM 3D software. The boundary conditions were as follows : 1) boundary surfaces of operating tools (lower die, upper die, rolls) ; 2) the surfaces of the deformed material that interact with the environment ; 3) the law of friction on contact with an operating tool ; 4) rheological model of the deformed material.

The following parameters were given as initial conditions of the model: 1) diameters and rotating speed of working rolls; 2) flow curve of the material from which the workpiece is made; 3) heating temperature of the workpiece in the oven; 4) initial dimensions of the workpiece; 5) friction coefficient m on contact with an operating tool; 6) pause time; 7) temperature of the environment ; 8) coefficients of thermal conductivity, heating capacity and ferocity of the workpiece's material ; 9) coefficients of thermal conductivity, heating capacity and ferocity of the operating tool's material ; 10) convection coefficient during thermal exchange with the environment ; 11) coefficient of deformational heating; 12) dimensions and the amount of finite elements.

The following assumptions were made in 3-D modelling of the process : 1) the deformed material is viscoplastic ; 2) the upper die, the lower die and the rolls are rigid ; 3) the stresses of contact friction are proportional to the yield strength of the shear.

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As a result of solving the three-dimensional task, the following values are determined : 1) temperature field; 2) stress field; 3) strain field.

The flow curve (deformation resistance) of 09G2S steels is described by the equation (1), and the equation (2) describes the flow curve of 10HSND steels.

$$\sigma_s = k_0 \varepsilon^{k_1} \dot{\varepsilon}^{k_2} \exp(-k_3 T), \quad (1)$$

where σ_s is the resistance to deformation, in MPa; ε is the true strain; $\dot{\varepsilon}$ – is the strain rate, s-1; T is the metal temperature, in °C; k0, k1, k2, k3 are the coefficients (see table 1).

$$\sigma_s = k_0 (10\varepsilon)^{k_1} \dot{\varepsilon}^{k_2} (0,001T)^{k_3}, \quad (2)$$

where k0, k1, k2, k3 are the coefficients (see table 2).

Table 1. Coefficients in the equation (1)

Coefficient				Range of deformation parameters change		
k0	k1	k2	k3	ε	$\dot{\varepsilon}$, s-1	T, °C
3727	0,1229	0,0718	0,00357	0,03 to 0,8	0,2...25	500 to 800
1265	0,1592	0,1048	0,00223	0,03 to 0,8	0,2...25	800 to 1200

Table 2. Coefficients in the equation (2)

Coefficient				Range of deformation parameters change		
k0	k1	k2	k3	ε	$\dot{\varepsilon}$, c-1	T, °C
82,01	0,226	0,122	-2,900	0,03...0,8	1...55	700...1200

2.1 Mathematical modelling of metal stress-strain state in the manufacturing of curvilinear bottoms

2.1.1 Modelling of thick-plate stamping process on a press

The diameter of the initial workpiece was 2660 mm, its thickness was 40 mm, it was made of 09G2C type steel. The height of the resulting metal part was 200 mm. The heating temperature of the workpiece was 900 °C. The deformation speed was 300 mm/sec, the friction coefficient was 0,7. Transporting the workpiece from the oven to the stamp took 60 sec. Deformation conditions were non-isothermal. Modelling conditions were symmetrical in one plane.

Fig. 1 - 2 show the changing stress field in the volume of the workpiece under deformation. Hot metal stamping is distinguished by significant variation of temperature across the volume of the workpiece. Therefore, considering that mechanic and plastic characteristics of a metal significantly depend on its temperature and

deformation speed, the changing temperature of the workpiece during stamping, the non-uniformity of the temperature field, the intensity of heat emission, and the friction conditions should all be taken into account when analysis the processes of hot stamping.

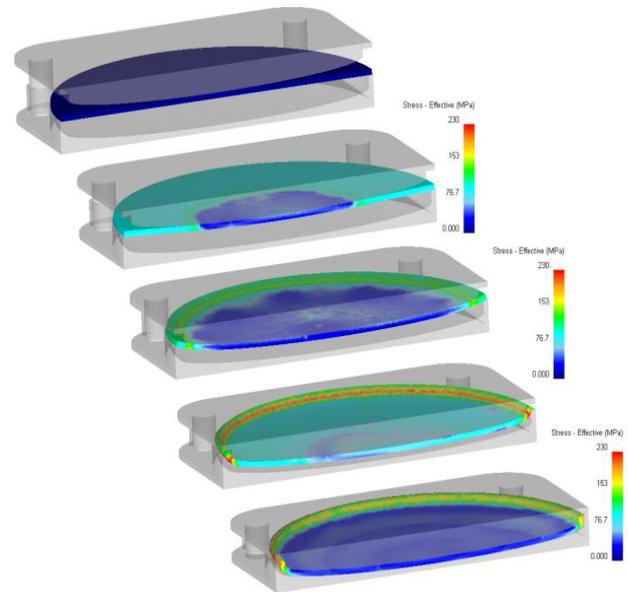


Figure 1. Stress-strain state of metal during thick-plate stamping of a curvilinear bottom

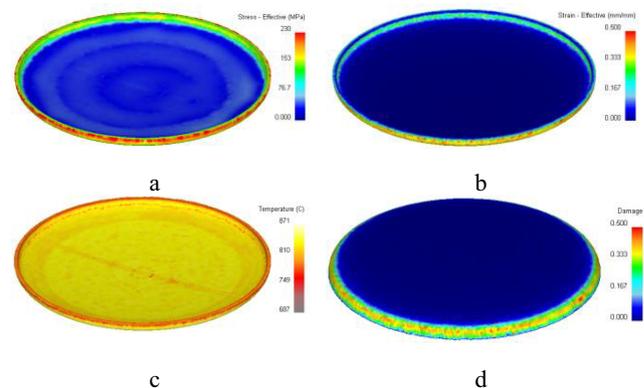


Figure 2. Curvilinear bottom: its stress field (a), deformation field (b), temperature field (c), damage probability field (d)

The deformation force was 26,1 MN (figure 3). Therefore, the mathematical model allows us to optimize the existing technologies of large-size metal part production, and to develop new ones, taking into account the metal stress-strain state.

2.1.2 Combined rolling-stamping process modelling

Two fundamentally new methods of thick plate rolling-stamping combined process for manufacturing large-sized bodies of revolution without using pressure equipment were developed. The main principle of this process is rolling of a pack consisting of two foundations - the upper die and the lower die - and the thick-plated workpiece between them. The first method of the combined process consists of picking up and gradual

rolling of the pack from the leading edge to the end section with the roll gap of pressure screws remaining in the same position. The second method includes the reverse rolling of the pack in working drive rolls, with the pack being placed in the beforehand separated rolls so that the center of the pack would be on the line that connects the rolls' axes. The rolling in this case is conducted with the changing position of pressure screws (the roll gap changes during the rolling process).

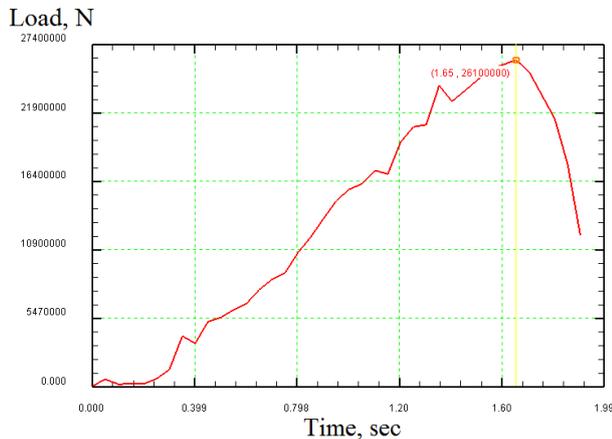


Figure 3. Change of deformation effort, in Newtons, relative to time, in seconds, in thick-plated curvilinear bottom stamping

The following parameter values were used in modelling:

The diameter of the initial workpiece was 2660 mm, its thickness was 40 mm, it was made of 09G2S steel. The height of the resulting metal part was 200 mm. The heating temperature of the workpiece was 900 °C. The strain rate was 300 mm/sec, the friction coefficient was 0,7. Transporting the workpiece from the oven to the stamp took 60 sec. Deformation conditions were non-isothermal. Modelling conditions were symmetrical in one plane.

The shapes of upper and lower dies and the FE model of the pack is shown in figures 4-6.

The modelling results have shown that the main issue that arises is the possible loss of pack fixity during rolling, and the consequent formation of defects in the form of folds. Accordingly, increasing the quality of manufactured parts is a primary problem during the process. In order to solve it, compliance with the requirements of material durability, form accuracy and surface quality. A necessary condition for this compliance is the absence of technological failures, e.g. flaw signs in the form of deformation localization with the proceeding breakdown; breakdowns die to the metal of the workpiece lacking plasticity; formation of folds, etc.

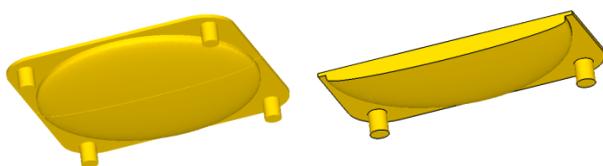


Figure 4. Upper die

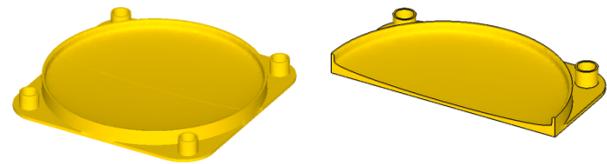


Figure 5. Lower die

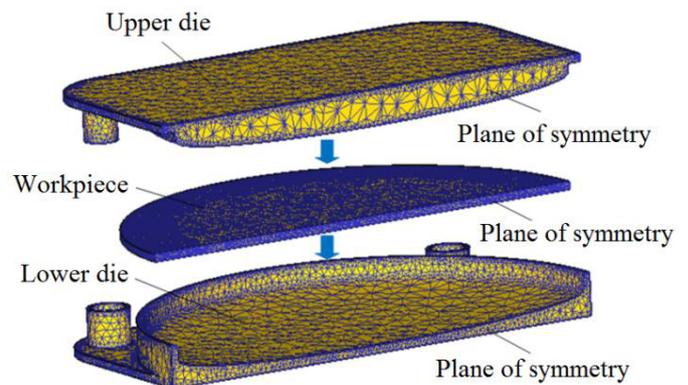


Figure 6. FE model of the packet

Figures 7 to 9 show cases of fixity loss. The deformation of the metal workpiece and the subsequent appearance of folds under the influence of tangential compressive stresses, eventually lead to spoilage of the workpiece. Folds, for instance, are formed in the workpiece's flange during the flanging of the convex curvilinear profile of the part. This flaw is theoretically repairable, however the technological process should be conducted as to prevent the conditions under which the compression becomes unfixed. Prevention of undesirable folds is a main task that arises during both planning and adjusting the combined rolling-stamping process.

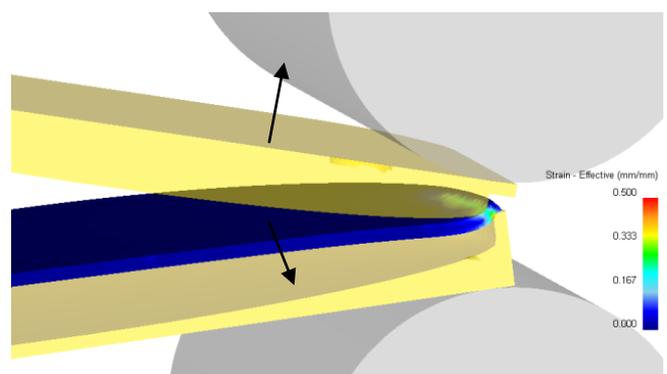


Figure 7. Loss of pack fixity during rolling

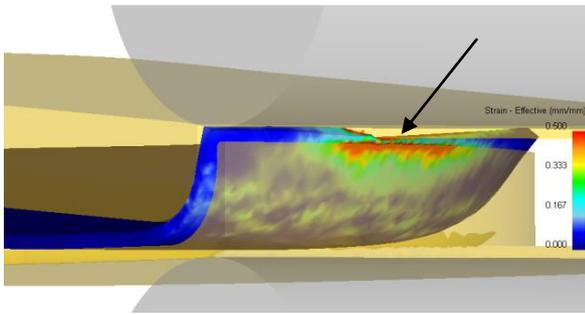


Figure 8. Detail deformation, appearance of folds

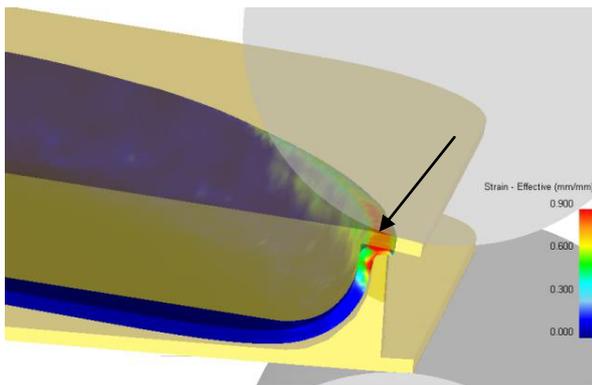


Figure 9. Detail deformation with the formation of a fold

Our investigation of stress and strain metal state was conducted for two deformation methods: direct and reversed. The direct method consists of picking up and gradual rolling of the pack from the front edge to the end section with the roll gap of pressure screws remaining in the same position. The 3-D modelling of the combined process was conducted with the assumption of the process being symmetrical about the vertical plane, in order to speed up the calculations (figure 10).

The model of the process is shown in figure 11. It includes assembling a pack from the upper die, the lower die and the sheet workpiece between them, and rolling the pack in the working rolls of the plate mill.

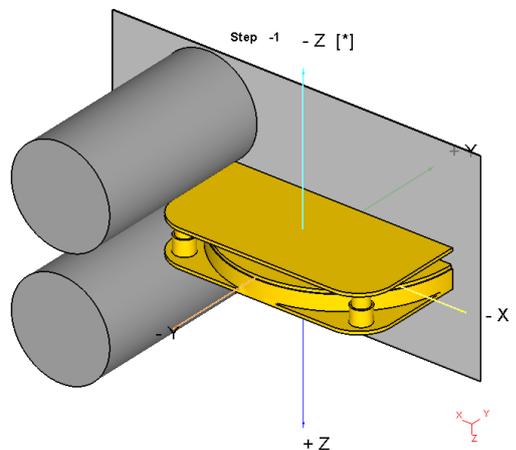


Figure 10. The symmetry plane of the combined rolling-stamping process

A vital part of the process being realized successfully is fulfilling the conditions of picking up the pack in its hot rolling (figure 12):

$$\Delta H_{pack} \leq 2R(1 - \cos \alpha), \quad (3)$$

$$\alpha = \arctg(m), \quad (4)$$

where ΔH_{pack} is the absolute compression of a pack, in mm ; m is the friction coefficient, and R is the radius of a roll, in mm.

$$H_{pack} = h_{top} + h_{blank} + h_{lower}, \quad (5)$$

where h_{top} is the height of the upper die, in mm; h_{blank} is the thickness of the workpiece, in mm; h_{lower} – is the height of the lower die, in mm.

The formula (3) can be rewritten as thus:

$$\Delta H_{pack} = h_{top}, \quad (6)$$

$$h_{top} \leq 2R(1 - \cos \alpha), \quad (7)$$

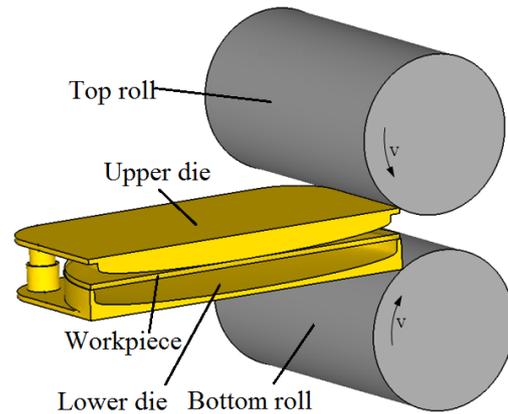


Figure 11. Forward method of thick plate rolling-and-stamping combined process

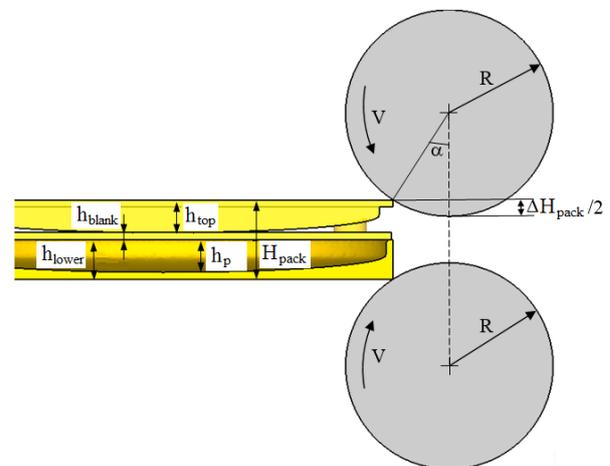


Figure 12. A scheme describing the conditions of the successful process

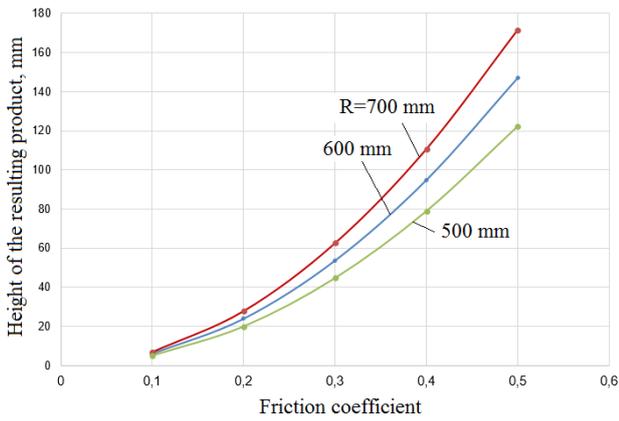


Figure 13. The influence of friction coefficient and roll radius on the maximally possible height of the resulting product

The height of the resulting product is determined by the height of the upper die, and thus also determined by the conditions in which the pack is packed up at the initial state of the combined thick-plated rolling-and-stamping process.

The interrelation between the maximum possible height of the resulting product, the radius of working rolls and the friction coefficient is shown in Figure 13.

An analysis of the temperature field has shown that during transportation time, the temperature of edge areas of a workpiece decreases significantly: from 900 °C to 764 °C. This can lead to higher stress in these areas during metal deformation, since the most intensive plastic strain takes place exactly there.

This testifies to the non-uniformity of plastic strain in the workpiece's volume about its central symmetry axis. The high intensity of stresses on the foremost area of the workpiece leads to a higher probability of cracks, folds there. On the foremost area of the workpiece the strain happens in a very short period of time, right during the pack is picked up by the rolls. As a result of this, the force rapidly increases, which can negatively affect the process stability and even lead to equipment damage.

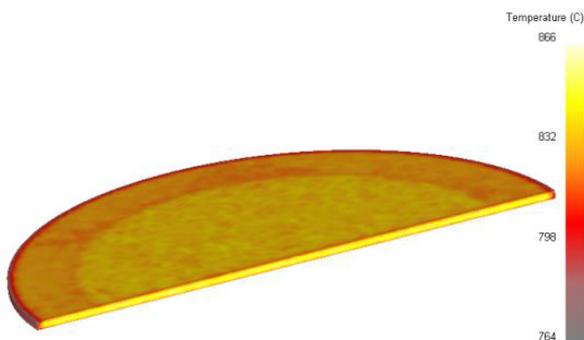


Figure 14. Temperature field of the initial sheet workpiece before deformation

An analysis of the stress and strain metal state in different stage of the combined thick plate rolling-and-stamping process according to the forward method has shown that stresses localize in the area where the elliptic bottom undergoes a plastic bend, and that this

localization is consecutive in time. Thus, in the first strain stage, during the pick-up, the highest stress intensity in the foremost area of the workpiece, and then it radially moves in the direction of the rear area of the workpiece (as illustrated by the arrows in Figure 15).

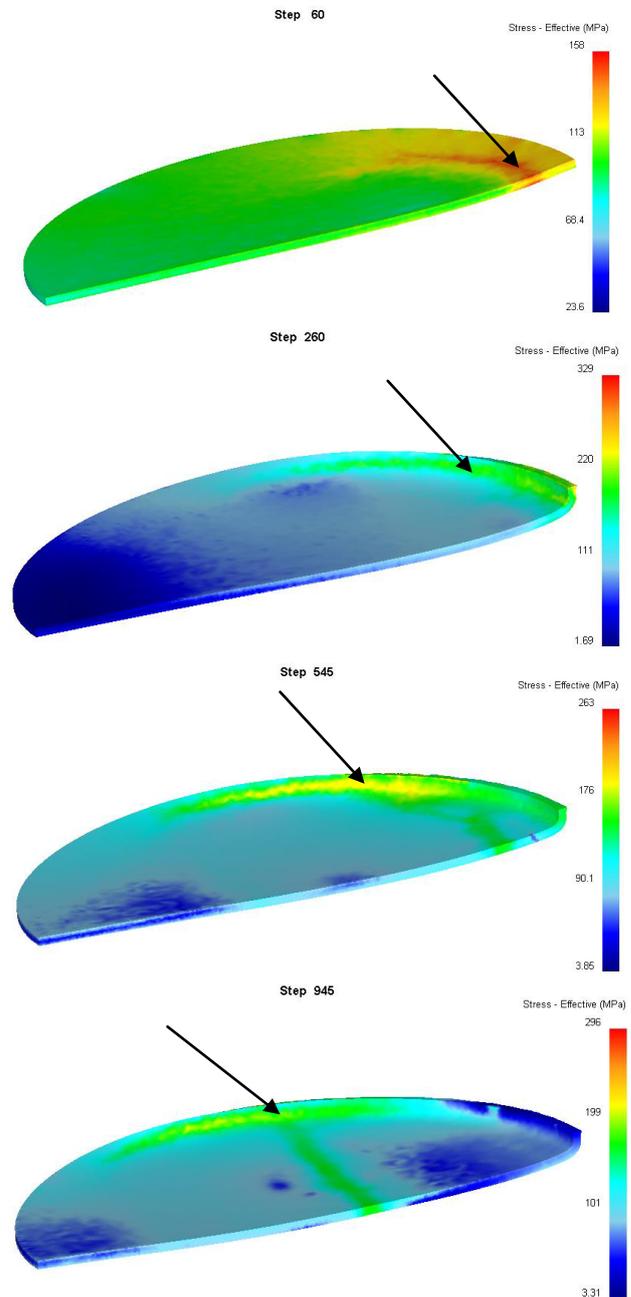


Figure 15. Change of stressed workpiece state in different calculation steps

The strain at the level 0,4 is localized at the external surface of a workpiece (Figure 16). The high strain here, combined with workpiece thickness of 40 mm can be critical in relation to the possibility of metal discontinuity flaw in this area during the time the workpiece is picked up by the rolls.

In manufacturing elliptical bottoms by the combined rolling and stamping method, the influence of the workpiece's relative thickness is especially important. If during the thin plate deformation the relative thickness

influences the flange fixity and leads to a certain change in the limiting drawing coefficient, during the deformation of a thick plate it influences the area of contact friction, the degree of wall thinning, and the circumstances of contact between the workpiece and the instrument.

Eventually, this leads to an increased danger of production defects due to excessive thinning of the wall and the formation of folds. Extensive mathematical modelling of the combined rolling-and-stamping process with different process parameters (changing the workpiece thickness from 40 to 60 mm, the strain rate, the temperature and friction conditions) has shown that in all cases the largest deformation localizes in the external radius of the bottom.

A particularity of the reverse rolling-and-stamping method (Figure 17) is that the process of tension and deformation distribution in the workpiece volume occurs differently. In particular, our analysis has shown that during the vertical-plane convergence of the rolls (due to pressuring mechanisms) the deformations are localized in the central part of the workpiece (Figure 18). During the further stages, tensions localize on the flanges of the elliptical bottom (Figures 19-20).

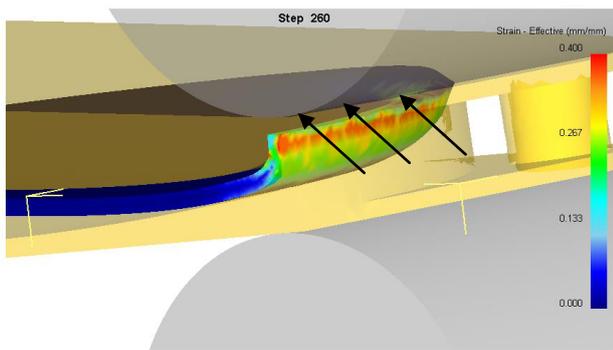


Figure 16. Intensity field of deformation during the moment the pack is picked up by the rolls

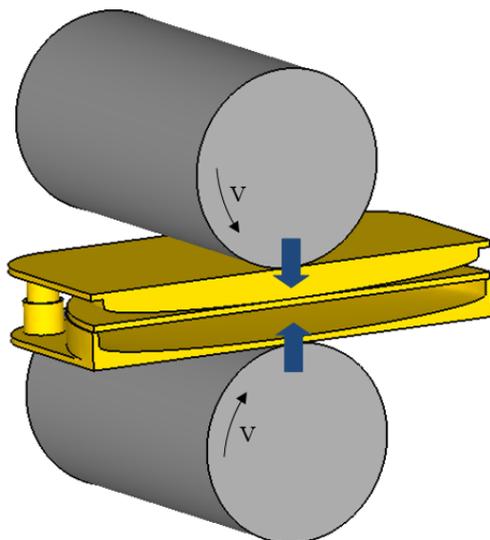


Figure 17. Reverse method of the combined thick plate rolling and stamping

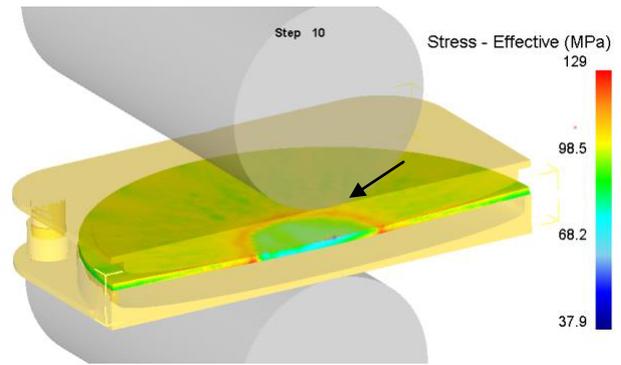


Figure 18. Stress intensity field of the workpiece's volume during the first deformation stage

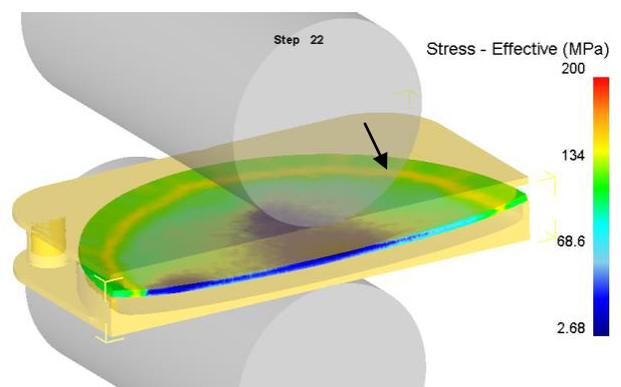


Figure 19. Intensity field of tensions in the volume of the workpiece during the second stage of deformation

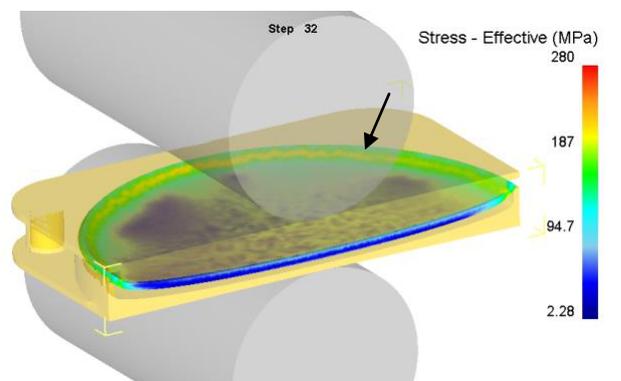


Figure 20. Intensity field of tensions in the volume of the workpiece during the second stage of deformation

The geometry of the resulting solutions is in good agreement (deviation is not higher than 6%) with the experimental results.

3 Conclusion

Two fundamentally new methods of combined thick plate rolling-and-stamping for manufacturing bodies of rotation (without using pressure equipment) were developed. The principle of rolling a pack of upper die, lower die, and the thick plate workpiece between them is the foundation of the whole process. The first method of

the combined process involves the pick-up and successive rolling of the pack from the foremost edge to the end area with the roll gap (pressure screw position) being kept the same all the way. The second method involves the reverse rolling of the pack in drive working rolls, with the pack being placed in the separated rolls so that its center is on the line connecting the rolls' axes, and the rolling being conducted with the changing positions of pressure devices (meaning, a changing roll gap).

The results of FE modelling of the combined rolling-and-stamping process with the help of DEFORM 3D software have shown that the key problems of the process is the loss of pack fixity during the rolling, and the corresponding defects in the form of folds, increasing the consumption index and increasing the production cost of the resulting detail.

The investigation and 3D modelling of the two methods of the combined process of thick plate rolling and stamping process were conducted. A 3D analysis of the metal stressed-strained state during the combined rolling and stamping process is worked. It was shown that on the 0,4 level the strain localizes at the external surface of the workpiece. A high strain value combined with workpiece thickness of 40 mm or more can be critical in relation to the possibilities of discontinuity flaws appearing in this area.

It was established that during the forward-method rolling the maximal pulling stresses arise in the forefront are of the pack, in particular, on the forefront areas of the top and the lower dies. The stress levels there can reach 1000 MPa. Such high values of tensile stresses are in large part explained by the fact that the workpiece is hot, and the instruments (the upper and lower dies, the rolls) are cold, having the same temperature as the environment.

For the reverse deformation method, the patterns of stressed-strained metal (workpiece and both dies) state change, depending on the process parameters (temperature of workpiece heating, its thickness, the speed of deformation, friction conditions) were established.

The modelling results allowed us to optimize the shapes of the upper and lower dies, and also to optimize the construction of the pack, taking the stability of the rolling-and-stamping process into account. The benefits and the flaws of both combined process methods were established. The reverse deformation method was determined to be preferable for practical realization, from the point of view of process stability and energy efficiency.

A complex technical solutions that allow the use of rolling mill for manufacturing large-size bodies of revolution was developed. Two combined processes - rolling and stamping, and also asymmetric rolling and bending - were proposed for this.

Acknowledgements

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References

1. V.A. Demin, Development of a method of the plate stamping processes designing on the basis of forecasting of technological failure: D. Sc. Thesis. Moscow (2003) 342.
2. H. Karbasian, A.E. Tekkaya, A review on hot stamping, *Journal of Materials Processing Technology*. 210 (2010) 2103-2118.
3. A. Pesin, V. Salganik, E. Trahtengertz, M. Cherniahovsky, V. Rudakov, Mathematical modeling of the stress-strain state in asymmetric flattening of metal band, *Journal of Materials Processing Technology*. 125-126 (2002) 689-694.
4. A. Pesin, Practical results of modeling asymmetric rolling, *Steel in Translation*. 33 (2003) 46-49.
5. A. Pesin, New solutions on basis of non-symmetric rolling model, *Stal*. (2003) 66-68.
6. A. Pesin, V. Salganik, E. Drigun, D. Chikishev, Device for asymmetrical rolling metal plate, RU Patent 38646 (2004).
7. A. Pesin, V. Salganik, E. Drigun, D. Chikishev, Device for asymmetrical rolling metal plate, RU Patent 2254943 (2005).
8. A. Pesin, V. Salganik, D. Chikishev, Device for asymmetrical rolling metal plate, RU Patent 54831 (2006).
9. A. Pesin, D. Chikishev, S. Blinov, Device for measuring a radius of curvature of the cylindrical surface of large parts, RU Patent 56592 (2006).
10. A. Pesin, D. Chikishev, S. Blinov, D. Pustovoytov, Device for asymmetrical rolling metal plate, RU Patent 87649 (2009).
11. M. Sverdlik, A. Pesin, D. Pustovoytov. *Advanced Materials Research* (2012)
12. A. Pesin, E. Drigun, D. Pustovoytov, I. Pesin. *MATEC Web of Conferences*. 26 03007 (2015)
13. A. Pesin, E. Drigun, D. Pustovoytov, I. Pesin. *Key Engineering Materials*. Vol. 685, (2016) 375-379