An Approach to Simulation of Flow Forming Using Elastic-Visco-Plastic Material Model

Nikolay Biba
(Micas Simulation Ltd.)
Alexey Vlasov, Sergei Stebunov and Alexander Maximov
(QuantorForm Ltd.)

ABSTRACT

The paper presents the experience of development and implementation of the elastic-visco plastic material model to flow forming process. As an incremental process the flow forming is characterised by much localised plastic deformation near the contact zones with the rolls while the rest of the workpiece can be considered as a “rigid” body. Meanwhile as it is shown in the paper it is impossible to neglect elastic components of strain even though they are much smaller compared to the large plastic strain that shapes the parts. The comparison of rigid-visco-plastic and elastic-visco-plastic models has shown that the influence of elastic components of deformation has a great influence on proper prediction of the deformation pattern and final product shape. The developed model has been implemented as a part of QForm v8 metal forming simulation software and is now in use for development of flow forming technology.

1. INTRODUCTION

Most bulk metal forming processes are numerically simulated using rigid-visco-plastic material model because the elastic deformations are very small compared to large plastic strain (Biba et al., 2008). The influence of elastic stress in non-deformed zones usually is not significant. The spring-back effect that is very important in sheet metal forming has no significant influence in bulk forming and is usually neglected as well. Nonetheless there is a group of cold bulk metal forming processes where small elastic strain has critical influence on the deformation pattern and final product shape. This effect can be observed in some incremental metal forming processes and particularly in flow forming (Figure 1).

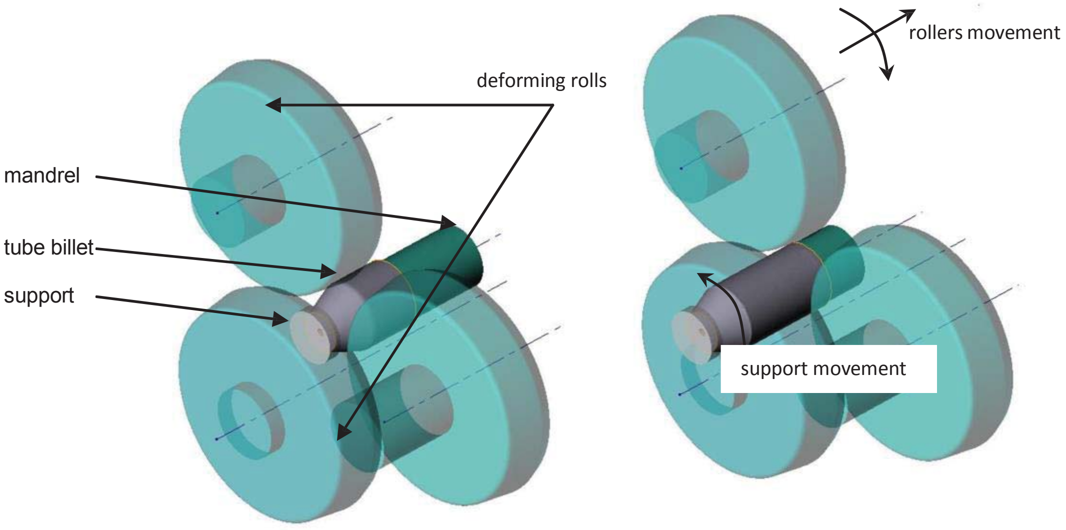

Figure 1: Scheme of flow forming (initial position — left and final stage — right)

A characteristic feature of this process is the presence of small local zones of plastic deformation under the deforming rolls. The remaining volume of the metal is in an elastic state.

There are several works dedicated to investigating flow forming processes both experimental and numerical (Wong et al. 2005, Hua et al. 2005, Kuss et al. 2014, etc).

The purpose of this work is to compare how the type of a material model (rigid-visco-plastic or elastic-visco-plastic) may influence the results of simulation. Besides the material model, the development of an effective numerical code for flow forming simulation also requires a special technique to calculate components of large strain tensor during the billet rotation. Furthermore, the rotating of the workpiece in an FE analysis tends to result in volume change due to projection of nodes along the tangential velocities so it is important to separate rotational and linear components of velocity when calculating new positions of nodes at each time increment.

2. RIGID PLASTIC SIMULATATION OF FLOW FORMING PROCESS

As a first test we have run a simulation of the flow forming process using a rigid-visco-plastic material model. Parameters of the process are the following:

- internal diameter of the tube billet made of steel C22 (DIN 1.0402) is 70 mm;
- initial wall thickness is 3.85 mm, final thickness is 1.8 mm (depth of penetration of three rolls correspondingly 1, 0.55 and 0,5 mm);
- billet rotation speed 580 rpm;
- linear velocity of rollers is 4 mm/s with free rotation around own axes:
- diameter of rolls — 255 mm and they have the same shape.

The results of simulation are shown in Figue 2. We use tetrahedral elements that automatically remesh and provide easier adaptation of the mesh: Making it fine in areas of intensive plastic deformation.

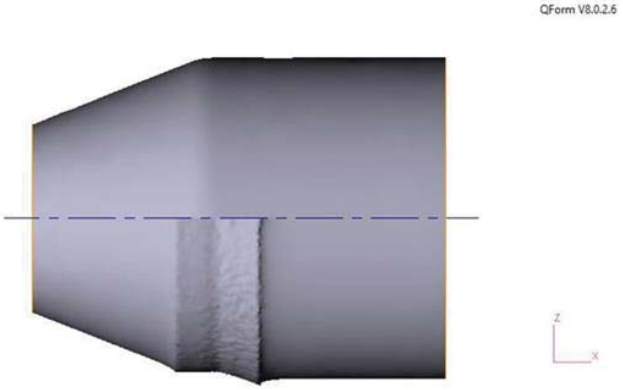

Figure 2: The initial (top half) and deformed (bottom half) shape of the bilet when simulating flow forming with the rigid-visco-plastic model of the material

As can be seen from Figure 2 there is no elongation of the billet during the process simulation in this case. We can observe the formation of a large circular bulge in front of the first roll and a smaller bulge behind while the last one is then smoothed by the following other two rolls. It is obvious that these results do not correspond to the actual deformation pattern where there is a gradual lengthening of the workpiece during the whole process. Any variation of the properties of deformed material (actually its flow stress), changing friction and heat transfer conditions at the contact with the rolls did not change the described above behaviour deformation pattern. Thus it was natural to make an attempt for simulation with an elastic-visco-plastic model.

3. ELASTIC PLASTIC FORMULATION

The elastic-visco-plastic model in QForm is based on the Prandtl-Reuss equations (Jones, 2009). It is assumed that the total strain during deformation is the sum of the elastic and plastic strains. When formulated in velocities these constitutive equations take the form:

$$\dot{\varepsilon}'_{ij} = \frac{\dot{\sigma}'_{ij}}{2G} + \frac{3}{2}\frac{\dot{\bar{\varepsilon}}^{p}}{\bar{\sigma}} \cdot \sigma'_{ij} \qquad (1)$$

where σ'_{ij} is the deviatoric stress, $\dot{\varepsilon}'_{ij}$ is the deviatoric strain-rate, $\bar{\sigma}$ is the effective stress, $\dot{\bar{\varepsilon}}^{p}$ is the plastic strain-rate of plastic strain, G is the shear modulus. In these equations the strain rate depends both on the deviatoric stress and its first derivative by time $\dot{\sigma}'_{ij}$. The first term in the formula is the contribution of elastic deformation and the second term is specified by plastic deformation of the material.

When using equation (1) for formulating a system of equations for numerical solving the elastic-plastic problem it is necessary to approximate the first derivative of the stress using its finite difference over a small time interval Δt:

$$\sigma = \frac{d\sigma}{dt} \approx \frac{\Delta\sigma}{\Delta t} \overset{\cdot}{=} \frac{1}{\Delta t}(\sigma - \tilde{\sigma}) \qquad (2)$$

where the sign `~` is used to denote the value of the function at previous instant of time and implicit integration is supposed to be used. Finally the expression for elastic-plastic model can be written as follows:

$$\sigma'_{ij} = 2G^{p}\Delta t \cdot \dot{\varepsilon}'_{ij} + \frac{G^{p}}{G}\tilde{\sigma}'_{ij} \qquad (3)$$

where

$$\frac{1}{G^{p}} = \frac{1}{G} + \frac{3\dot{\bar{\varepsilon}}^{p}}{\bar{\sigma}} \qquad (4)$$

Equations (3) should be complemented by the relation between the increments of volume strain and mean stress:

$$\sigma_0 = K\Delta t\dot{\varepsilon}_V + \tilde{\sigma}_0 \qquad (5)$$

where K is the bulk elastic modulus.

To get complete system of governing equations we have add to (3) and (5) also equilibrium equations

$$\sigma_{ij,j} = 0 \qquad (6)$$

compatibility conditions

$$\dot{\varepsilon}_{ij} = \frac{1}{2}\left(v_{i,j} + v_{j,i}\right) \qquad (7)$$

energy balance equation for thermal task

$$\rho c\dot{T} = \left(k_1 T_{,i}\right)_{,i} + \beta\bar{\sigma}\dot{\bar{\varepsilon}} \qquad (8)$$

and expression for the flow stress:

$$\bar{\sigma} = \bar{\sigma}(\bar{\varepsilon}^{p}, \dot{\bar{\varepsilon}}^{p}, T) \qquad (9)$$

where σ_{ij} , $\dot{\varepsilon}_{ij}$, v_i – stress, strain-rate and velocity components respectively, $\bar{\varepsilon}^p, \dot{\bar{\varepsilon}}^p, T$ – effective stress, effective strain and effective strain-rate, respectively, T – temperature, β – heat generation efficiency which is usually assumed as $\beta = 0.9 \div 0.95$, ρ – density, c – specific heat and k_1 – thermal conductivity.

The governing equations have been transformed into discrete form by means of virtual work-rate principle and finite element technique resulting in non-linear system of algebraic equations where nodal values of velocity components and mean stress are considered as independent variables. Velocity and mean stress are approximated using linear shape functions in triangle (2D) and tetrahedral (3D) finite elements. Energy balance equation (8) is treated by means of weighted residual (Galerkin) method. Iterative updating of heat generation and flow stress provides thermo-mechanical coupling of the problem.

4. ELASTIC PLASTIC SIMULATATION OF FLOW FORMING PROCESS

The use of the elastic-plastic material model described above has radically changed the billet deformation pattern.

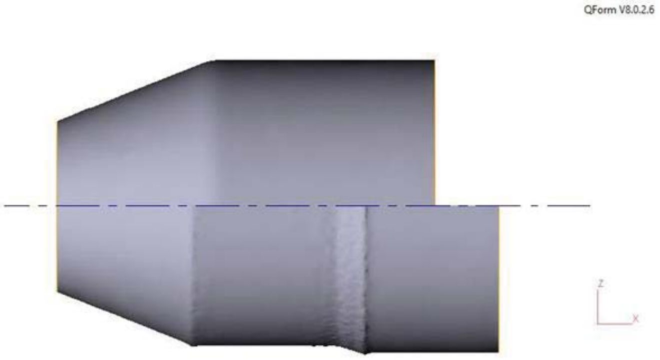

Figure 3: The initial (top half) and defrmed (bottom half) shape of the billet when simulating flow forming with the elastic-visco-plastic model of the material

As seen from Figure 3 the bulge that appears in in front of the first roll is substantially less than the one shown in Figure 2 and there is a gradual lengthening of the billet after the movement of rolls. Thus the use of the elastic-plastic model can adequately describe the material deformation in flow forming.

5. COMPARING RIGID-PLASTIC AND ELASTIC-PLASTIC SOLUTIONS

Comparison of the results of simulation done using the two different models of deforming material allows us to make certain conclusions why the elastic-plastic model works better than the rigid-plastic one. Figure 4 shows the distribution of velocities along the axis of rotation of the workpiece for both variants of the material.

As can be seen the velocity distribution in two cases is very different. The extending of the non-zero axial velocity in the case of elastic-plastic model is substantially greater than for the rigid-plastic solution where it is limited to a relatively small area near the contact with the tool. At the same time the maximum axial velocity in the deformation zone of a rigid-plastic model is about two times higher compared to the elastic-plastic model (from -200 mm/s to +400 mm/s versus -100 mm/s to +200 mm/s respectively though these values don't show on Figure 4).

The strain-rate in the rigid-plastic model is also about two times higher compared to the elastic-plastic model but the difference between them is decreasing with distance from the contact area.

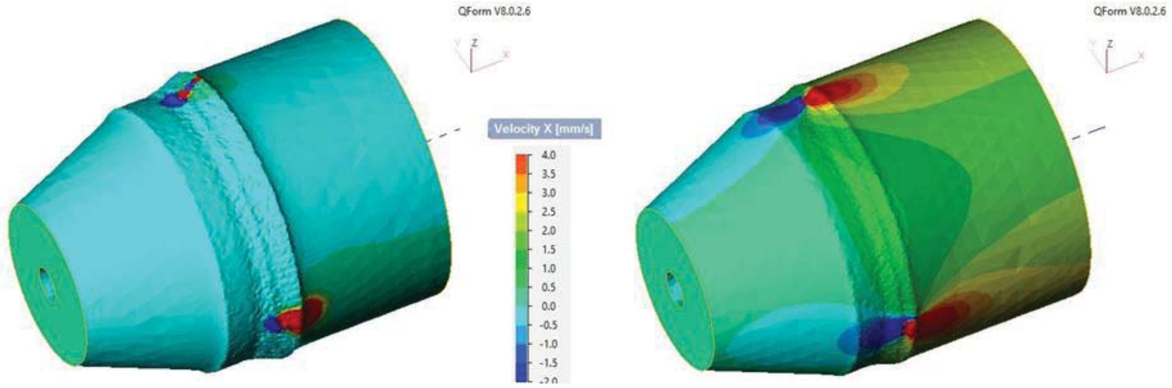

Figure 4: Distribution of axial velocity for a rigid-plastic (left) and elastic-plastic (right) models. The velocity variation range here is limited from -2.0 mm/s to +4 mm/s

Thus for the first case we have an intense deformation in a small area near the contact with the tool, which decreases rapidly with increasing distance from the contact. Such a deformation pattern causes the creation of a bulge of material in front of the rolls but no elongation of the workpiece can be observed. In the second case the axial velocity in the free end of the workpiece is substantial. Although axial displacements are largely restricted by the elastic deformation, nevertheless partially they remain in the workpiece since the presence of plastic zones prevents complete unloading of the elastic deformation.

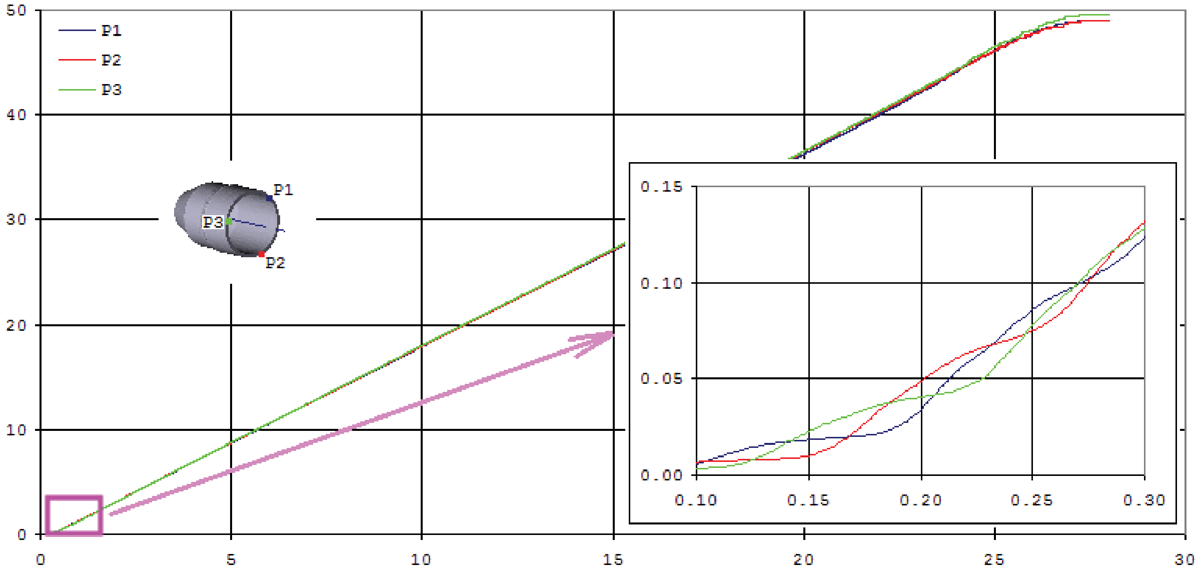

Figure 5: The axial displacement of the tracking points placed at the end of the workpiece versus time

Figure 5 shows graphs of displacement in three points placed at the end of the workpiece. Magnifying the scale we can clearly see that their displacement has a wavy character that corresponds to changing their positions with the respect to the rolls. When the roll passes through the line where the point is placed the local maximum of displacement is observed and then follows relative decreasing of the displacement. However due to plastic deformation some part of the longitudinal deformation is irreversible that finally causes an almost uniform elongation of the preform.

The developed model implemented in QForm V8 also provides calculation of the other parameters of a flow forming process like the temperature and strain (Figure 6). Using coupled modelling of the billet deformation and thermal problem in the tools (Stebunov et al., 2011) allows for evaluating the heating of the tools during deformation (Figure 7).

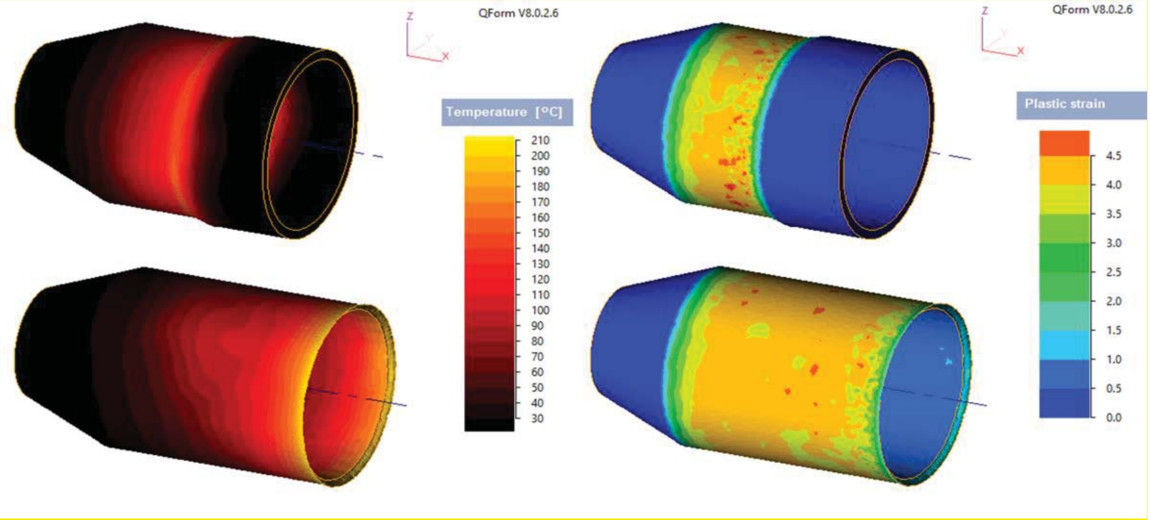

Figure 6: Distribution of the temperature (left) and plastic strain (right) fields in flow forming

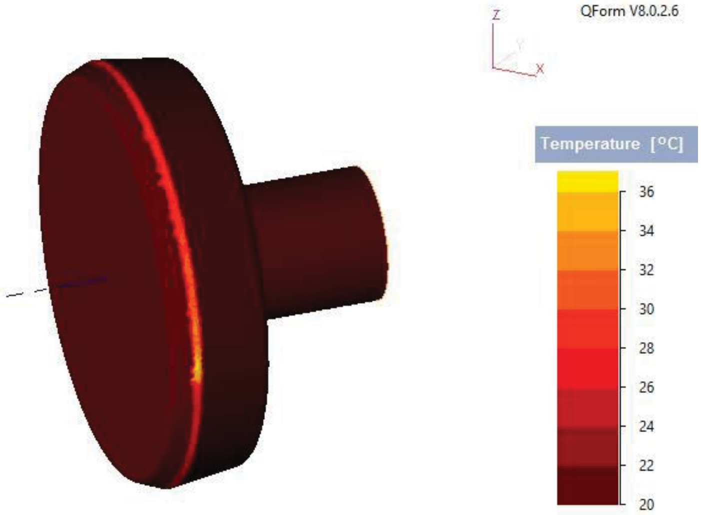

Figure 7: Heating up of the rolls in the contact zone

6. CONCLUSION

The use of rigid-visco-plastic material model for simulation of a flow forming processes in some cases may lead to unacceptable results. Even though the elastic strain component is less than 0.004 (0.4%) and seems incomparable to plastic strain that may reach 2-4 units in this process it has significant influence on formation of the product shape. The elastic-visco-plastic material model provides much better prediction of the product shape. It also provides for predicting distribution of the other parameters like temperature in the billet and rolls. Further development of the model requires analysis of the influence of the contact conditions (friction and heat transfer coefficient) and comparing with experimental results.

REFERENCES

Biba, N., Stebunov, S. and Vlasov A., 2008, Material forming simulation environment based on QForm 3D software system, 12th International Conference Metal Forming 2008,Vol. 2, pp.611–616

Hua, F.A., Yang, Y.S., Zhang, Y.N., Guo, M.H., Guo, D.Y., Tong, W.H. and Hu, Z.Q., 2005, Three- dimensional finite element analysis of tube spinning, Journal of Materials Processing Technology, Elsevier 168, pp.68–74

Jones, R. M., 2009, Deformation Theory of Plasticity, Bull Ridge Publishing, pp. 640

Kuss, M. and Buchmayr, B., 2014, Radialschmieden versus Zylinderdrückwalzen, BHM (2014) Vol. 159 (5): Springer-Verlag Wien, pp.208–213

Stebunov, S., Biba, N., Vlasov A. and Maximov, A., 2011, Thermally and Mechanically Coupled Simulation of Metal Forming Processes, Proceedings of the 10th International Conference on Technology of Plasticity, Aachen, Germany, pp.171-175

Wong, C.C., Lin, J. and Dean T.A., 2005, Effects of roller path and geometry on the flow forming of solid cylindrical components, Journal of Materials Processing Technology, Elsevier 167, pp.344–353