Simulation of upsetting process using kinematic schemes of metal flow

K N Solomonov1*, L I Tishchuk1, S N Lezhnev2 and E A Listrov3
1Branch of Rostov State University of Railways Engineering in Voronezh, Voronezh, Russia
2Rudny Industrial Institute, Rudny, Kazakhstan
3Voronezh State Agrarian University, Voronezh, Russia

*konssol@list.ru

Abstract. The problems of simulation on the basis of kinematic schemes of metal flow, which is observed in the processes of forging and stamping workpieces with flat areas, are considered. Presented traditional kinematic schemes of metal flow: normal and radial. To solve these problems, a modernized program complex EQUI was developed, which is used for computer simulation of metal flow in the workpiece plane. It is shown that for any parameters of upsetting process is a real «intermediate» kinematic scheme of metal flow, which consists of areas of the flow normal to the contour and areas of radial flow. The results of a virtual experiment were obtained using the program complex DEFORM, which has proven well in solving plastic forming problems. For computer simulation of the spatial diagram of contact stresses and the dividing line of metal flow is selected known software COMPAS. The horizontal projection of the solid model allows you to get an image of the dividing line of metal flow. Comparison of results, obtained in the COMPAS and EQUI, shows good agreement.

1. Introduction
In the domestic and foreign literature [1-36], a lot of attention is paid to the issues of macrostructural changes in the processes of plastic deformation and related problems in the metallurgical field. However, there remain a number of open topics that require additional research.

Under certain conditions, in some processes of forging and stamping, when the metal flow on the workpiece web has a significant effect on the forming, a deformation scheme of upsetting is observed. To study the patterns of metal flow on the workpiece plane, the choice of the kinematic scheme of metal flow (KSMF), which most accurately describes the plastic deformation of the workpiece plane, is essential.

2. Analysis of various approaches to solving the problem
Famous soviet scientists, M. Storozhev and E. Popov, in his book «The theory of metal forming» give the limit cases KSMF – normal and radial (figure 1). In accordance with normal KSMF flow lines (FL) are directed normal to the contour of the workpiece. Then, a rectangular plate in the rain should turn into a polygon.
In accordance with the radial KSMF streamlines are directed along the radius of a circle at an angle to the contour of the workpiece. Then, in the process of deformation rectangle grows in size, but not change its shape. Referring to the work of predecessors, the authors of this book argue that the form KSMF mainly depends on the friction coefficient (exponent). In this case, the normal KSMF typical case where the friction coefficient is 1, and the radial – zero. It is clear that in practice, both options are unattainable because assumed that the friction coefficient on metal forming (MF) varies from 0.2 to 0.6.

In real processes, precipitation rectangle is deformed into an ellipse, and then in a circle, and there are so-called «ears». These facts are described in the experiments, C. Zobbe, whose results were published in 1908 in his article «On the technology of forging». Similar results were obtained I. Tar-novsky in the 50-60 years of last century. He conducted experiments on a relatively thin steel and lead samples, the ratio of thickness to which the linear dimension in the plan were approximately equal to 0.1. In experiments with plasticine, held V. Abashkin at the beginning of this century with the aim of physical simulation of forging operations, observed «bulging sides» and «ears». In this case, unlike the free-precipitation, we have the so-called «hard endpoints» that restrict the metal flow. Described experiments conducted for over 100 years by different researchers, indicate that actually there is some «intermediate» KSMF, which agrees with the opinion of M. Storozhev and E. Popov.

![Figure 1. Normal and radial KSMF](image)

Attempt to combine the normal and radial circuits made at the end of the last century, researchers led by I. Kostarev. They raised the idea that at the initial moment of deformation occurs KSMF normal, and then – «pseudoradial» which combines elements of the normal and radial KSMF: the dividing line of metal flow (DLMF) are located as well as in a normal, but MF directed along the radii of the arcs of some circles, the positions are determined by boundary conditions. It would seem that such an approach from the normal scheme of little use because it is unclear what constitutes the initial moment and when it ends. However, it seems that it is a normal scheme allows us to estimate (to express analysis) of the pattern of metal flow, which is extremely important in a production environment. Let the laid large errors, but the result can be obtained quickly and clearly. Especially, the normal scheme is relatively easy to formalize and allows you to use so-called «sand analogy» used in the theory of flow of a thin plastic layer (TFTPL) A. Ilyushin. Minus only in that it only describes the deformation of thin pieces and does not account for the friction coefficient.

3. Research methods
For a final clarification, looks like a real KSMF need to conduct experiments. However, the first such experiments already conducted a number of researchers, as mentioned above, and secondly, we need such experiments that will reveal the velocity field or the displacement of the entire area of workpiece, that is to define «structure» of the metal flow. And as with physical simulation to make the pattern of the metal flow is not visually very clear. Anyway, this problem is very complicated. If we take into...
account the inevitable time and financial costs of preparing and conducting the experiment, the problem altogether is becoming unattractive.

The only productive output in this situation – replacing the physical experiment computer simulation.

*Computer simulation* today is considered the most productive and powerful way to simulation that integrates and numerical and graphical methods.

All methods of computer simulation can be divided into two categories: methods of simulation processes (MSP) and methods simulation objects (MSO).

MSP can be attributed to the CAM/CAE and other systems that can simulate the process in a particular subject area. Such programs are called applications. In the field of MF, these include DEFORM, FORGE, ANSYS, SPLEN and others.

The MSO include the CAD systems to simulation the geometric objects (from primitives to complex curved surfaces). In addition, such systems provide an opportunity to design complex machinery and to prepare them for the design documentation. Examples of these CAD systems are COMPAS, SolidWorks, Unigraphics.

Vivid demonstration of the possibilities of automation of engineering calculations and computer simulation can serve as a software complex EQUI (figure 2), implemented in an environment of visual programming DELPHI, which is based on normal KSMF.

The program complex EQUI, designed to calculate the parameters of the forging and simulation of plastic deformation of the workpieces consist of three major programs that provide the solution of static, kinematic and dynamic problems.

![Figure 2](image.png)

**Figure 2.** Capabilities of the program complex EQUI

The solution of the static problem is consistent with the principle of the shortest normal, according to which the metal to the contact plane flows along FL, directed orthogonally to the contour of forgings. In this case DLMF is the locus of points equidistant from the contour of workpiece, or equidistant.

The solution of the kinematic problem is based on the principle of least perimeter, according to which the true pseudoradial scheme of metal flow, which is characterized by the fact that FL are directed orthogonally to conditional curve, which is a level line on the surface of the contact stresses. Then the metal flows along the radius of a circle, called a conditional contour.

Dynamic problem is reduced to constructing a spatial diagram of contact stresses (SDCS), which is a combination of conical and polyhedral surfaces. And in projection on the plane of contact edges of the surface are the DLMF and the line slope - FL.

In the program complex EQUI [37-40], which obviously relates to MSP, provided the unit to build SDCS obtained on the basis of a flat pattern of metal flow. To construct the SDCS necessary KSMF
located on the contact plane as DLMF, «to restore the space» until the volume figures. Such a problem causes considerable complexity in the formalization of the solution.

However, simulation of normal KSMF, and along with it and SDCS based on an analogy with the equal-slope surface (ESS), possibly in a simpler way, namely, using one of the MSO, such as COMPAS. It should, incidentally, be noted that apparent simplicity is due to two factors: firstly, one of the methods of obtaining solid models into a COMPAS called the «extrusion», which is the construction of the ESS on a given contour, which is consistent with the ideas TFTPL, and secondly, simple, the problem is just for us – users of the COMPAS, and for developers of this software the problem of constructing a spatial model was hardly simpler than that set himself the author EQUI.

To simulate SDCS and DLMF known software COMPAS convenient enough so that, firstly, it is easy to learn, and secondly, squeezing a solid model on the flat contour is such that all the way, we obtain a surface tilted at an angle to the plane of the contour. Consequently, the solid model – is the ESS, similar in form SDCS. In the transition to drawing the horizontal projection of this model depicts DLMF.

If you look at the two modular problems: upsetting a rectangular plate with two circular cutouts and a round plate with a round neck – that for them in the COMPAS is easy to obtain the solution (figure 3). Solid model is SDCS. On the projection drawing can be seen as located DLMF. This approach is simpler than using EQUI, so it does not require numerical tasks contour elements.

![Figure 3. Solid model of SDCS](image)

Solid model obtained in the COMPAS, it is convenient to use for visual images SDCS. This allows you to quickly compare the need to strengthen the media for a wide variety of contours. For example, if you compare the so-called «roof», obtained for a rectangular contour with a model derived for the rectangle with a hole, it is obvious that deformation plate with a cut requires a lot less effort than for the solid plate. Comparison of the model in terms of showing the position DLMF, obtained COMPAS and EQUI, gives a good match.

It seems that the possibility of simulating the ESS in the COMPAS is not limited. This is confirmed by solid models SDCS for complex multiply contours. However, for a seemingly simple, simply connected contours can not build a model. COMPAS can not «pull» (squeeze) to the top of this surface. Multiply contours are free of these difficulties, because they have no need to «pull» high up the simulated surface.

Opportunities solid simulation of surfaces in SolidWorks is much broader, however, and this computer system does not always produce a solution. More sophisticated and complex systems such as Unigraphics give almost unlimited possibilities in this regard. From the foregoing it follows that for the computer simulation SDCS, corresponding mathematical model TFTPL, may be used as an the MSP and MSO.
For a more accurate simulation of KSMF most effective application software packages such as DEFORM, FORGE, ANSYS, SPLEN, etc.

One of the representatives of programs, based on finite element method (FEM) is DEFORM, developed by the American company Scientific Forming Technologies Corporation (SFTC), a leader in the field of simulation of metal forming. DEFORM can simulate almost all of the processes, used in MF (forging, stamping, rolling, pressing, etc.), as well as the operation of heat treatment (quenching, aging, tempering, etc.) and machining (milling, drilling, etc.). This program is well established in solving many practical problems, it is successfully used by many enterprises in our country and abroad. Therefore, to study the processes of MF has been selected as the program DEFORM for simulation of virtual experiments. Virtual experiments were performed on upsetting of rectangular plates with different aspect ratio and thickness.

In order to study the effect of friction coefficient on KSMF conducted virtual experiments to upsetting of plate Aluminium alloy 3003 (aluminum wrought alloys used for the manufacture of welded tanks, gasoline and oil pipes, radiators etc.). Use the preset to the plan dimensions 100x50x5 mm at a temperature of heating workpiece 380º C and the stamp 420º C, taking into account the heat exchange with the environment. Experiment on the upsetting was carried out in conditions, close to real.

As a result, the velocity field obtained by displacement of metal particles in the contact plane of the deformed sample and the instrument (figure 4), which give a clear idea of KSMF. For ease of comparison, the simulation results were compared with the same circuit deformation degree 40%.

Research was also conducted as KSMF depends on other process parameters.

![Figure 4](image)

Figure 4. The results of the virtual experiment with a friction coefficient:
   a) k = 0.1; b) k = 0.4; c) k = 0.8; d) k = 0.99.
To determine the dependence KSMF of deformed alloy made of upsetting samples from AMts, Steel 35 and perfectly plastic material. It turned out that for various alloys KSMF looks approximately the same.

4. Results obtained
At increasing of thickness of the workpiece KSMF tends to the radial scheme irrespective of the friction indicator. For thick pieces speed of metal flow rate is significantly reduced compared with thin workpieces. For thin workpieces of friction indicator is the overwhelming factor in choosing KSMF. Temperature and speed modes of deformation of metallic materials depending on their structure and rheological state show that the grain sizes of these alloys can be attributed to the medium and fine grained, which corresponds to most structural alloys used in industry for forging and stamping. It is important to note that the rheological properties of metals will differ marginally from each other in view of equal opportunities intergrain slip. For these metals slip between the grains is about 5% of the total strain. Basically, deformation occurs due to changes in the shape of the grains. Consequently, such metals can be considered the metal plastic.

![Intermediate KSMF](image)

5. Summary
With great probability we can accept, that for any parameters of the upsetting is a real «intermediate» KSMF (figure 5), which consists of areas of the flow normal to the contour and areas of radial flow. Different variations of the intermediate KSMF serve some large-scale model of the law of least resistance, at which the radial and the normal scheme is its extreme cases.

References
[1] Bratan, S., Bogutsky, B., Roshchupkin, S. Development of mathematical model of material removal calculation for combined grinding process (2019) Lecture Notes in Mechanical Engineering, 0 (9783319956299), pp. 1759-1769.
[2] Gutsalenko, Y., Bratan, S., Roshchupkin, S., Dyadichev, V., Menyuk, S. Investigation of the Structure and Properties of Copper-Tin Bonding M2-01 in Diamond Grinding Wheel Introducing Additional Energy in the Form of Electric Discharges into the Processing Zone (2019) Materials Today: Proceedings, 11, pp. 586-590.
[3] Ryabicheva, L., Dyadichev, V., Roshchupkin, S., Dyadicheva, E., Menyuk, S., Dyadichev, A. Structure formation of powder copper-titanic materials at higher temperatures (2019) Materials Today: Proceedings, 19, pp. 1922-1927.
[4] Gusev, V.V., Roshchupkin, S.I., Moiseev, D.A., Melnikova, E.P. Analysis of grinding process with the use of field theory (2020) IOP Conference Series: Materials Science and Engineering, 709 (2), 022001.

[5] Gorbatyuk, S.M., Morozova, I.G., Naumova, M.G. Color Mark Formation on a Metal Surface by a Highly Concentrated Energy Source (2016) Metallurgist, 60 (5-6), pp. 646-650.

[6] Gorbatyuk, S.M., Zarapin, A.Y., Chichenev, N.A. Reengineering of spiral classifier of catoca mining company ltd, Angola (2018) Mining Informational and Analytical Bulletin, 2018 (2), pp. 215-221.

[7] Gorbatyuk, S.M., Zarapin, A.Y., Chichenev, N.A. Retrofit of vibrating screen of catoca mining company (Angola) (2018) Mining Informational and Analytical Bulletin, 2018 (1), pp. 143-149.

[8] Glukhov, L.M., Gorbatyuk, S.M., Morozova, I.G., Naumova, M.G. Effective laser technology for making metal products and tools (2016) Metallurgist, 60 (3-4), pp. 306-312.

[9] Bast, J., Gorbatyuk, S.M., Kryukov, I.Yu. Study of the temperature fields in the mold of a horizontal continuous caster (2011) Metallurgist, 55 (3-4), pp. 163-166.

[10] Kirillova, N.L., Radyuk, A.G., Titlyanov, A.E., Gorbatyuk, S.M. Improving air-tuyere operation in blast furnaces by means of coatings and sealant (2013) Steel in Translation, 43 (5), pp. 231-235.

[11] Gerasimova, A., Gorbatyuk, S., Devyatariova, V. Application of gas-thermal coatings on low-alloyed steel surfaces (2018) Solid State Phenomena, 284, pp. 1284-1290.

[12] Gorbatyuk, S., Kondratenko, V., Sedykh, L. Tool stability analysis for deep hole drilling (2018) MATEC Web of Conferences, 224, 01035.

[13] Gorbatyuk, S.M., Sedykh, L.V. Improving the durability of rolling-mill rolls (2010) Metallurgist, 54 (5-6), pp. 299-301.

[14] Bast, J., Gorbatyuk, S.M., Kryukov, I.Yu. Horizontal hcc-12000 unit for the continuous casting of semifinished products (2011) Metallurgist, 55 (1-2), pp. 116-118.

[15] Gorbatyuk, S.M., Morozova, I.G., Naumova, M.G. Reindustrialization principles in the heat treatment of die steels (2017) Steel in Translation, 47 (5), pp. 308-312.

[16] Gorbatyuk, S.M., Pavlov, S.M., Shapoval, A.N. Experience in application of screw rolling mill for deforming the billets of refractory metals (1998) Metallurg, 5, pp. 32-35.

[17] Zakharov, A.N., Gorbatyuk, S.M., Borisevich, V.G. Modernizing a press for making refractories (2008) Metallurgist, 52 (7-8), pp. 420-423.

[18] Keropyan, A., Gorbatyuk, S., Gerasimova, A. Tribotechnical Aspects of Wheel-Rail System Interaction (2017) Procedia Engineering, 206, pp. 564-569.

[19] Gorbatyuk, S.M., Osadchii, V.A., Tuktarov, E.Z. Calculation of the geometric parameters of rotary rolling by using the automated design system autodesk inventor (2011) Metallurgist, 55 (7-8), pp. 543-546.

[20] Radyuk, A.G., Gorbatyuk, S.M., Gerasimova, A.A. Use of electric-arc metallization to recondition the working surfaces of the narrow walls of thick-walled slab molds (2011) Metallurgist, 55 (5-6), pp. 419-423.

[21] Keropyan, A., Gorbatyuk, S. Impact of Roughness of Interacting Surfaces of the Wheel-Rail Pair on the Coefficient of Friction in their Contact Area (2016) Procedia Engineering, 150, pp. 406-410.

[22] Gorbatyuk, S.M., Gerasimova, A.A., Belkina, N.N. Applying thermal coatings to narrow walls of the continuous-casting molds (2016) Materials Science Forum, 870, pp. 564-567.

[23] Basyrov, I.I., Bardovsky, A.D. Innovative crushing technique and vertical roll crusher design (2020) Mining Informational and Analytical Bulletin, 2020 (2), pp. 121-129.

[24] Bardovsky, A.D., Gerasimova, A.A., Basyrov, I.I. Constructive solutions for upgrading of the drive of processing equipment (2020) IOP Conference Series: Materials Science and Engineering, 709 (2), 022015.
[25] Bardovsky, A.D., Gerasimova, A.A., Basyrov, I.I. Study of oscillating process of harp screens (2019) Lecture Notes in Mechanical Engineering, 0 (9783319956299), pp. 133-139.

[26] Gorbatyuk, S.M., Morozova, I.G., Naumova, M.G. Development of the working model of production reindustrialization of die steel heat treatment (2017) Izvestiya Ferrous Metallurgy, 60 (5), pp. 410-415.

[27] Artiukh, V., Mazur, V., Prakash, R. Increasing Hot Rolling Mass of Steel Sheet Products (2016) Solid State Phenomena, 871, pp. 3-8.

[28] Nikitchenko, A., Artiukh, V., Shevchenko, D., Prakash, R. Evaluation of Interaction Between Flat Car and Container at Dynamic Coupling of Flat Cars (2016) MATEC Web of Conferences, 73, 04008.

[29] Sorochan, E., Artiukh, V., Melnikov, B., Raimberdiyev, T. Mathematical Model of Plates and Strips Rolling for Calculation of Energy Power Parameters and Dynamic Loads (2016) MATEC Web of Conferences, 73, 04009.

[30] Artiukh, V., Mazur, V., Pokrovskaya, E. Influence of Strip Bite Time in Work Rolls Gap on Dynamic Loads in Strip Rolling Stands (2016) MATEC Web of Conferences, 86, 01030.

[31] Kukhar, V., Artiukh, V., Serduik, O., Balalayevo, E. Form of Gradient Curve of Temperature Distribution of Lengthwise the Billet at Differentiated Heating Before Profiling by Buckling (2016) Procedia Engineering, 165, pp. 1693–1704.

[32] Mazur, V., Artiukh, V., Matarneh, M.I. Horizontal Force During Rolling as Indicator of Rolling Technology and Technical Conditions of Main Rolling Equipment (2016) Procedia Engineering, 165, pp. 1722–1730.

[33] Nikitchenko, A., Artiukh, V., Shevchenko, D., Murgul, V. Modeling of Operation of Elastic-Frictional Draft Gear by NX Motion Software (2017) Procedia Engineering, 187, pp. 790–796.

[34] Artiukh, V., Mazur, V., Shilova, L. Device for Making Horizontal Wedge Thrust of Rolling Stand (2017) MATEC Web of Conferences, 106, 03002.

[35] Artiukh, V., Mazur, V., Adamtsevich, A. Priority Influence of Horizontal Forces at Rolling on Operation of Main Sheet Rolling Equipment (2017) MATEC Web of Conferences, 106, 04001.

[36] Artiukh, V., Mazur, V., Kargin, S., Bushuev, N. Reasonability to use device for making horizontal wedge thrust of rolling stand (2018) MATEC Web of Conferences, 170, 03011.

[37] Solomonov, K. Development of software for simulation of forming forgings (2014) Procedia Engineering, 81, pp. 437-443.

[38] Solomonov, K., Tishchuk, L., Fedorinin, N. Simulation of forming a flat forging (2017) Journal of Physics: Conf. Series, 918, 012038.

[39] Solomonov, K., Tishchuk, L. Virtual and physical simulation forming of flat workpieces under upsetting (2019) Procedia Manufacturing, 37, pp. 467-471.

[40] Solomonov, K.N., Tishchuk, L.I. Simulation of deformation processes in upsetting (2019) Journal of Physics: Conf. Series, 1348, 012020.