ENGINEERING TRANSACTIONS • *Engng. Trans.* • **53**, 1, 31–41, 2005
Polish Academy of Sciences • Institute of Fundamental Technological Research
10.24423/engtrans.430.2005

EXPERIMENTAL MODELLING OF THE INFLUENCE OF BOUNDARY CONDITIONS ON KINEMATICS OF THE EXTRUSION PROCESS

G. Skorulski

Technical University of Białystok
Mechanical Department,
Wiejska 45 C, 15–351 Białystok, Poland
e-mail:skorgreg@pb.bialystok.pl

The aim of this paper is to analyses the influence of boundary conditions on plastic flow kinematics during hot extrusion of aluminium alloys. Clay and plasticine have been used as a substitute material. The shape and distribution of a dead zone, conditions of increasing the boundary layers and their influence on flow kinematics have been done using the modelling experiment. Kinematics of plastic flow and especially, range of deformation region allows to predict stresses distribution on contact surface between the die, container and the extruded material.

1. Introduction

In modelling experiments of plastic flow, especially of the metal extrusion processes, very often plasticine has been used as a substitute material [6]. The classical extrusion process researches were executed also on real materials [7, 10]. The boundary layer was excluded completely as a result of these investigations. Moreover, the influence of the boundary layer on plastic flow kinematics was excluded as well. It took place because the phenomenon of increasing the boundary layer appears under special conditions in the extrusion process. Mostly the motion of the ram effect has been observed, especially in the vicinity of regions situated near the ram during the process. The experiments on real aluminium alloys and numerical simulations have confirmed the existence of a boundary layer in hot extrusion processes [8, 9]. The same assumption was made for the physical model, which has been analysed in the present work. It seems to be important to prove that the boundary layer occurs using the substitute materials. In this case the low cost of the experiments and equipment has determined the methodology. Therefore, special model experiments using substitute material have been designed and carried out. To ensure that such model experiments provide useful information it is essential to select model materials and prepare samples that would exhibit (preferably at room temperature) similar behaviour and similar deformation mechanisms as those present during the actual deformation process of aluminium alloys. The correct modelling must be conducted using similarity criteria. From the definition of the modelling follows the function of dependence of the variables of object and its model. The rules of probability usually have an application in the case of simple investigations, described by the rules of classical mechanics. Mechanical properties and characteristics of aluminium and other alloys in eleveated temperatures are presented in [1, 5, 10, 11, 12].

In this situation several realised criteria of similarity are satisfied. Then the criteria determine the similarity conditions in quantitative terms. The most important criterion of the analysed extrusion process is similarity of plastic flow kinematics, e.g. compatibility of strain velocity fields of the model and real objects.

2. Experimental stand

To investigate the effect of the boundary conditions on the deformation of plastic materials, a special experimental stand has been designed and built. A cylindrical die and workpiece was cut along a longitudinal plane including the symmetrical axis of the die holes. On the surface of the partition the tapped holes were made. In this way, the assembly within the container and plexiglass plate has been done. Special brackets have been added to avoid cracking failure. One of the container walls has been made of transparent plastic so that the material flow and the deformation progress could be observed during the tests. The extrusion process of substitute materials has been registered by a digital video camera. The experimental stand is shown in Fig. 1.

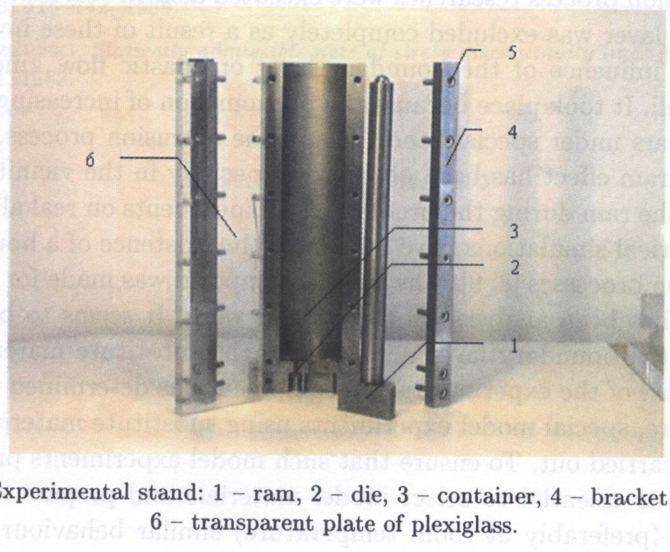

Fig. 1. Experimental stand: 1 – ram, 2 – die, 3 – container, 4 – bracket, 5 – bolt, 6 – transparent plate of plexiglass.

3. Preparation of the samples

The major purpose of the experiments was verification of the physical phenomena that are observed in hot extrusion of aluminium alloys. It was necessary to find substitute material. Its characteristic and material properties were determined by the theory of similarity and knowledge about the plastic flow of aluminium alloys in elevated temperature. Experiments on two different materials were made. They were clay and plasticine. The material's curves have been obtained in classical tests of compression. The Instron machine has been used for this tests. These curves may be described by the following function:

a) for plasticine:

$$\sigma_i = 120 \cdot \dot{e}_i^{0.090} \text{ [MPa]}$$

b) for clay:

$$\sigma_i = 160 \cdot \dot{e}_i^{0.095} \text{ [MPa]}$$

where: σ_i – actuall yield stress, $\dot{e}_i$ – strain velocity [1/s].

Plasticine has been chosen as a major substitute material. Experiments with clay have been made as well, but the results were different from those expected. However, the results of these tests have been presented. They may be helpful during modelling of cold extrusion processes, when the history of deformation indicates the absence of a boundary layer. Therefore in this case the shape and distribution of a dead zone may be of interest. The technique of preparing samples was the same. The samples have been made as half-rounded moulding in black and white colour (plasticine) and two shades of brown (clay). The samples were cut into slices and put on the container one after another. The thickness of the slices was 10 mm. This kind of distribution was important and allows to investigate the history of deformation describing the above slices (deforming vertical lines) in the analysed multi-channel extrusion process. Two kinds of plasticine samples have been used. Firstly, the substitute material was not modified. In the second case, plasticine was mixed with rape oil (10 % oil in volume). The addition of rape oil has been reduced the friction forces on the contact surface between container, die and extruded material. The effect of decrease of the yield point was then observed as well.

4. Experimental technique

To ensure that the modelling process should be similar to the real process, an additional condition must be fulfilled. The friction on the parting plane of the samples must be the same as that during the extrusion process using cylindrical samples. So the friction on the contact surface between sample and plexiglass plate cannot occur. This condition has been realised by putting the acidless vaseline on the plate of plexiglass. The accuracy and precision of preparing samples (initial pressure) have not allowed to insert lubricants into plasticine slices. It has been confirmed by the pictures presented that the sticking phenomenon has not occurred. When the sample of clay was prepared, the contact surface between the sample and plexiglass plate was moistened with a rape oil film. The sticking effect did not occur either. All the tests have been carried out at room temperature using a standard Instron 1112 machine. The deformation of the plasticine and clay layers has been photographed at a number of deformation steps (that is for several positions of the extrusion punch) and registered using a video camera. The velocity of the ram was 125 mm/min.

5. Discussion of the test results

The extrusion process registered by a video camera was divided into deformation stages (that is for several positions of the extrusion punch). The time interval between the pictures was 2 sec. The pictures are presented in Figs. 3, 4, 5. This way of registration allows to investigate the history of deformation. The analysis of each increased process step is possible as well. First of all, the results of modelling experiments are satisfied. The basic characteristic of plastic flow of hot aluminium alloys has been reflected. Three major aspects, e.g. the boundary layer occurring, the distribution of dead zones and the plastic deformation in the region close to the die holes have indicated that there were stronger similarities between the plastic flow of real and modelling materials (Fig. 5). At the beginning of the process the influence of the ram motion was observed. After

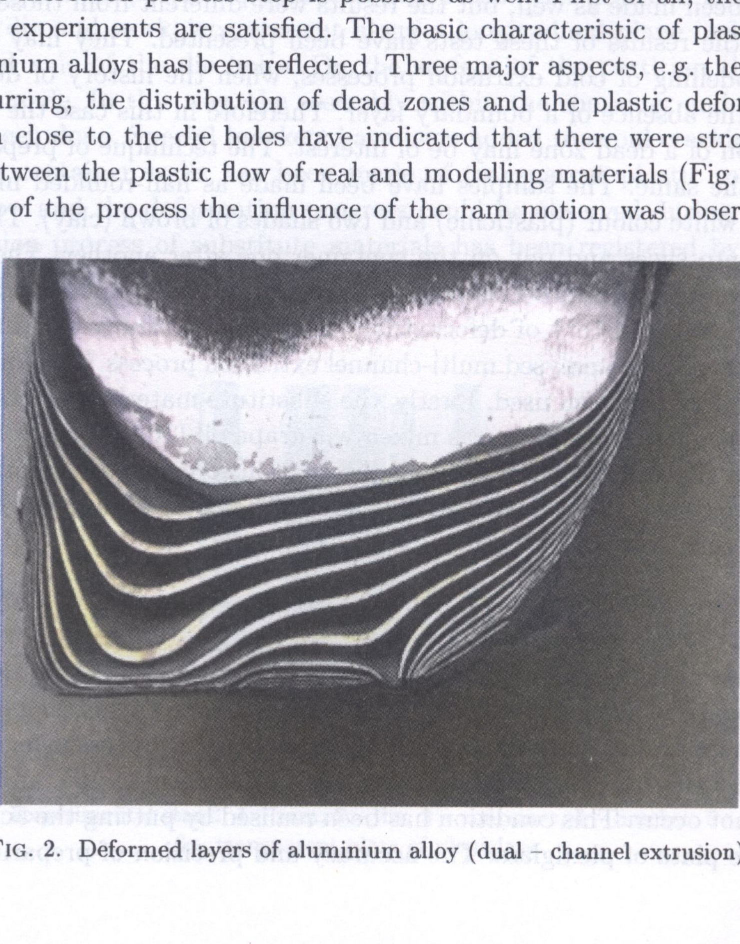

FIG. 2. Deformed layers of aluminium alloy (dual – channel extrusion).

that the boundary layer occurred. In the pictures presented, the increase of the boundary layer is seen. The velocity of the flow in vicinity of this layer is practically close to zero. Therefore the lines between black and white plasticine slices are very densely distributed near the wall of the container. Moreover, a strong deformation in the vicinity of the die holes has been observed in the pictures presented. Generally from experimental tests it is seen that the image of plastic flow is qualitatively consistent with the flow of real material. The experiments on real aluminium alloy have been made in a special press (Mini–press). The cylindrical workpiece was cut into several slices. Between these slices silver foil was placed. After finishing the process, the extruded material was tested by electrolytic etching. The image of the deformed layers is shown in Fig. 2.

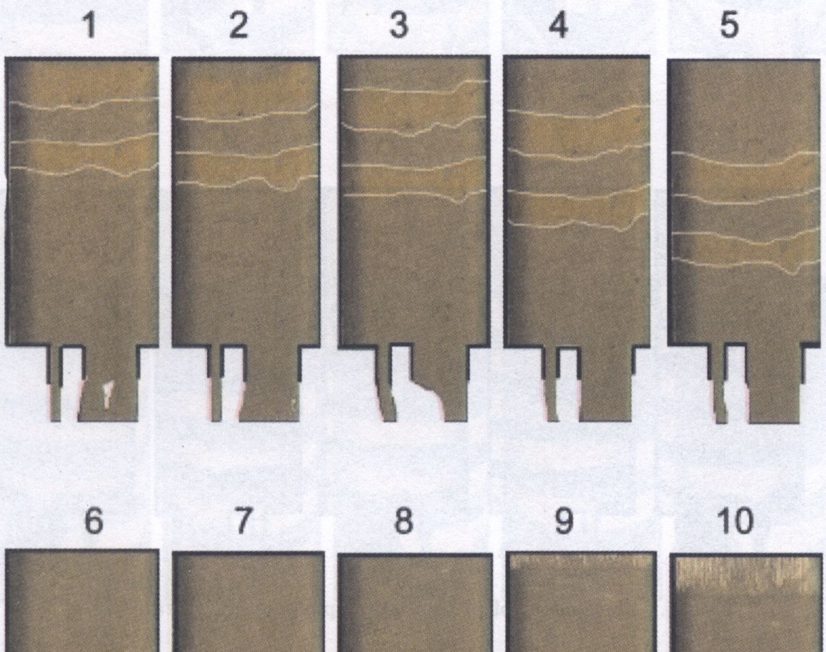

FIG. 3. The images of plastic flow – two colours of clay.

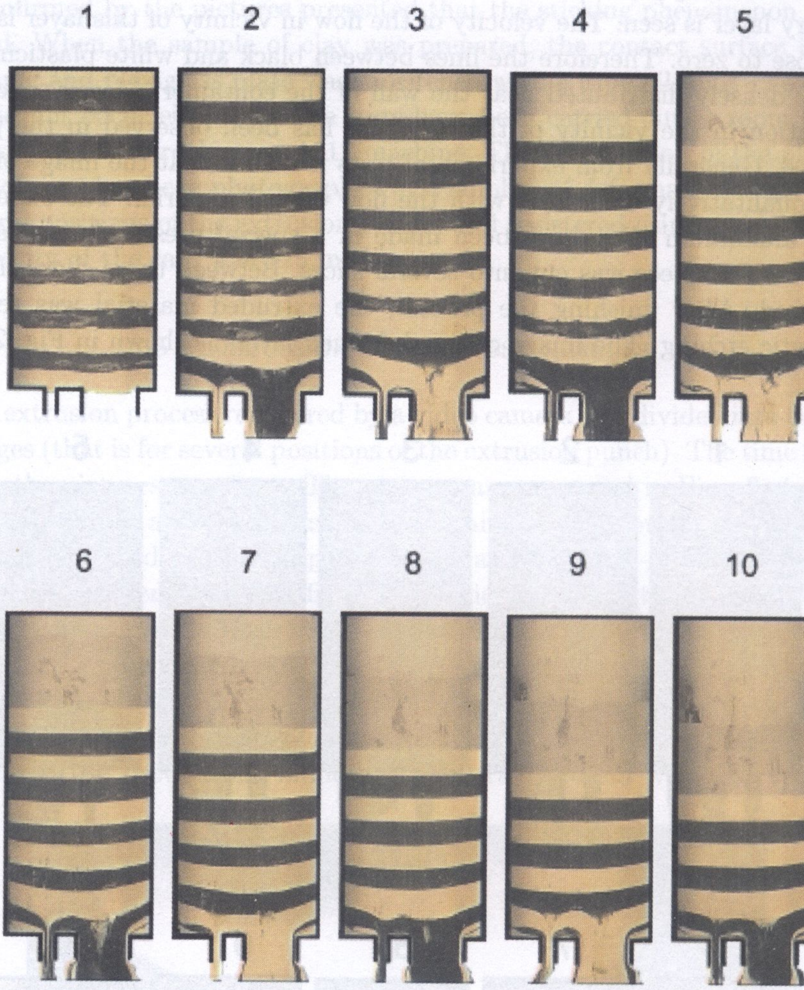

FIG. 4. The images of plastic flow – plasticine with rape oil.

In addition, the test results have the same fields of plastic deformation as the analogous fields of aluminium alloys. Several tests have been made to obtain this result. The boundary conditions may be modelled by special preparation of the samples. The addition of rape oil to plasticine has a very strong influence on plastic flow kinematics and boundary conditions. For example, in Fig. 4 an identical test of extrusion is shown, where the boundary layer has not appeared. In Fig. 3 the flow of clay has been presented. In this case the boundary layer has not occurred either. The pictures in Fig. 5 have shown consecutive phases of increasing the boundary layer and plastic deformation of the material in the vicinity of the die holes. The last picture shows the shape of the dead zone, which is determined by the geometrical parameters of the die.

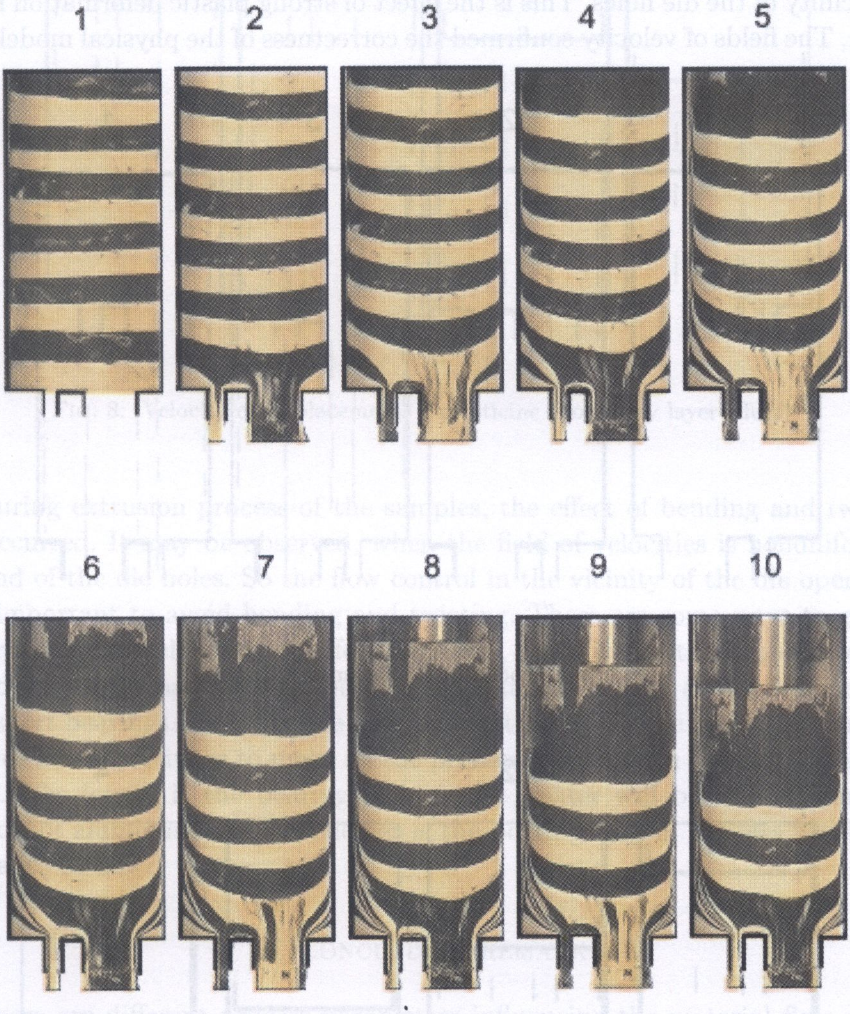

FIG. 5. The images of plastic flow – plasticine. Increasing of boundary layer.

The influence of the boundary conditions on plastic flow kinematics in the extrusion process in Figs. 6, 7, 8 have been presented. For a given deformation stage, the distribution of the flow velocities can be evaluated by comparing two layers obtained for two consecutive punch positions, which have been plotted respectively in Figs. 6 ÷ 8. The vectors of velocity have been located in interesting cross-sections only, especially on the symmetrical axis of the container, on the symmetrical axes of die holes and the near the wall of the container. In the region of contact of the samples with the wall of the container next to the die holes, the velocity of plastic flow are almost zero. The largest modules of velocity occur in the vicinity of the die holes. This is the effect of strong plastic deformation in this region. The fields of velocity confirmed the correctness of the physical model used.

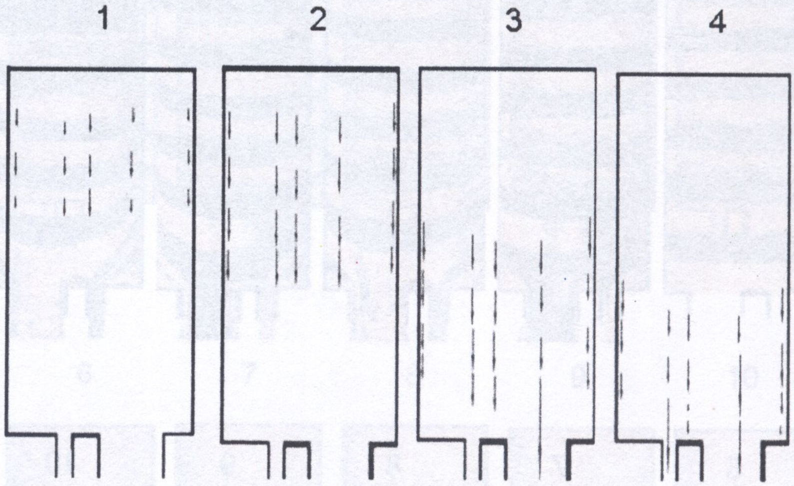

FIG. 6. Velocity of displacements (clay).

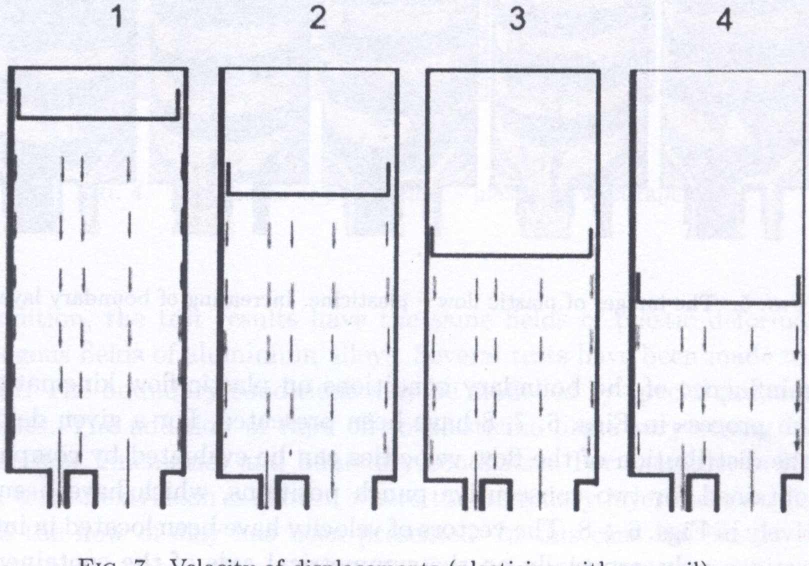

FIG. 7. Velocity of displacements (plasticine with rape oil).

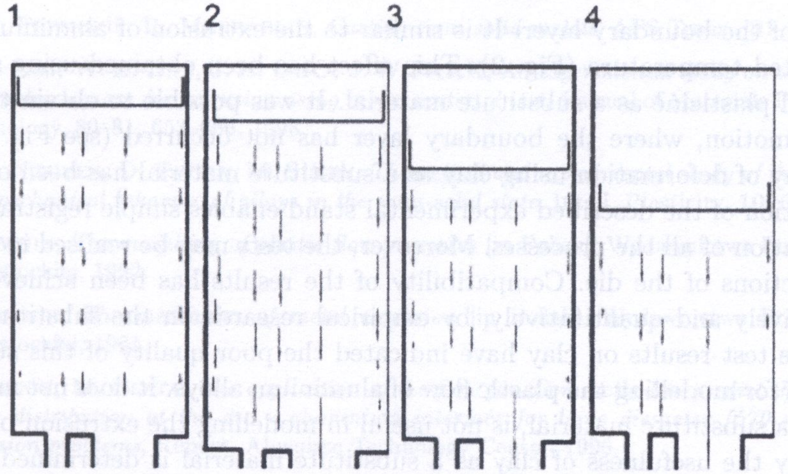

FIG. 8. Velocity of displacements – plasticine (boundary layer effect).

During extrusion process of the samples, the effect of bending and twisting has occurred. It may be observed, when the field of velocities is nonuniform at the end of the die holes. So the flow control in the vicinity of the die opening is very important to avoid bending and twisting. There are some ways to get the uniform velocity fields. Due to effective design, the thick parts of a profile can be slowed due to the use of longer bearings to match the speed of the thinner parts with short bearings. The effective bearing length controls the metal flow through the die. The objective is to make all the profiles emerge from the die at the same speed. The longer is the bearing length, the greater will be the resistance to the flow of aluminum and the shorter is the bearing length, the less will be the resistance to flow.

6. Concluding remarks

There are different process parameters influencing the material flow during extrusion of plastic materials. The test results simply provided the following results:

- influence of the boundary conditions,
- shape and localization of dead zones,
- the plastic flow in the advanced phase of extrusion.

Boundary conditions have a basic influence on the process. Using two different substitute materials such as plasticine and clay, different results have been obtained. The sticking of sample material to the wall of the container cause the growth of the boundary layer. It is similar to the extrusion of aluminium alloys at elevated temperature (Fig. 2). This effect has been obtained using specially prepared plasticine as a substitute material. It was possible to obtain the effect of ram motion, where the boundary layer has not occurred (see Fig. 4). The same way of deformation using clay as a substitute material has been observed. Application of the described experimental stand enables simple registration and visualisation of all the processes. Moreover, the tests may be realised in different cross-sections of the die. Compatibility of the results has been achieved, both qualitatively and quantitatively, by empirical research on the substitute material. The test results on clay have indicated the poor quality of this substitute material for modelling the plastic flow of aluminium alloys. It does not mean that clay, as a substitute material, is not useful in modelling the extrusion processes. Probably the usefulness of clay as a substitute material is determined for cold extrusion. The changes of kinematic flow as a result of increasing the boundary layer is very significant. The area of strong plastic deformation is growing up in this case. It means that the contact stresses distribution depends on increasing of the boundary layers. It is an important clue to design the dies in extrusion processes, which is similar to aluminium flow. On the other hand, the knowledge about flow kinematic and deformation range allows to predict the stress distribution.

The dual-channel extrusion, which is presented in this work is a non-symmetric process. Bending and twisting of the final product has been also obtained. Different cross-sections of the die holes have determined different speeds of two extruded parts. The solution of this problem, described above (see Sec. 5) require also optimal disposition of extruded sections on the die surface. Experimental research is a simple way to recognize the good disposition. Substitute materials, such as plasticine, have reduced the costs of such experiments.

The most important result of the modelling tests is recognizing the phenomenon of increasing the boundary layer and dead zone distribution. The assumption and methodology of the experiments have been chosen correctly. This proves the necessity of such kind of experiments in the future. They will give important clues, very useful for designing the real and multi-channel extrusion processes.

References

1. C. P. Chen, C. Y. Tsab, *Semi-solid of A356 Al alloys*, Proceedings of the 4-th International Conference on Semi-Solid Processing from Alloys and Composites, Sheffield, June 1996.

2. S. Erbel, K. Kuczyński, Z. Marciniak, *Plastic working* [in Polish], PWN, Warszawa 1986.

3. M. C. Flemings, R. Mehrabian, *Casting semi-solid metals*, AFS Trans., **81**, 81, 1973.

4. Y. H. Kim, W. B. Bae, J. R. CHO, J. W PARK, *An experimental study on the nonaxisymmetric square die extrusion using model material test*, Journal of Materials Processing Technology, 80–81, 653–656, 1998.

5. T. G. Nguyen, D. Favier, M. Suery, *Theoretical and experimental study of the isothermal mechanical behavior of alloys in the semi-solid state*, Int. J. Plasticity, **10**, 663, 1994.

6. J. Piwnik, *The modelling of plastic flow processes* [in Polish], Wydawnictwa Politechniki Białostockiej, 1992.

7. J. Piwnik, *The mechanics of metal extrusion* [in Polish], Wydawnictwa Politechniki Białostockiej, 1991.

8. J. Piwnik, M. Plata, *The application of the flow function method to predict the normal stress distribution at the die – aluminium interface for large diameter (570 mm) tube extrusion problems*, Report, Alusuisse Technology Center, 1996.

9. M. Plata, J. Piwnik, *Theoretical and experimental analysis of seam weld formation in hot extrusion of aluminium alloys*, Report, Alusuisse Technology Center, 2000.

10. M. Plata, J. Piwnik, *Extrusion of semi-solid aluminium alloys*, Report, Allusuisse Technology Center 1996.

11. J. F. Seconde, M. Suery, *Effect of solidification condition on deformation behavior of semi-solid Sn-Pb alloys*, J. Materials Science, **19**, 3995, 1984.

12. D. B. Spencer, R. Mehrabian, M. C. Flemings, *Rheological behaviour of Sn-15 pct Pb in the crystallization range*, Metall. Trans. A, 3A, 1925.

Received July 2, 2003; revised version May 26, 2004.