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MODELLING OF STRAIN FIELD IN EXTRUSION BY DIE GEOMETRY (*)

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The strain distributions within the deformation zone and the total strain in the extruded product cross-sections for AlCu4Mg alloy were determined. The visioplasticity method was used in calculations. The plane indirect mode of extrusion was performed with variable die geometry. The strain distribution within the deformation zone can be affected by the shape of the die and in this way, the material structure can be controlled. The range of deformation zone depends on the die used. The most uniform strain distribution and material structure were obtained when the so-called convex-faced die was applied.

1. INTRODUCTION

The extrusion process is one of the most important technologies used in metal working. The final shape of the product can be obtained in this process in a single operation. However, extrusion products are known to have nonhomogeneous structure and mechanical properties in their cross-sections. In case of some hot-extruded aluminium alloys, this leads to the extensive grain growth in the peripheral layer of the product.

In this paper an experimental study of determining the strain field in hot extrusion of aluminium alloy of AlCu4Mg-type is presented. The material structure is also examined. In author's opinion, this should explain the relationship between the state of strain in the deformation zone and structural anomaly in the material extruded.

2. CHARACTERIZATION OF STRAIN FIELD IN EXTRUSION PROCESS

Under the ram pressure the deformation zone forms within the feadstock (billet) in the vicinity of the die (Fig. 1). Its range depends on many tech-

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nological and materials factors. In a corner between the container and the die appears a dead metal zone. This is a part of the billet that can not be extruded due to friction on the tool surface. Finally, the third area can be separated: a shear zone lying between the deformation zone and the dead one. As a matter of fact, the shear zone may be considered as a peripheral part of the deformation zone. Its thickness is affected mainly by the nature of the material and the local friction conditions.

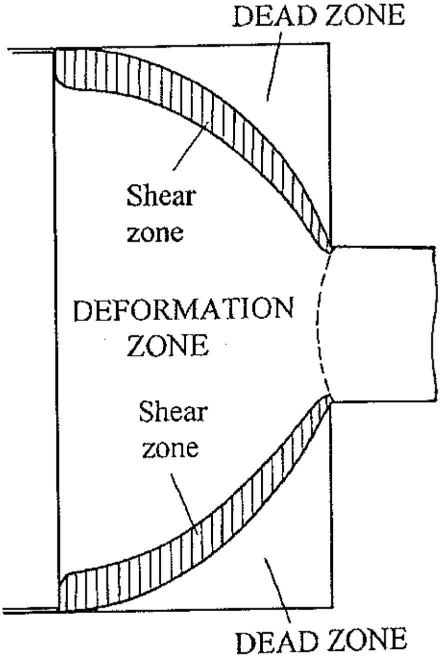

FIG. 1. Characteristic zones within the billet during extrusion.

Thus, the non-uniform flow pattern is a characteristic feature of the extrusion process. The metal from the peripheral part of the billet is moving much slower than in the central part due to friction. Therefore, one may assume that deformation is the result of relative displacements of the supposed layers of material, i.e. by shearing. This process becomes more intensive just in the shear zone. Such a flow mechanism leads to a considerable differentiation of the strain field within the billet, and finally causes the non-uniform distribution of the total strain over the product cross-section. In other words, both in the shear zone and the peripheral part of the product, a strong strain gradient occurs resulting in a nonhomogeneous structure and properties of the material extruded [1, 2]. The flow mechanism described above affects also the temperature field within the billet. However, according to the numerical calculation [3], this phenomenon in case of extrusion of aluminium alloys may be neglected. The temperature rises usually in the deformation zone during the process, but its variation both in the billet and the product cross-sections is rather small.

There are several methods allowing to influence the mode of the metal flow in a container. Good results can be obtained by applying the indirect extrusion, in which the friction forces between the billet and the container are eliminated. Thus, a more homogeneous structure both along and across the product can be achieved using this kind of process. The lubricants can be used in the direct and indirect process to reduce the friction on the contact surface between the billet and the tools. The metal flow control can be realized also by using the so-called stream-lined dies; however, their application in practice is not effective enough.

Our knowledge of the real deformation mechanism occurring during the hot extrusion process is still incomplete. There is a limited amount of results concerning the unique deformation mode together with the structure evolution taking place during the process. The latest investigations of BOCHNIAK and KORBEL [4] indicate that proper knowledge of the real deformation mechanism can considerably improve the effectiveness of the working processes.

The principal aim of this paper is to study the strain field in the extrusion process. The influence of a new kind of die on a strain distribution within both the billet and the final product was also investigated. The results were compared with those obtained in the case of standard conical and flat-faced dies.

3. ANALYSIS OF STRAIN FIELD IN EXTRUSION

There are two effective methods available to determine the strain state in metal working processes: visioplasticity and finite element method (FEM). Fundamentals and the first practical application of the visioplasticity method for quantifying the strain field in extrusion was presented by THOMSEN *et al.* in 1954 [5]. Since that time the method was used to analyse both the plane strain and axisymmetric processes [6, 7]. The method is discussed in detail in [8]. It requires a precise experiment to be performed which consists in a partial deformation of a sample having a grid on its surface.

The FEM makes it possible to predict both the strain and stress fields, but it does not require any experiments. The accuracy of the method depends on correct assumption of the boundary conditions and the material data.

3.1. Experimental procedure

The strain analysis was preceded by the extrusion test in a special equipment. The test was carried out under the plane strain conditions using the indirect method. Three kinds of dies were employed: conical, flat and a convex one. The schematic diagram of the tests is shown in Fig. 2. As it results from the diagram, the punch played the role of a die. The convex-faced die is a quite new concept in which the angle between the die working surface and the extrusion direction is greater than 90°. Such type of the die causes a radial flow of metal in the deformation zone, i.e. perpendicularly to the extrusion direction, increasing the hydrostatic pressure in front of the die, and leading to the equalization of the metal particle velocities in the die orifice. This advantage makes it possible to increase the maximum exit speed of the metal, especially when the extruded materials exhibit a low deformability [9].

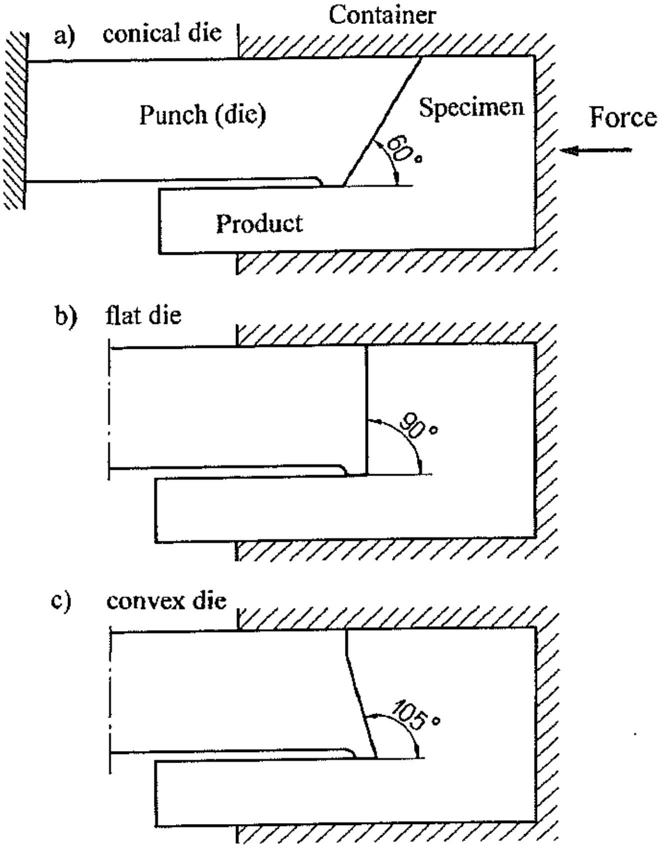

FIG. 2. Schematic diagram of extrusion test.

The test conditions were as follows:

material tested	AlCu4Mg alloy (AA2017),
extrusion temperature	450° C (723 K),
extrusion ratio R	3.5 ($R = F_0/F_1$ – reduction in area),
sample dimensions	$42 \times 42 \times 6$ mm,
die angle α_d	60°, 90° and 105°,
extrusion speed v_0	0.3 mm/s.

The material investigated exhibits a tendency to abnormal non-uniformity of structure in the extruded product. The sample for the strain analysis is shown in Fig. 3. At first the sample was extruded without the grid until the steady flow conditions were obtained. Once the the flow state was established, the test was interrupted and a square grid was machined on the one half of the sample. The coordinates of the nodal points before and after the small extrusion step were taken for the strain determination using the visioplasticity method. Due to this procedure, the displacement of the nodal points and velocity components were determined more precisely.

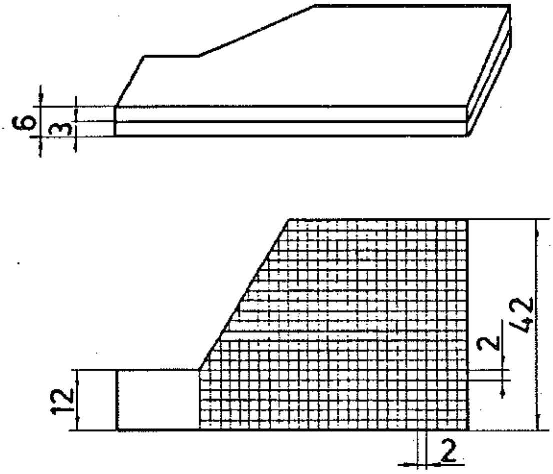

FIG. 3. The sample for strain analysis.

3.2. Calculation procedure

The incremental visioplasticity method was employed for the strain field calculations. In this technique the increments of the local strain or infinitesimal strains are determined. First, the displacements of nodal points l and the angles α between the displacement vectors and the extrusion direction were measured. For the small extrusion step made with speed v_0, the components of metal particle velocities were calculated from the following equations:

$$v_x = \frac{l\cos\alpha}{dt} \cong \frac{l\cos\alpha}{\Delta t}, \qquad v_y = \frac{l\sin\alpha}{dt} \cong \frac{l\sin\alpha}{\Delta t}, \tag{3.1}$$

where $dt \cong \Delta t = s/v_0$ – time of deformation.

The components of strain rate tensor at each nodal point can be calculated from the equations

$$\begin{aligned} \dot\varepsilon_x &= \frac{dv_x}{dx} \cong \frac{\Delta v_x}{\Delta x}, \\ \dot\varepsilon_y &= \frac{dv_y}{dy} \cong \frac{\Delta v_y}{\Delta y}, \\ \dot\gamma_{xy} &= \frac{dv_x}{dy} + \frac{dv_y}{dx} \cong \frac{\Delta v_x}{\Delta y} + \frac{\Delta v_y}{\Delta x}. \end{aligned} \tag{3.2}$$

The effective strain rate $\dot{\overline{\varepsilon}}$ for plane strain conditions is given by

$$\dot{\overline{\varepsilon}} = \frac{2}{3}\left(3\,\dot\varepsilon_x^2 + \frac{3}{4}\,\dot\gamma_{xy}^2\right)^{1/2}.$$

The incompressibility condition for the plane strain process can be written in the form

$$\dot\varepsilon_x + \dot\varepsilon_y = 0.$$

Practically, the components of the strain rate tensor can be determined graphically or numerically from the relations $v_x = f(x,y)$ and $v_y = f(x,y)$. Smoothing of the v_x and v_y data in z and r directions was carried out using at least the fourth-order polynomial fit. By multiplying the strain rate components by the time of deformation $dt \cong \Delta t$ we get the strain increments (or infinitesimal strains)

$$\begin{aligned} d\varepsilon_x &= \dot\varepsilon_x\ dt \cong \dot\varepsilon_x\ \Delta t, \\ d\varepsilon_y &= \dot\varepsilon_y\ dt \cong \dot\varepsilon_y\ \Delta t, \\ d\gamma_{xy} &= \dot\gamma_{xy}\ dt \cong \dot\gamma_{xy}\ \Delta t. \end{aligned} \tag{3.3}$$

As it results from Eqs. (3.3), the strain increments are proportional to the respective components of the strain rate tensor. The effective strain increments are calculated from the dependence

$$d\overline{\varepsilon} \cong \Delta\overline{\varepsilon} = \frac{2}{3}\left(3d\varepsilon_x^2 + \frac{3}{4}d\gamma_{xy}^2\right)^{1/2}. \tag{3.4}$$

The effective total strain distribution on the product cross-section can be computed by integrating $d\overline{\varepsilon}$ or summing $\Delta\overline{\varepsilon}$ along the experimentally determined flow lines. The flow line is a particle path in the stationary process. Additionally, the total strain gradient on the product width expressed by $|d\overline{\varepsilon}/dy|$ was calculated.

4. Results and analysis

Kinematics of the metal flow is described by the velocity components v_x and v_y distributions for the dies investigated. These relations in the form of constant velocity lines are shown in Figs. 4 – 6. The range of the deformation zone varies with the die angle α_d. The broadest deformation zone was

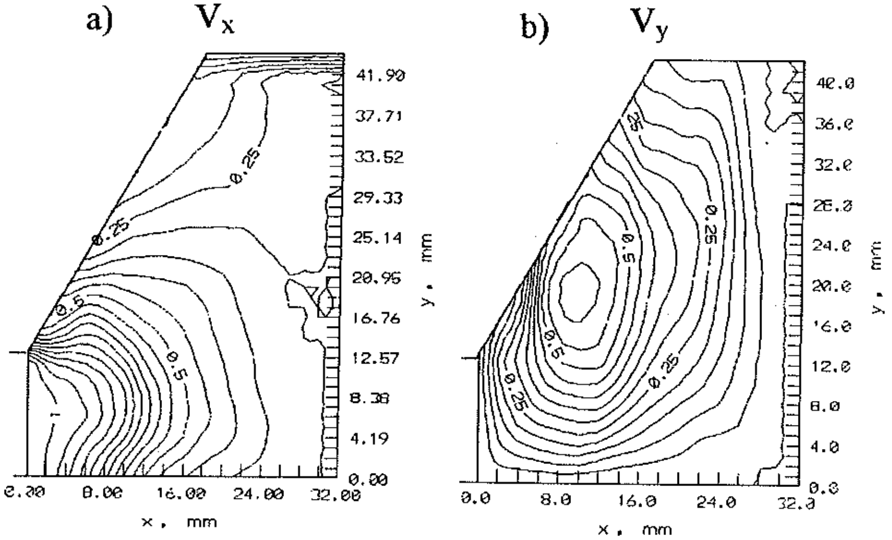

FIG. 4. Flow distribution described by constant velocity lines during extrusion through conical die, a) v_x component, b) v_y component.

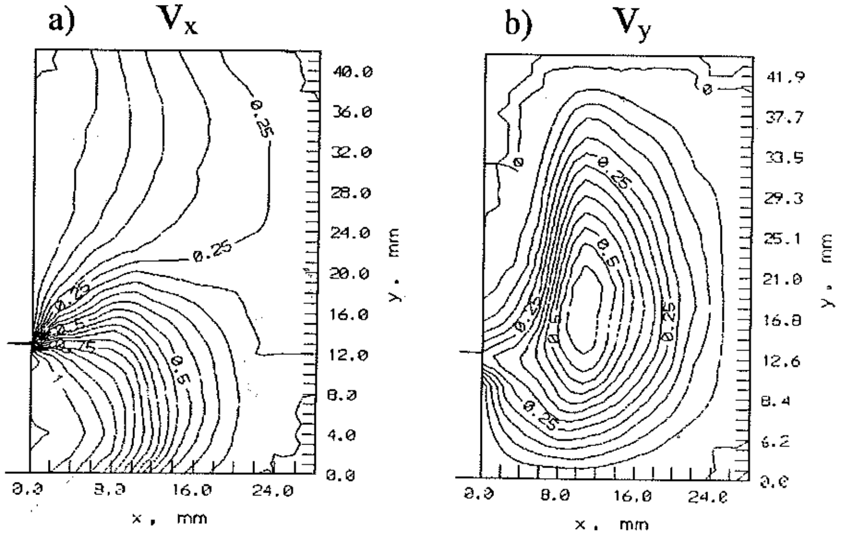

FIG. 5. Flow distribution described by constant velocity lines during extrusion through flat die, a) v_x component, b) v_y component.

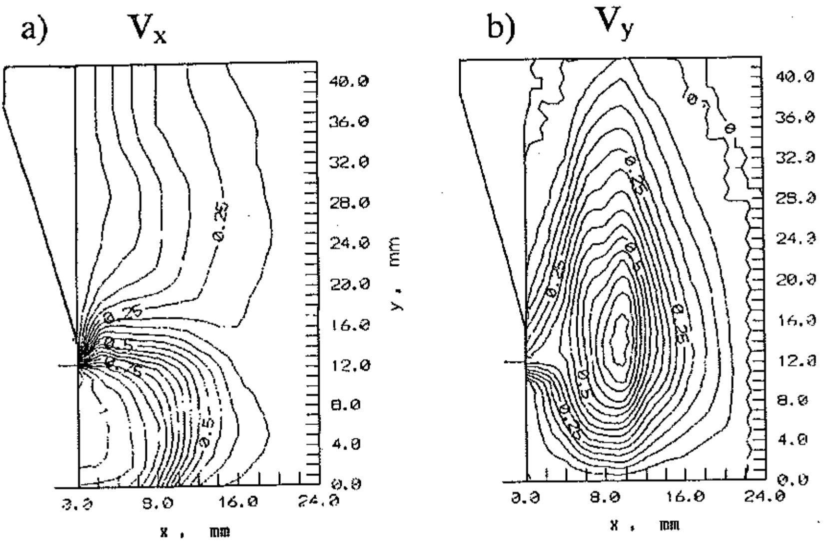

FIG. 6. Flow distribution described by constant velocity lines during extrusion through convex die, a) v_x component, b) v_y component.

obtained for the conical die, and the smallest for the convex one having the inclination angle equal to 105°. The region of the maximal v_y values moves downwards into the deformation zone with the increase of the die angle. It means that in case of the convex-faced die, the radial metal flow dominates within the deformation zone. Considering that the constant velocity lines in the Figs. 4–6 are spaced at every 0.05 of deformation, it is easy to see that the maximum v_y value for this die is 0.75 mm/s (Fig. 6b), whereas for the other cases it is only 0.60 mm/s. Such mode of metal flow will result in increasing of the hydrostatic pressure in the lower part of deformation zone. In the axisymmetric process this should promote a more uniform distribution of metal particles at the moment of exit from the die. This phenomenon may explain the increase in a permissible exit speed of metal extruded through convex-faced dies in relation to the traditional ones, especially when the extruded materials are difficult to form.

Basing on the velocity distribution, the components of strain rate tensor $\dot{\varepsilon}_x$, $\dot{\varepsilon}_y$ and $\dot{\gamma}_{xy}$ were calculated next. These results are discussed in detail in paper [8]. Next the effective strain increments $d\bar{\varepsilon}$ at each nodal points were computed (Fig. 7). The data shown in Fig. 7c indicate that distinct center of strain increments localized in the lower part of the deformation zone appears during extrusion through a convex die.

The diagram in Fig. 7 enables the author to determine the deformation zones boundaries for all the dies tested. The smallest deformation zone occurs for the convex die, thus, the extrusion load can be reduced in this case

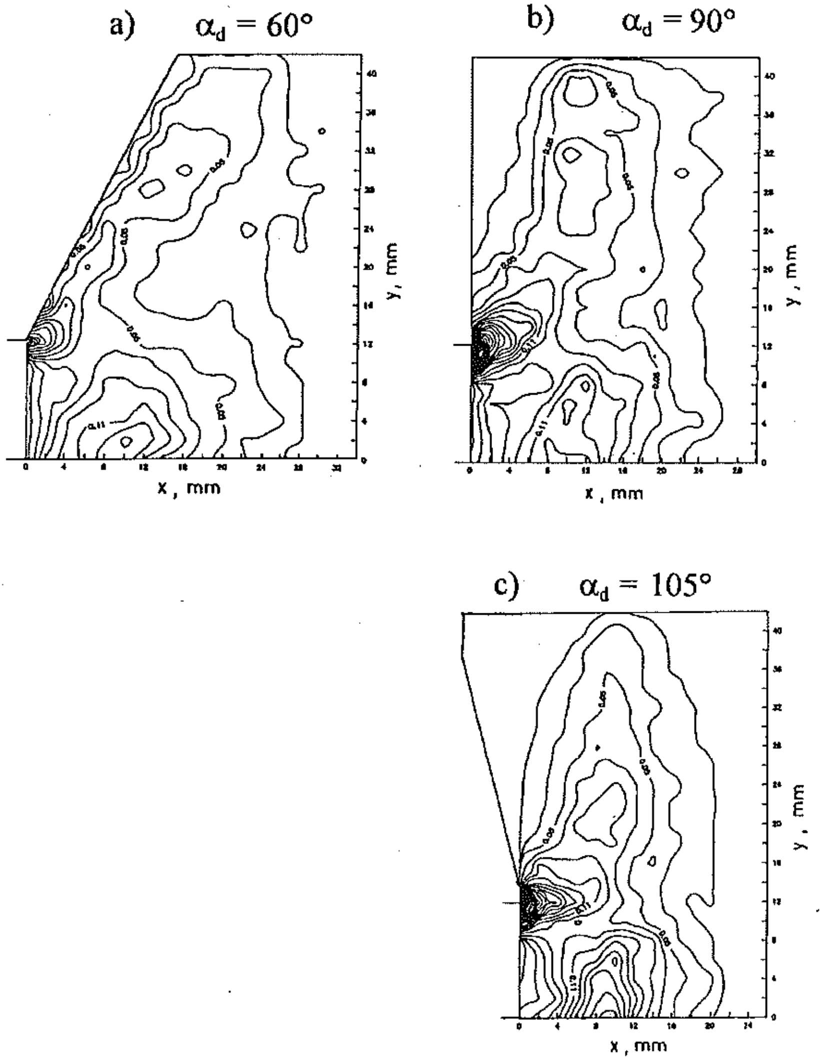

FIG. 7. Effective strain increments distribution in the form of constant $\bar{\varepsilon}$ lines during extrusion through different dies, a) conical die, b) flat die, c) convex die.

because the friction force on the dead zone surface is minimized. For both the convex and flat-faced dies, a strain peak is observed near the die edge connected with a rapid change in the direction of metal flow in this region.

Integrating $d\bar{\varepsilon}$ along the experimentally determined flow lines, shown in Fig. 8, the total effective strain $\bar{\varepsilon}$ distribution through the cross-section was calculated. Two maxima of $\bar{\varepsilon}$ are observed in Fig. 9: the higher one is localized at the die edge (right-hand side of the graph), and the lower one at the second die edge. The higher maximum moves aside the die edge when the die

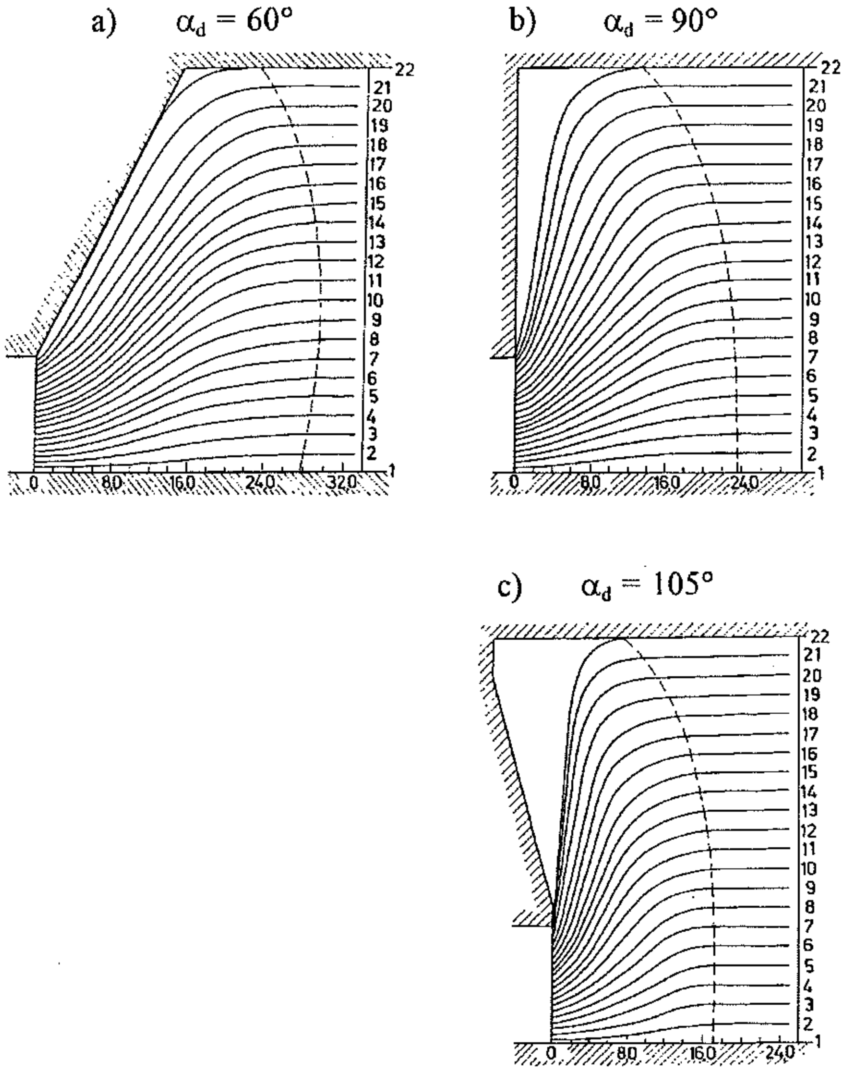

FIG. 8. Course of flow lines for different dies.

angle α_d increases. The total strain value on the product surface is relatively low due to the braking effect of friction. The most homogeneous effective strain distribution occurs in case of the convex die. This fact is connected with a characteristic mode of metal flow described above. The ratio of strain non-uniformity can be estimated on the basis of a strain gradient distribution, expressed by $|d\bar{\varepsilon}/dy|$, where y is the product width. As it is seen from Fig. 10, the lowest strain gradient was achieved also for the convex die. This follows from the existence of the region of strain concentration mentioned previously (Fig. 7c).

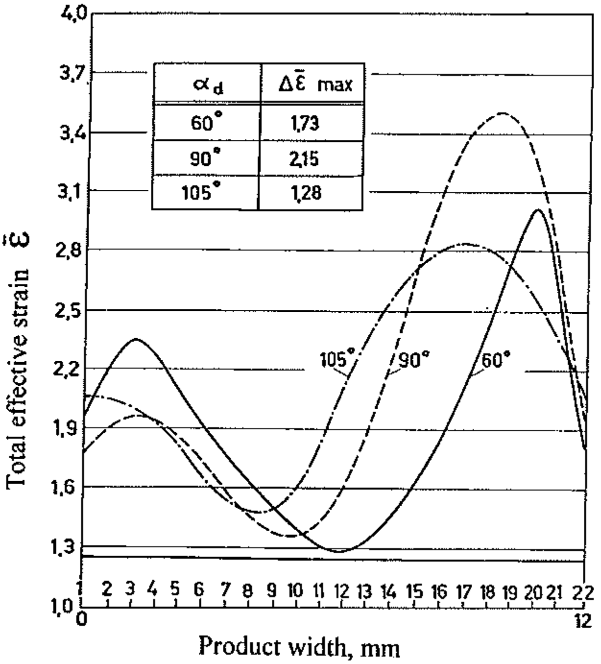

FIG. 9. Total effective strain distributions on the product cross-sections for different dies.

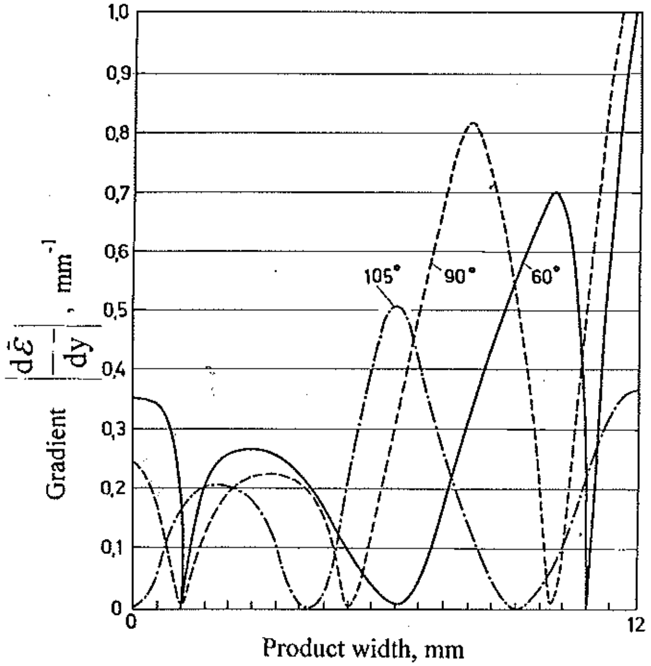

FIG. 10. Effective strain gradient on the product cross-section for different dies.

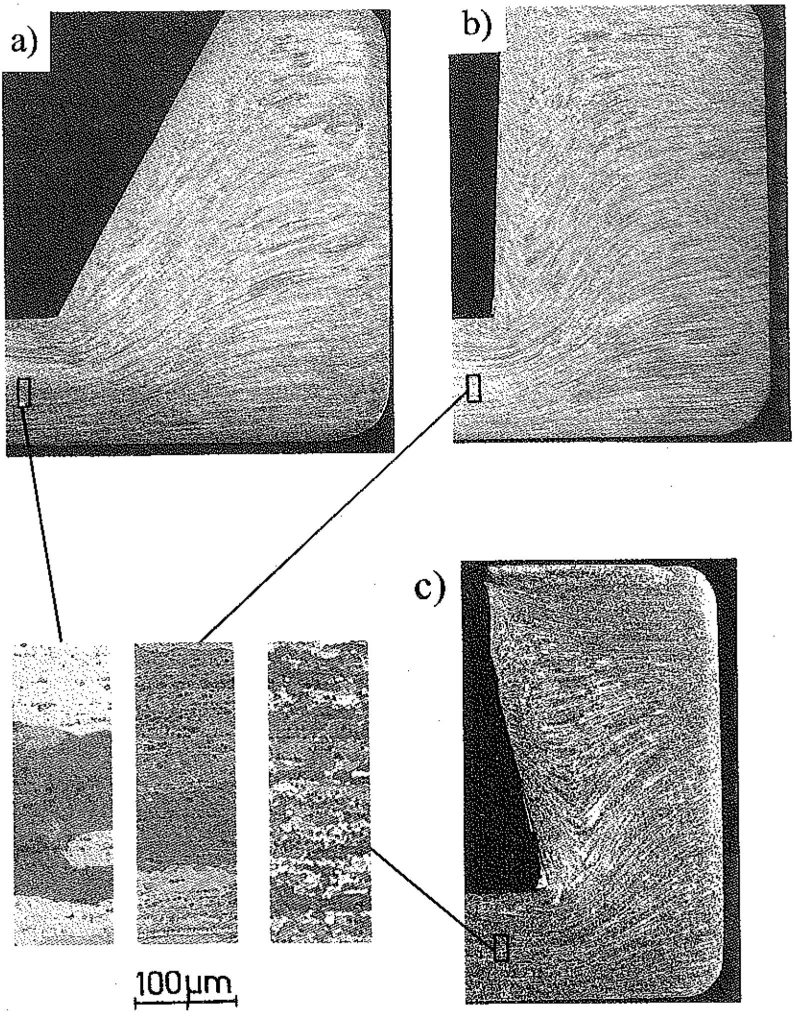

FIG. 11. Macrostructures of AlCu4Mg alloy extruded through different dies.

The structure examinations were also made for the material extruded through the die tested. For example, in Fig. 11 the macro- and microstructures of the AlCu4Mg alloy after extrusion are presented. In spite of the visible symptoms of the recrystallization, the directional character of structure can be seen for all cases investigated. Nevertheless, the fine grain structure demonstrates only the material extruded through the convex die (Fig. 11c). This fact, in the author's opinion, can be interpreted as indicating that there is a close relation between the final material structure and a strain or strain gradient distribution on the product cross-section. Probably, the strain differentiation is necessary to produce considerable grain growth in a material.

5. Conclusions

The strain field during extrusion depends on the kind of the die used. Extrusion through convex-faced die changes the mode of metal flow in the deformation zone, and leads to more uniform distribution of the total strain on the product cross-section. By the die geometry the structure of an extruded material can also be affected. An advantageous effect was obtained by using the convex-faced die. Therefore, it is possible to relate the strain distribution expressed by the strain gradient to the structure and properties of a product.

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