MATERIAL FLOW PATTERN AND STRUCTURE EVALUATION DURING EXTRUSION OF 2024 ALUMINIUM ALLOY

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Curgerea neuniformă a materialului în timpul deformării este o caracteristică a procesului de extrudare. Metalul de la periferia produsului curge mai încet decât materialul din partea centrală. Acest mod de curgere este influenţat de frecarea prezentă la suprafaţa de contact dintre semifabricat şi containerul matriţei. În partea periferică a produsului se dezvoltă un puternic gradient de deformaţii care în partea centrală este mult mai mic. Starea de deformaţii şi a altor variabile care influenţează structura materialului, cum ar fi tensiunea hidrostatică, sunt foarte puternic influenţate de geometria profilului matriţei. Proiectarea corespunzătoare a profilului matriţei de extrudare poate conduce la un control al structurii produsului obţinut şi la o reducere considerabilă a neomogenităţii acestuia. Rezultatele experimentale au fost utilizate la simularea numerică cu elemente finite. Datele obţinute în urma simulării numerice cu programul FORGE 2, sunt confirmate şi de cele obţinute pe cale teoretică şi experimentală.

The non-uniform material flow is a characteristic feature of the extrusion process. The metal in the peripheral part of the workpiece normally flows much slower than in the central part. This type of flow is strongly influenced by the friction which is presented at the die contact surfaces. In the peripheral part of the workpiece a large strain gradient will develop, whereas in the centre, the gradient is much smaller. The strain distribution and other important variables that influence material structure, such as hydrostatic stress, are strongly dependent on the geometry of the extrusion dies. Careful design of the extrusion die profile can therefore control the product structure and can be used to minimise the amount of inhomogeneity imparted into the product. Experimental data have been used for the finite element numerical simulation of the extrusion process. The data obtained by numerical simulation with FORGE2 programme confirm the theoretical and experimental outcomes.

Keywords: metal flow pattern, flat die, friction, finite element, equivalent strain

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1. Introduction

Both the quality and accuracy of the extruded parts depend on a large range of factors such as: the type of the material being deformed, the way of its flowing during the deformation process, the type of the tools material, the stress state, the working temperature, the friction conditions, the type of the lubricants and how they are used etc [1-4].

Due to friction the metal in the outer layer of the billet moves much slower than that in the centre. Therefore, it is observed that deformation is the result of relative displacements which lead to shearing between the adjacent layers of material. The most deformed metal layers in the final product are those located between the outer surface and the half of the radius of the extruded product. The intensity of deformation of central layers is often twice smaller than that of the layers located close to the surface. This flow mechanism leads to a considerable differentiation of the strain fields within the billet, and finally causes the non-uniform distribution of the total strain, microstructure and properties of the material over the product cross-section. A large number of the publications dealing with the influence of the metal flow pattern on the microstructure and mechanical properties of extruded products has been published, among which works by Sheppard [4], Kusiak et al., [5] Libura et al.[6,7] are worth mentioning.

In the extrusion practice of the metallic materials the die geometric shape may influence the technological process development, and together with technological parameters contribute to the products proper quality [6-9].

The geometric shape of the tools is the main factor by which an optimum technological process is developed. The process is considered to have an optimal development if the material flow speed in the deformation zone is as uniform as possible, if at least in the deformation zone the stress diagram is close to the compression three axial diagram and lastly, if the extrusion pressure values are as low as possible.

2. Analysis of the deformation process

The rational development of the deformation process is one of basic criteria of extrusion technology optimisation. It means to meet certain conditions of the material flow where the deformation non-homogeneity must be the lowest, and the deformation degrees must be less than the admissible ones.

The material flow during the deformation process considerably affects the product quality – its structure and properties, the process efficiency and the deformation force size. In terms of optimisation of the material flow during deformation process the most favourable technological variant is the one which generates a uniform distribution of the particle velocities in the die orifice [5-8].

The material flow, due to direct or indirect extrusion, is a very complex approach from the analytical point of view.

There are many methods available to obtain a picture of the flow. Two of the most powerful methods to obtain a detailed flow pattern to be discussed are visioplasticity and the finite element method.

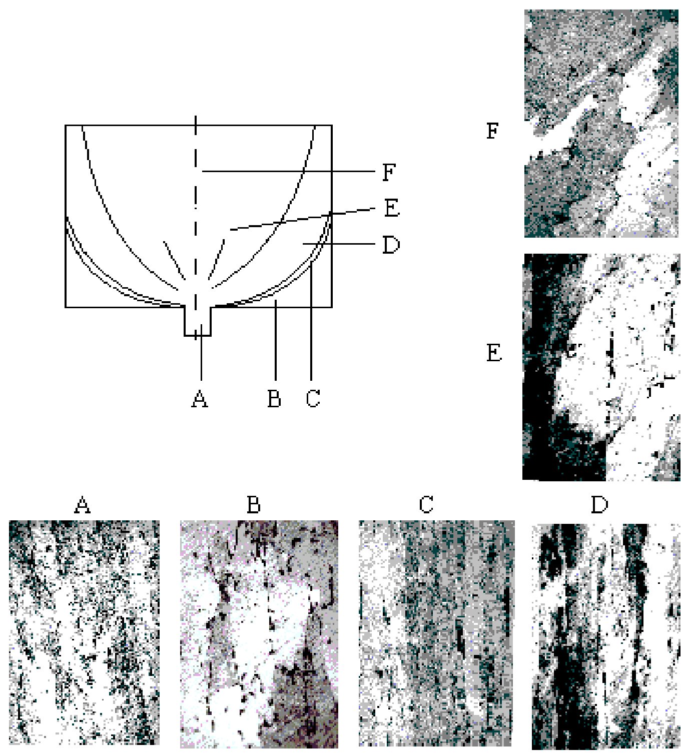


Fig. 1. Evolution microstructure during hot extrusion process
A – deformed product; B – dead material zone; C – shear zone; D – zone intimate to C; E – central deformation zone; F – undistorted material

Fig. 1 shows the structure evolution of an aluminium alloy type 2024 (AlCu4Mg) deformed in the following conditions:

-extrusion temperature: 450°C (723 K),

-extrusion ratio, ε=8.5,

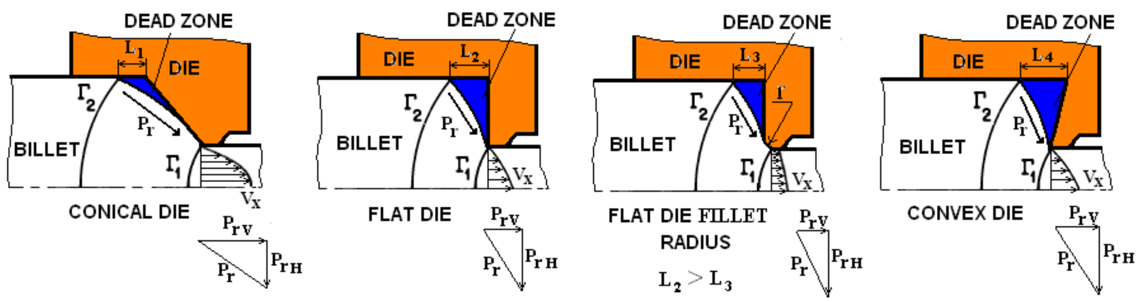
-die angle, α_d=90°,

-extrusion velocity, u_0=1.2 m/s.

The initial dendritic cast microstructure from the central upper part (E, F) of the billet is recovered also in the undistorted dead zone (B).

The increasing of the extrusion force, in the first step of the deformation process, is due not only to the friction forces between billet and container but also due to the shearing forces which appear in zone C (Fig. 1) between the undistorted material (E, F) and dead zone (B). Here, like in the nearest zone (D), the material is strongly deformed. Following to the shearing, a sliding process between the formed dead zone (B) and undistorted material (E, F) will take place until the end of the extrusion process.

This zone can be considered at the periphery of the deformed zone. The material type and the local friction conditions can influence its forms, as well as



a) b) c) d)

Fig. 2. Theoretical investigations of metal flow
a) conical die; b) flat die; c) flat die fillet radius; d) convex die; V_x- velocity diagram

its thickness.

In some cases of hot extrusion of both aluminium and aluminium alloys (i.e. AlCu4Mg), these lead to an extensive grain growth in the peripheral layer of extruded product [5-9].

The set of extrusion tools, die, container and ram, must be built to limit the friction with the billet. This is because the friction during the deformation process has a high influence on the occurrence of defects in the extruded products.

The metal flow pattern which determines strain distribution, material's microstructure and mechanical properties over the product cross-section can be influenced by the local friction conditions and consequently by the material state, the die geometric shape and by the size and appropriate positioning of the dead zone (Fig.2).

Fig. 2 shows the pattern of material flow for typical conical, flat and convex dies and for a flat die with a fillet radius in the deformation zone. In the case of typical dies due to dead zone size and position, shear band length and extrusion pressure amount, the material from the centre moves faster than that from the surface during extrusion process. This kind of material flow leads to a strong material inhomogeneity. However, in the case of the extrusion with a flat die with a fillet radius in the deformation zone the radial metal flow dominates within the deformation zone and therefore the material structure in cross section will be more uniform.

The experimental researches were focused on two directions:

1) the influence of the die shape on the metal flow pattern during extrusion process;

2) the influence of the viscous state material extrusion on the quality of the deformed product.

However, in this paper only the influence of the die geometric shape and the appropriate positioning of the dead zone over metal flow pattern will be presented.

3. Experimental procedure

The influence of the die geometric shape on the metal flow pattern during the extrusion process was studied using a die set with different shapes: conical, flat and convex [6,8,10,11].

The strain analysis was performed on the basis of the extrusion tests. Lead samples Pb99.5 were used to investigate the influence of the fillet radius of a die on the strain field and mechanical properties at cross-sections during direct extrusion, because it satisfies both commercial and technological conditions.

The selected Pb99.5 lead as testing and modelling material for hot extrusion was also done because at room temperature (20°C, 293K), it satisfies both rheological and thermomechanical conditions for aluminium alloys extruded at hot temperature (400÷500°C). The strain hardening curve of the lead determined from the tensile tests was:

$$\sigma_p = 7 + 33\, \varepsilon^{0.1546}\, \varepsilon^{0.2445} \qquad (1)$$

where:

σ_p - yield stress; ε- effective strain rate; ε- effective strain.

The working conditions were the following:

-extrusion temperature: 20°C (293°K);

-extrusion ratio, ε = 5.06 and 20.25;

-sample dimensions:-length, H=75 mm;

-billet diameter, D_o = 45 mm; -product diameter, D_f = 10 and 20 mm;

-die angle, α_d : 45°, 60°, 90°, 105°, 120° and 135°;

-fillet radius, r_f: 0, 1.5, 3, 4.5 mm.

The extrusion loads were monitored in all the tests. Additionally, some of the samples which were extruded had a square grid 4 x 4 mm drawn at their longitudinal cross section, as it is shown in Fig. 3. These samples were used for the investigation of the flow pattern during the extrusion. The strain field was determined using the visioplasticity method [4,5], in which the strain tensor components are calculated from the measurements of the coordinates of nodes for the initial grid and for the deformed grid obtained by an interruption of the process when the marked part of the billet was in the die.

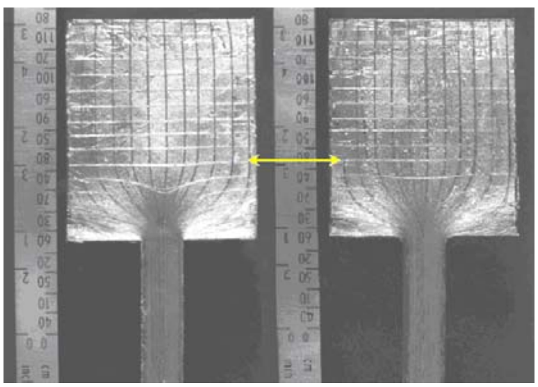
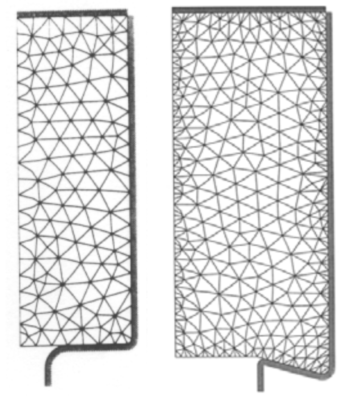


Fig. 3. Experimental investigations of metal flow a) typical flat die; b) flat die fillet radius, r_f=3 mm



a) b)

Fig. 4 Billet automatic meshing and remeshing: a) flat die fillet radius; b) convex die

4. Calculation procedure

The pattern of material flow during the extrusion process (Fig.3) was also analysed by the finite element method using the commercial code FORGE2® developed by CEMEF, Sophia Antipolis, France [5,8,13,14]. This program is oriented towards the thermomechanical finite element modelling of the axis-symmetric forging as well as the plane state forging.

The axis-symmetrical version of the simulation program FORGE2® has been used to simulate forward hot extrusion of AlCu4Mg alloy. Briefly, the rheological parameters of material within FORGE2® are described by Norton-Hoff law, written as follows:

$$s = 2k(\sqrt{3}\dot{\bar{\varepsilon}})^{m-1}\dot{\varepsilon}, \quad (2)$$

where: s- deviator stress tensor; $\dot{\varepsilon}$ - strain rate tensor.

K and m are material consistence and strain sensitivity coefficient respectively. Generally both are functions of temperature T and equivalent strain $\dot{\bar{\varepsilon}}$. In order to define the material consistence in FORGE2® program, the

strain hardening power was used. The billet was modelled by means of second order triangular elements with 6 nodes, Fig. 4.
Automatic procedure to create a mesh and to perform a remeshing was used. The Newton- Raphson method was applied to solve the equations system.

5. Results and Discussion

The experimental results (Fig. 3) as well as the data provided by the reference papers [4-6,8,12] allowed us to point out that the conical, flat or convex die with a fillet radius leads to a considerable change of the metal flow pattern during the extrusion process. In the case of extrusion with a flat or convex die the radial metal flow dominates within the deformation zone. Such a mode of metal flow results in an increment of the hydrostatic pressure in the lowest part of the deformation zone, which was confirmed also by the calculations. It also determines a more uniform distribution of metal velocity and strain at the moment of exit from the die.

Based on the upper bound method the optimum value of the fillet radius was determined, in such way that the relative pressure to be a minimum one [8]:

$$\frac{\partial\left(\dfrac{p_F}{\sigma_0}\right)}{\partial r_r}=0 \quad \text{that is: } r_f=k^*(R_f/2), \qquad (1)$$

where: k=1.2-1.85, correction coefficient (the material was considered homogeneous, isotropic and perfectly plastic); -p_F - deformation pressure; -$D_f=2^*R_f$ – product diameter; -σ_o- yield strength.

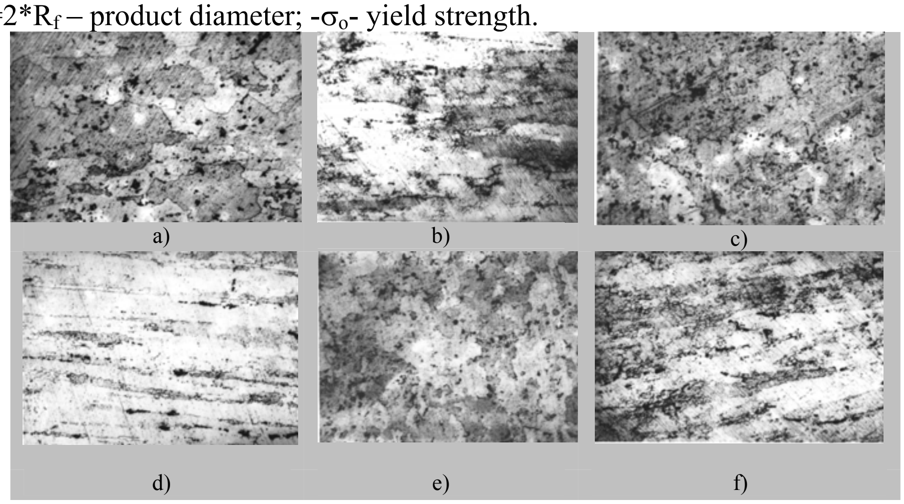
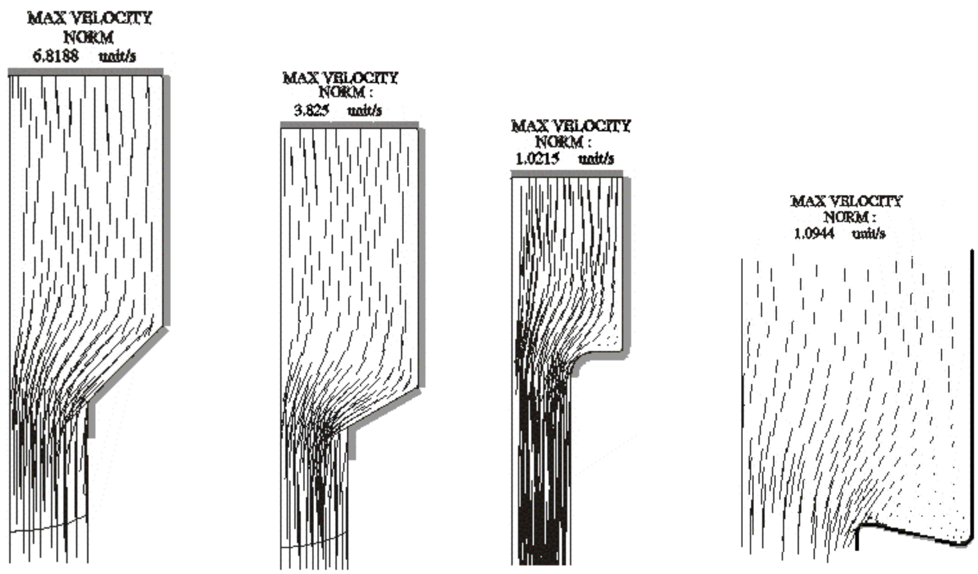


Fig. 5. Structural aspects of hot extruded aluminium alloy type AlCu4Mg (2024) as follows: a, c, e - cross section; b, d, f - longitudinal section; a, b - located close to the surface; c, d - located between a, b and e, f e, f - located in the centre of product

The theoretical investigations and experimental results obtained on lead with different dies showed that the most favourable flow pattern was observed in the case of a flat die fillet radius, presented in Fig. 3. At the same level, in the centre of the billet closed to lowest part of the deformation zone, on can see that the perpendicular grid lines in the case of a typical flat (Fig. 3a) move much faster – almost twice, than those in the case of a flat die fillet radius (Fig. 3b).

The reduction of the dead zone size or its favourable positioning (Fig. 2c) could ensure a metal radial flow resulting in a decreasing of the friction, and implicitly of the deformation non-uniformity.



a) b) c)

Fig. 6. Calculated velocity field during extrusion through conical dies: a) typical conical dies; b) flat die fillet radius, r_f=3 mm; c) convex die

The experimental researches on Pb99.5 lead were verified on the aluminum alloy type AlCu4Mg (Fig. 5). The microstructures in cross section show that the structure is as uniform as possible. This is due to the radial metal flow pattern induced by the fillet radius. The radial metal flow dominates the deformation zone of the die. In longitudinal section it can be noticed that the most deformed metal layers in the final product are those located between the outer surface and the half of the radius of the extruded product.

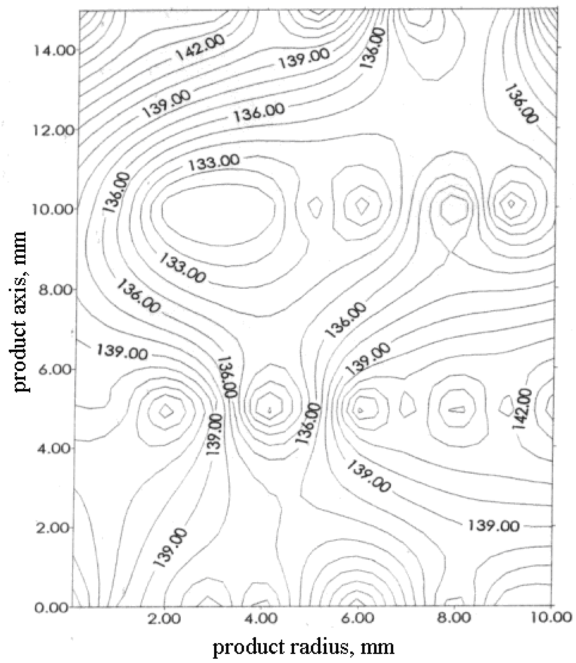


Fig. 7. Microhardness map

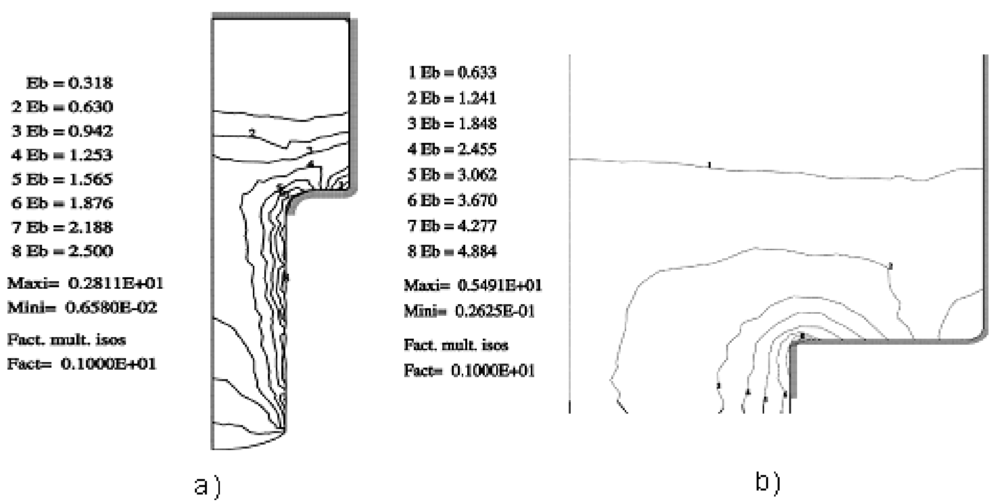


Fig. 8. Calculated equivalent strain during extrusion through a flat die with a fillet radius, r_f=3.0 mm (a) and r_f=0 mm (b)

In the case of a flat die a fillet radius doesn't mean that its presence will lead to an increase of material velocity in the exit office of the die. The main effect of the fillet radius consists in a more uniform velocity of extruded material (Fig. 3 and Fig. 6).

The presence of a fillet radius will introduce a radial pressure which will delay the material flowing from the center of the product and consequently the intensity of deformation of central layers will be very close to those from the surface. In this way the product structure and properties can be controlled.

The extruded material microhardness was also measured, Fig. 7. It can see on the obtained microhardness map that the material in cross section is as homogeneous as possible and confirm experimental and calculation results.

The plots obtained from the finite element simulation [15-17] are presented in the following figures. Fig. 8 shows calculated distributions of the equivalent strain in the deformation zone. These results agree with the experimental data. The strain inhomogeneity decreases with the increasing of the fillet radius of the die. The lowest inhomogeneity is observed for r_f = 3.0 mm, then it starts to increase slightly again. The strain distribution and other important variables that influence material structure, such as hydrostatic stress, are strongly dependent on the geometry of the extrusion dies [18,19,20]. This correlation between die fillet radius and the flow uniformity is also confirmed by the results of calculation of other process parameters like velocities shown in Fig. 6 and hydrostatic pressure shown in Fig. 9.

Analysis of the hydrostatic stresses (Fig.9) shows a strong relation between the hydrostatic pressure and the fillet radius. It can be concluded at this stage that an introduction of a die fillet radius in the axisymmetric extrusion process promotes a more uniform distribution of metal velocity (Fig. 6) and strain (Fig. 8) at the moment of exit from the die. This phenomenon is explained by an increase of the hydrostatic pressure of metal extruded through a die with a radius comparing to the traditional ones, especially when the extruded materials are difficult to deform.

6. Conclusions

Taking into account the above mentioned results we can conclude:

1. By means of a suitable design of the die geometric shape, it is possible to obtain a favourable positioning and/or a dead zone size reduction. This determines an important reduction of the friction in the deformation zone and of the extrusion pressure as well;

2. The most favourable extrusion technological variant is the one that determines a uniformisation of the material particle flowing velocity through the deformation zone and consequently a reduction of the structural nonuniformity;

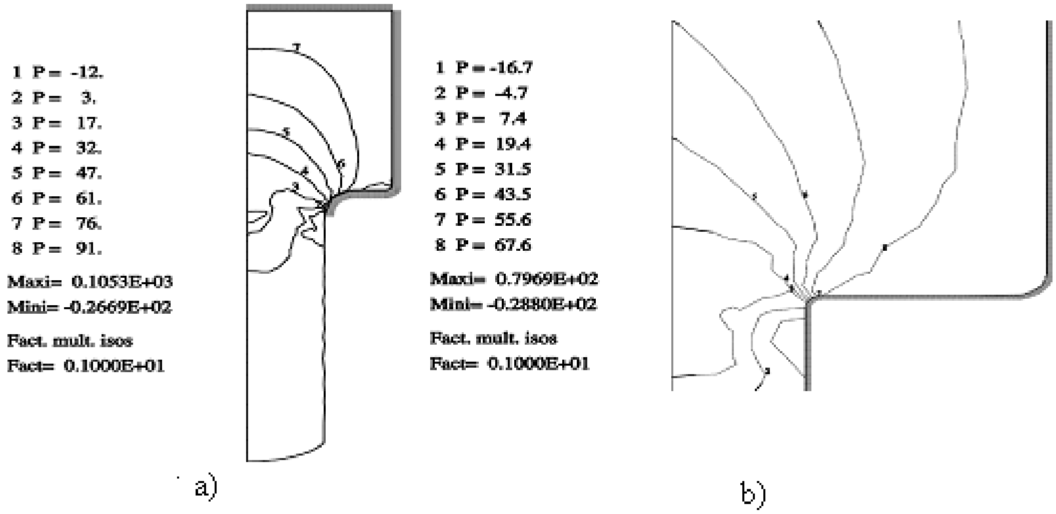


Fig. 9. Calculated Hydrostatic pressure during extrusion through a flat die with a fillet radius, r_f=3.0 mm (a) and r_f=0 mm (b)

3. The increase of the hydrostatic pressure inside the deformation zone together with a radial flow and an uniformisation of the material flow velocity results in a better metal particle distribution when leaving the die. That fact results in an uniformisation of the grain size within the cross section of the product, and in mechanical properties consequently;

4. Careful design of the extrusion die profile can therefore control the product structure and can be used to minimise the amount of inhomogeneity imparted into the product.

5. The homogeneity and mechanical properties in cross-section of the extruded product can be controlled when a die with a fillet radius in plastic range is used. In consequence, the quality of the extruded product can be improved;

6. Analysis of both experimental and theoretical results showed that the strain inhomogeneity decreases with the increasing die fillet radius;

7. The results obtained by means of the numerical simulation are in good agreement with those obtained experimentally.

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