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PHYSICAL MODELING OF THE PLASTIC FLOW IN THE EXTRUSION PROCESS OF LAYERED COMPOSITE MATERIAL USING DIFFERENT DIE GEOMETRY

FIZYCZNE MODELOWANIE PLASTYCZNEGO PŁYNIĘCIA METALU W PROCESIE WYCISKANIA WARSTWOWEGO KOMPOZYTU Z ZASTOSOWANIEM MATRYC O RÓŻNEJ GEOMETRII

The results of physical modeling of the extrusion of layered composite, in particular dealing with the influence of the die geometry on the character of plastic flow of the core-sleeve system composite have been presented. The influence of the concentric arrangement of components in the initial billet as hard core and soft sleeve on final effect of simultaneous plastic flow of various materials to obtain required layered composite has been analysed. The model materials like soft lead, hard lead alloy soft and hard plasticines and set of the dies of different geometry has been used in experimental procedure of direct extrusion.

The experimental results of the extrusion of composite material using flat, conical and convex dies indicate possibility to obtain advantageous flow pattern for suitable convex dies. Basing on the analysis of the character of plastic flow (basing on visioplasticity method) with taking into account relative velocity distribution in the orifice region, size and shape of the deformation zones and extrusion load in particular the best convex die geometry in comparison with others has been proposed.

Basing on analysis of different results of the co-extrusion of different materials e.g. relatively small plastic zone, relatively low extrusion load and equalization of velocities of particles in the region the die orifice may indicate adequate convex die geometry for realizing extrusion process of composite material of the core-sleeve structure.

Zaprezentowano wyniki badań eksperymentalnych fizycznego modelowania wyciskania kompozytów warstwowych ze szczególnym uwzględnieniem wpływu kształtu matrycy na charakter plastycznego płynięcia warstwowego materiału złożonego o układzie rdzeń-powłoka. Pokazano wpływ różnych struktur wlewka o układzie koncentrycznych warstw: rdzeń twardy- powłoka miękka na efekt wspólnego odkształcenia materiałów o różnych właściwościach w celu uzyskania kompozytu warstwowego o wymaganych cechach. Zastosowano materiały modelowe: ołów miękki, twardy stop ołowiu, miękką i twardą plastelinę oraz komplet matryc o różnej geometrii w procesie współbieżnego wyciskania.

Wyniki fizycznego modelowania kompozytu warstwowego z zastosowaniem płaskich, stożkowych i wypukłych matryc wskazują na możliwość uzyskania korzystnego sposobu płynięcia w przypadku zastosowania odpowiednio dobranych matryc wypukłych. W oparciu o analizę charakteru plastycznego płynięcia (zastosowanie metody wizjoplastyczności) ze szczególnym uwzględnieniem rozkładu względnych prędkości cząstek w obszarze otworu matrycy, wielkości i kształtu stref plastycznych oraz siły wyciskania zaproponowano odpowiednią geometrię matrycy do określonego wyrobu kompozytowego. Bazując na analizie wpływu parametrów geometrycznych matrycy pozwalających na zmniejszenie stref odkształcenia, siły wyciskania oraz wyrównania prędkości wypływu materiału w obszarze otworu matrycowego wykazano celowość zastosowania odpowiednio dobranych do typu kompozytu matryc wypukłych.

1. Introduction

Longitudinally oriented metal composites e.g. of sleeve – core system may be obtained in the course of the extrusion process. Such types of metallic composite materials are heterogeneous materials consisting of two or more components bonded together under adequate conditions of the process. One of the important advantages of this process is that the final shape of the product can be obtained in a single operation with large change of shape and there is possibility of changing the deformation zone by changing the shape of the die. Material flow during extrusion process strongly depends on the die design. Choice of adequate die geometry guarantees controlling metal flow under conditions of plastic

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deformation. Traditional dies for extrusion of bars and rods are conical dies and flat face dies [1-3]. In the case of the extrusion of layered composite, the type of flow of the core and sleeve can be completely different. From this point of view it is necessary to learn about specific features of the composite flow to facilitate proper designing the die for given type of the extruded product. The type of flow of the composite depends on kind of the components of composite, friction conditions and die geometry [4, 5, 11-17]. The formation of the deformation zone depends on the die shape, too. Description of the actual character of the plastic deformation of different materials deformed simultaneously is important in order to be able to obtain the required metal composite. Physical modeling supplies such information, what is especially important in the case of composed material to be extruded.

Results of the extrusion process are due primarily to the shape of the flow field and the characteristics of the material. It is necessary to be able to determine the conditions for sound flow, which is more complicated in the co-extrusion of various metals. The flow patterns of different metals (typical flow patterns S, A, B, C according to Pearson's classification-Fig.1 [18-19]) existing under conditions of the extrusion process may indicate the shape and changeability of plastic zones in simultaneous extrusion of two different materials. There are most important factors influencing such more complicated plastic flow. Flow pattern S is characterized by the maximum possible uniformity of flow in the container. Plastic flow takes place mainly in a deformation zone directly in the front of the die. The major part of the non-extruded billet pushed as a rigid body through the die, remains undeformed. This very uniform flow can take place only when there is no friction at the liner wall or at the surface of the die and the die holder. In practice, frictionless extrusion is impossible, but flow patterns of this type are closely approximated when very effective lubrication is used (e.g. hydrostatic extrusion or indirect extrusion with a die lubricant). Flow type A occurs when there is virtually no friction between the container and the billet but significant friction at the surface of the die and its holder. This retards the radial flow of the peripheral zones and increases the amount of shearing in the region. A slightly larger dead metal zone and wider deformation zone appear in comparison with flow type S. In the center flow is still relatively uniform. Type A occurs during the lubricated extrusion of soft alloys (e.g. lead, tin, tin bronzes). Flow pattern B occurs if there is friction at both the container wall and at the surfaces of the die and die holder. The peripheral zones are retarded at the billet/container interface, whereas the lower resistance causes the material in the center to be accelerated towards the die. The shear zone between the retarded regions at the surface and the accelerated material in the center extends back into the billet to an extent that depends on the extrusion parameters and the alloy. The dead metal zone is large. Flow type B is seen in single phase (homogeneous) copper alloys that do not form a lubricating oxide skin and in most aluminum alloys. Type C flow occurs in hot extrusion when the friction is high, as in type B, and the flow stress of the material in the cooler peripheral regions of the billet is considerably higher than that in the center. The billet surface forms a relatively stiff shell. The conical dead metal zone is much larger and extends from the front of the billet to the back. Flow type C will occur when there is a hard billet shell and the friction at the container wall is high. It can also occur if there is a large temperature difference between the billet and the container. This type flow can take place in the extrusion of tin and aluminum and its alloys. The extrusion defect known as pipe is caused by type C flow. Extrusion defects are produced by undesirable metal flow.

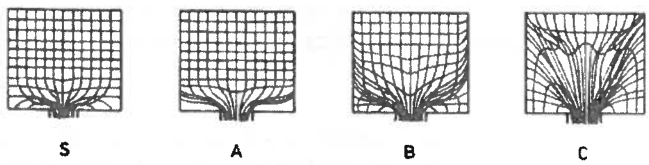


Fig. 1. Different types of flow in extrusion of single metal [19]

In the case of simultaneous plastic flow of various materials deformed together in co-extrusion it is necessary to determine the type of composite material flow of core-sleeve system. The four main flow patterns for such type of composite have been proposed in [5, 17] and flow patterns of composite have been compared with flow patterns of theirs components (core and sleeve as single material flow in extrusion) – (Fig. 2). Main factors influencing such metal composite flow are:

– The combination of the flow types of the components and the conditions of contact and interface (core-sleeve) friction. The more turbulent the type of flow and the worse the conditions of friction, the greater and more irregular is the shape of the plastic zone.

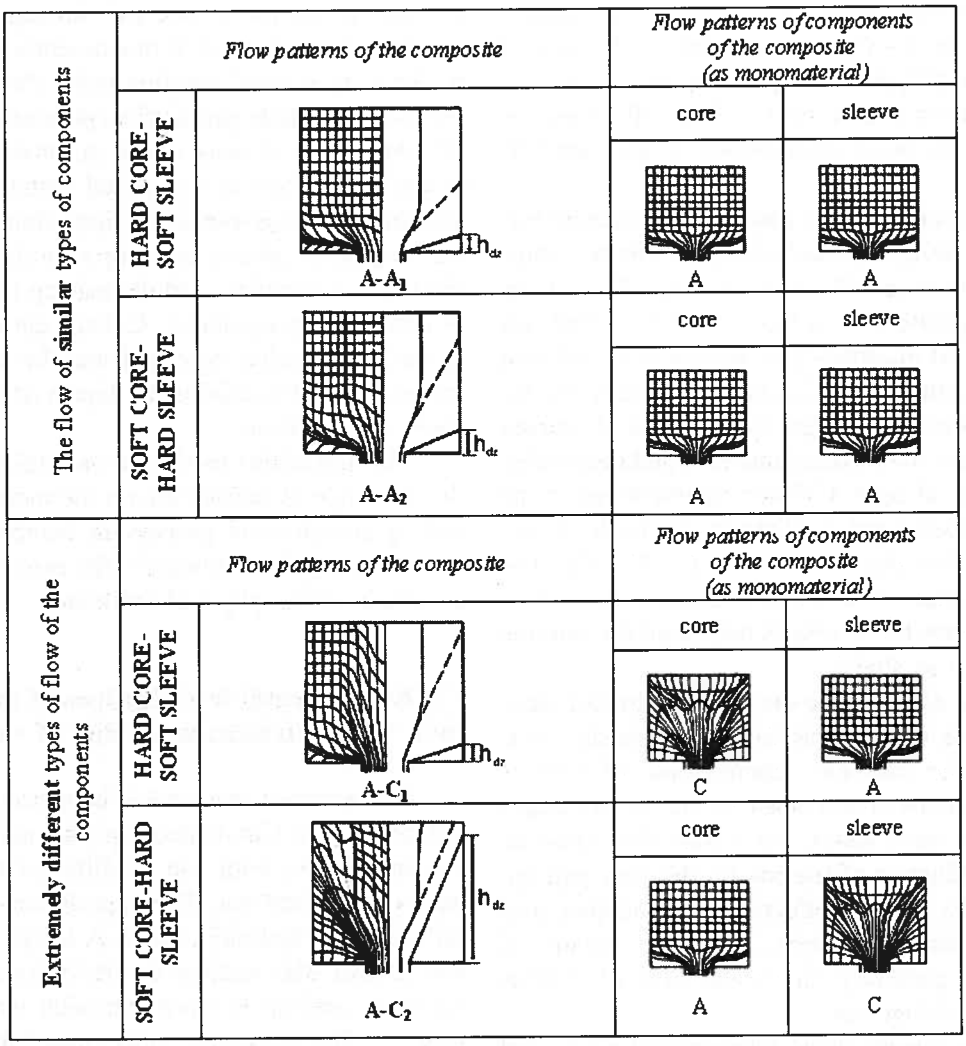


Fig. 2. Main types of flow in the co-extrusion of metal composites: $A - A_1$, $A - A_2$, $A - C_1$, $A - C_2$, (h_{dz} – parameter (height) of the dead zone). Broken line indicates the slope of the core-sleeve interface line and the type of flow [17]

– Volume ratio of the composite components. It has been shown that there is an emphatic difference between the forming of the plastic zone in the hard core-soft sleeve and the soft core-hard sleeve systems.

– Flow stress ratio $(\sigma_{phard\ component}/(\sigma_{psoft\ component})$. There is a different influence of this parameter for various systems of components in the layered composite. A limit value of this ratio protects the composite from defective flow. More differentiated materials lead to more complex form of plastic zones. Considering die shape it should be indicated that for a flat die a dead zone creates "natural die" and its boundary is a part of the boundary of the plastic zone and adequate conical die (a dead zone does not exist) is a part of the boundary of plastic zone.

It is possible to divide the combination of flow patterns of various materials in extrusion (at the stage of steady flow):

a) simultaneous flow of materials of the same type of flow (single metal)
b) simultaneous flow of materials of extremely different flow patterns (according to Pearson's classification).

Types of flow for real monomaterials: *A, B, C* (*S* – ideal theoretical one) may be combined in different way. Flow pattern acc. To type $A - A$ is dealing with simultaneous flow of core and sleeve of the same type of flow *A*, both in the case of hard core-soft sleeve $A - A_1$ and soft core-hard sleeve $A - A_2$, when flow stress of the components are not so different. Dead metal zone is mostly formulated in the sleeve region (using flat die) and forms "natural die" for the core. High of the dead zone (the angle of "natural die") is rather independent on extrusion ratio and components volume ratio, because it is material feature and for cases presented above there are the some types. Differences in the arrangement of components in the composite may effect on the form of simultaneous flow.

Flow of composite materials of extremely different flow pattern is type $A - C$. It means flow of the core of type A and sleeve of type C or opposite case – core acc. to type C and sleeve acc. to type A. Big differentiation of mechanical features of components is presented by type $A - C_2$.

Big differences in the flow patterns, mechanical features (flow stress ratio) and core or sleeve volume ratios, their arrangement in the billet have primary effect on the character of composite flow. It has been shown, that soft sleeve (flow type A) improves flow pattern $A - C$ of hard core-soft sleeve system ($A - C_1$), because it acts like lubricant. Hard sleeve of turbulent type of flow A worsen flow of such system $A - C_2$ dominant in it and decreasing uniformity of flow of type A. Other combinations of the flow patterns decide on intermediate cases: $A - B_1$, $A - B_2$, $B - C_1$, $B - C_2$, $B - B_1$, $B - B_2$, $C - C_1$, $C - C_2$. The character of influence of submitted factors on these flow patterns is analogous to the results presented for extreme cases, but it is not so sharp.

The optimum angle of the die for co-extrusion does not have the same meaning as for monomaterial. It is connected with the different requirements of various metals in designing the proper shape of the die. A conical die may eliminate dead zones, but it may also cause an increase in the influence of friction on the flow pattern.

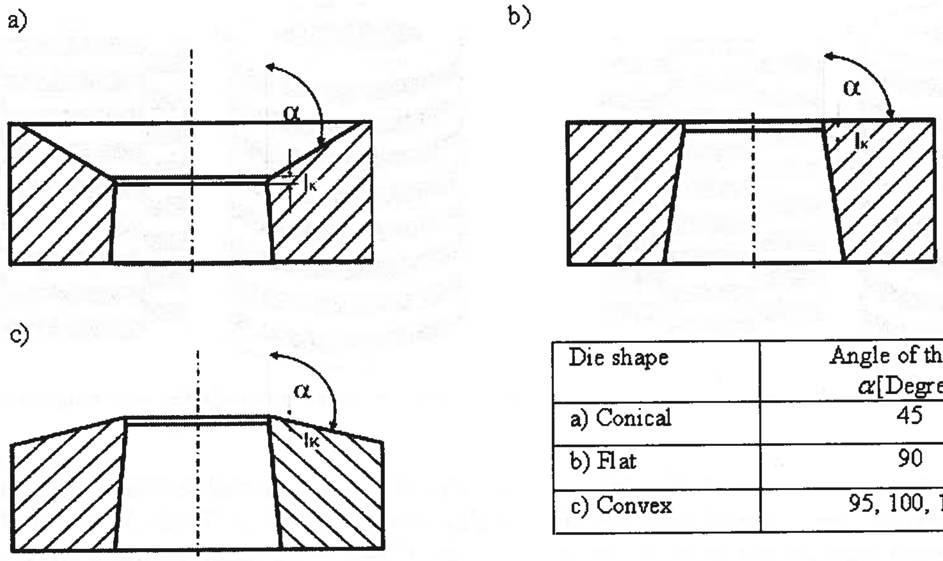
The possibility of very effective and sensitive controlling of the flow has been found by means of well-matched die geometry for co-extrusion of various materials deformed together.

Basing on the results of the experimental works and theoretical modeling the flow of monomaterial in extrusion using a convex die [6-10], it has been found that such tool may cause better, more regular and laminar flow. Convex dies are characterized by a die angle larger than 90 deg. Although such angle of the die causes the formation of the dead zone, but it gives much better flow pattern including radial flow zone near the orifice of convex die, which is favorable for increasing the charge velocity in the die orifice [8]. Basing on the profitable results of the extrusion of monometals using convex dies, it seems to be good solution using the same type of the die (with adequate geometrical parameters for given type of composite). It may cause an advantageous changes in the flow mode of composed material of core-sleeve structure, what is especially important in the deformation region of sleeve creating a more uniform velocity field in the extrudate and decreasing tendency to cracks of composite components. Convex die makes better flow pattern with radial flow and may be conducive to better bonding of component's layers of the composite of sleeve-core system.

The aim of this work is to determine the influence of the die angle of convex die on the metal composite flow during co-extrusion process in comparison with other kinds of dies (flat, conical) in the extrusion of composite materials within physical modeling.

2. Experimental investigations of metal composite flow in co-extrusion using dies of various geometry

To determine mechanical behaviour of different metals under their simultaneous plastic deformation, the extrusion process with use of different types of the dies has been carried out. The experiments were performed on a vertical hydraulic press. A set of flat dies, conical and convex dies leading to the various extrusion ratios (λ) were used in forward extrusion without lubrication (Fig. 3). The composite billets consisting of the following model materials: soft (pure) plasticine and hardened plasticine and hard lead (PbSb3)- as a core and soft lead (99.98%Pb) – as a sleeve have been used for testing. The composite billets have been prepared in concentric layout: core with circular section – sleeve in hard core-soft sleeve with various volume ratio of the core i.e.: Vcore/Vcomposite =0.08 and Vcore/Vcomposite =0.31. Basic parameters of performed extrusion tests are presented in Table 1.



Die shape	Angle of the die α[Degree]
a) Conical	45
b) Flat	90
c) Convex	95, 100, 105

Fig. 3. The dies used in the extrusion process: a) conical die, b) flat die, c) set of convex dies (bearing length l_K=2mm)

TABLE 1

Process parameters used in experimental work

Parameter	Unit	Value
Temperature of extrusion	°C	20
Billet diameter D_0	mm	36
Billet height L_0	mm	72
Extrusion ratio $\lambda = D_0^2/d^2$ (d – diameter after extrusion)	–	3; 12
Extrusion speed (ram speed)	mm/s	1

Material of the billet for extrusion process using non-metallic model materials was: white and black plasticine of the characteristics (σ=f(ε)) shown in Fig. 4. In order to prepare complex samples, some plasticine has been hardened with Al_2O_3 powder. In order to obtain stress-deformation characteristics, samples in cylinder form of diameter 36 and height of 54 mm have been subjected to static upsetting test. All upsetting tests have been performed using PE film as a lubricant (0.05 mm thick) placed between tool plates and sample end face. σ – ε characteristics, describing dependence between stress σ and actual deformation (logarithmic) ε for soft plasticine (without hardening additive) and Al_2O_3 powder hardened plasticine have been determined based on experimental results. The relationship σ=f(ε) for soft and hardened plasticine is presented in Figure 4. Composite billets consisting of alternate layers of white and black plasticine in form of cylinders (36 × 72 mm) has been used for testing (Fig. 5).

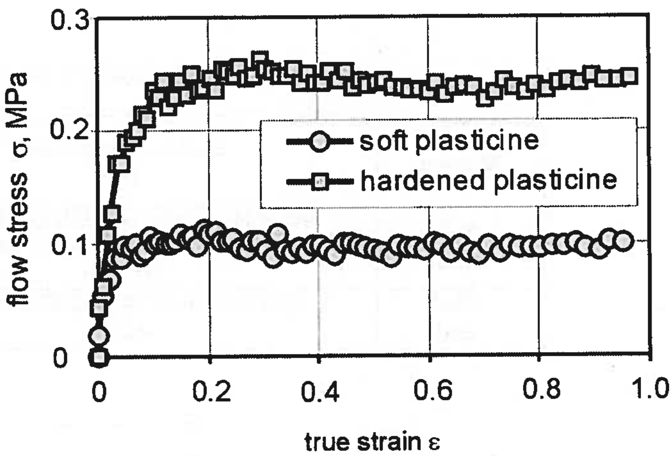


Fig. 4. Flow stress-true strain curves for soft plasticine and hardened plasticine

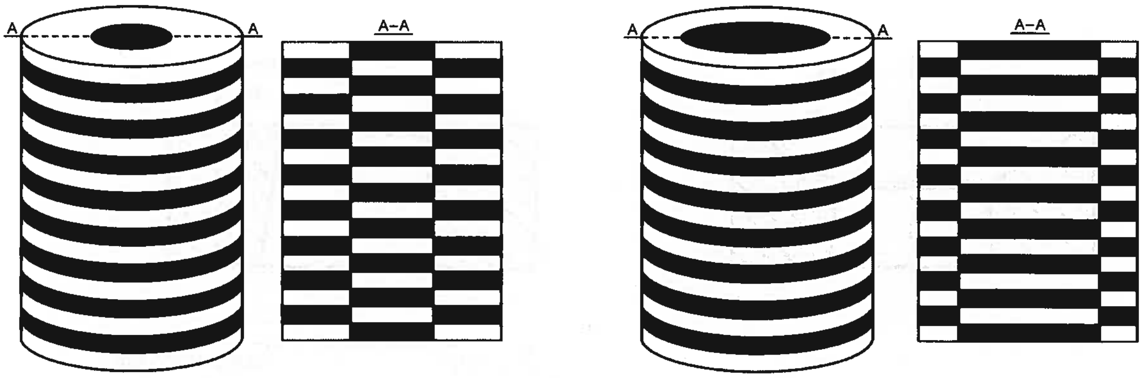


Fig. 5. Composite billets consisting of alternate layers of white and black plasticine in the form of cylinders with longitudinal sections

Plasticine was used because its flow characteristics at room temperature replicates well enough such metals as aluminum and aluminum alloys at extrusion temperature [20]. About 50% of initial billet length was extruded each time.

Testing of layer composite extrusion using metallic model materials has been performed using two-layer samples (Fig. 6). Selected features of materials used for testing are presented in Table 2. Material characteristics describing relationship between stress σ and actual strain (logarithmic) ε for soft lead and hard lead have been determined based on experimental test (uniaxial compression) – Fig. 7.

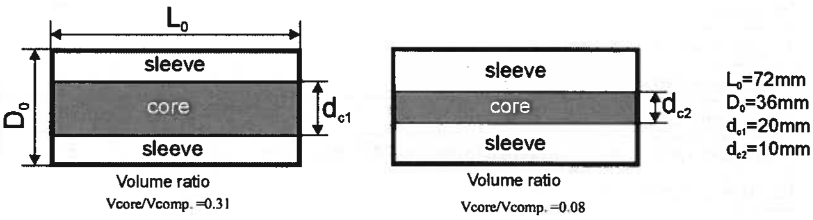


Fig. 6. The scheme of longitudinal sections of the composed billet of sleeve-core system with various volume ratios

TABLE 2

Some features of materials used in investigations

Material	Chemical composition [%]	Yield stress [MPa]	Brinell Hardness HB
Soft lead	99.98 Pb; 0.002 Ag; 0.001As; 0.001Sb; 0.001Sn; 0.002Cu; 0.002Fe; 0.001Zn; 0.005Bi	5	5.3
Hard lead	2.5-3.5 Sb; 0.015As; 0.04Cu; 0.012Fe; 0.01Bi	10	8.7

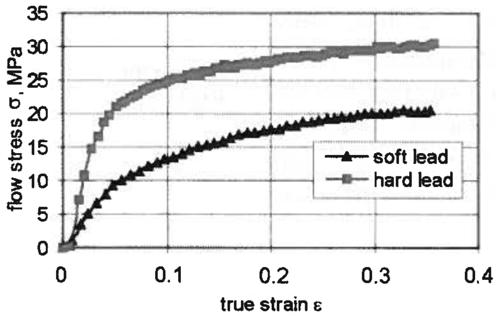


Fig. 7. Flow stress-true strain curves for soft lead and hard lead alloy

In the case of metallic model materials it was possible to use visioplasticity method, enabling strain field analysis based on deformation of square grid (1.5 mm mesh side) spread over the surface of longitudinally cut billet. Therefore before extrusion each layer of the composite rods was firstly, split into two equal halves and square grids of 1.5 × 1.5 mm were inscribed onto the longitudinal symmetrical plane of the split half. Then two halves were fitted together and put into the container to realize the experiments of the extrusion of composite rods.

3. Results and discussion

As the first stage of experimental work – the physical modeling of the extrusion processes has been carried out with use of plasticines as modeling materials. After performing extrusion tests, die with the rest of billet and extruded material have been pushed out from the container and separated. Billet remainders after extrusion have been longitudinally cut and obtained image of material flow have been photographed. Observation of obtained material flow images, after partial extrusion of billets, allowed approximate, qualitative definition of means of material flow through tested dies. Typical images of model material flow (plasticine) during extrusion through conical, flat and convex dies for hard core – soft sleeve configuration with extrusion ratios of λ=3 and λ=12 have been presented in Figure 8.

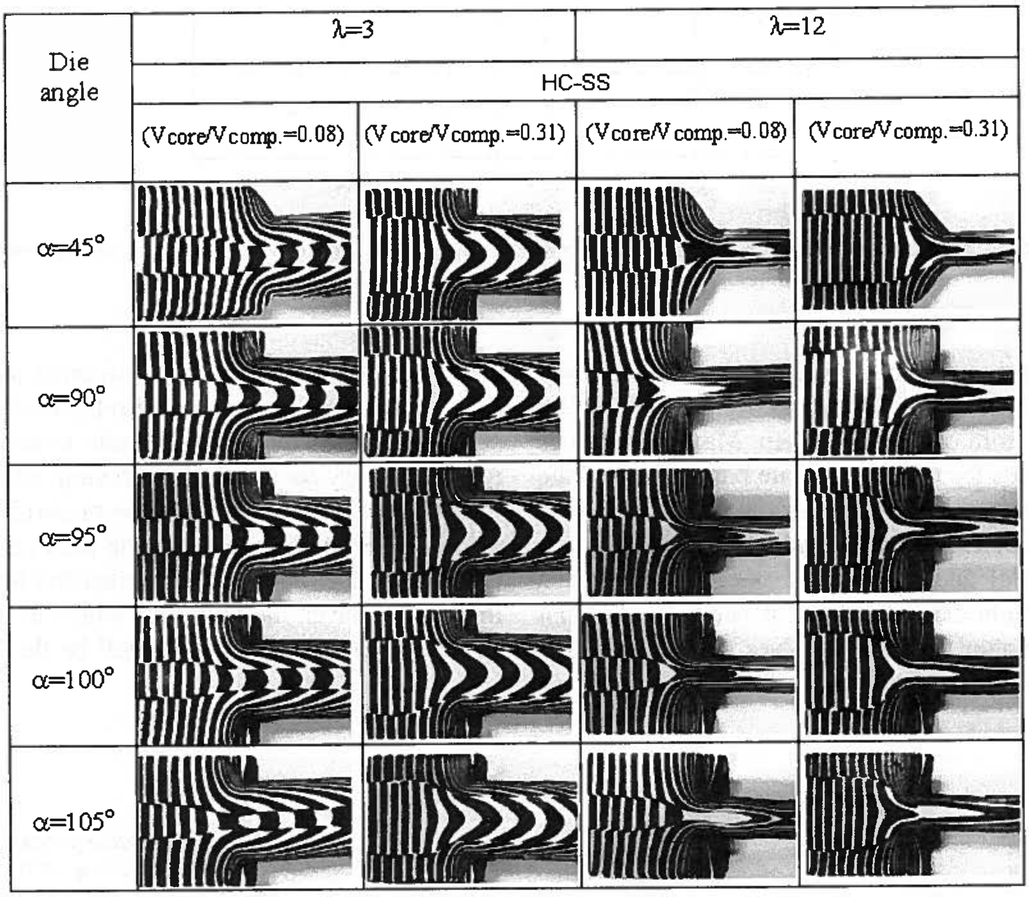


Fig. 8. The physical modeling of extrusion of layered composites with use of soft plasticine and hardened plasticine (hard core-soft sleeve system (HC-SS))

Based on obtained flow images, extrusion ratio of composite components has been determined core – λ_c and sleeve – λ_s in relation to global extrusion ratio – λ, resulting from tool geometry [17], where

$$\lambda_c = \frac{d_{co}^2}{d_c^2} \tag{1}$$

$$\lambda_s = \frac{D_o^2 - d_{co}^2}{d^2 - d_c^2} \tag{2}$$

$$\lambda = \frac{D_o^2}{d^2} \qquad (3)$$

where: d_{co} – diameter of core before extrusion, d_c – diameter of core after extrusion, D_o – diameter of billet, d – diameter after extrusion

Graph (Fig. 9) presents dependence between extrusion ratio of composite and ratios of its components on the die angle for the volume ratio of core in composite equal to 0.08 (Vcore/Vcomp.=0.08) and 0.31 (Vcore/Vcomp.=0.31). Lower diversity of extrusion ratio of composite components applies to larger extrusion ratio – λ=12. Higher result diversity can be observed for composites with smaller core volume ratio. As demonstrated by the results, it is possible to limit large differences between deformation sizes by using proper die geometry.

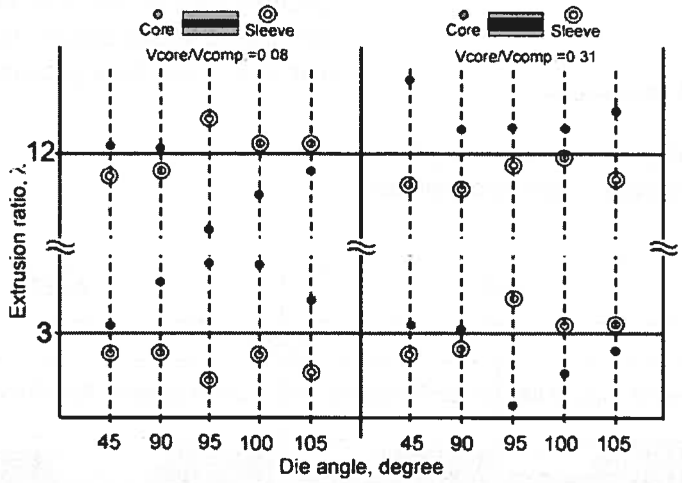


Fig. 9. Dependence of the global, core and sleeve extrusion ratio on the angle of the die for two volume ratio of the core; hard core - soft sleeve system

Extrusion process force characteristics has been prepared for tested composites by set of the dies, based on data recording from computer system. Maximum values of extrusion loads for each composite based on used die have been determined using those characteristics (Fig. 10). It allowed determining a relation between die geometry (die angle) and extrusion load. Analyzing each value of maximum extrusion load, it can be stated that the die angle higher than 90° involves reduction of this value. Higher volume ratio of soft core in composite will lead to increase of maximum extrusion load in the case of using convex dies compared to flat dies. During analysis of die angle effect on maximum extrusion load value it is necessary to consider extrusion ratio. In the case of extrusion with extrusion ratio of λ=12 a tendency to obtain lower maximum extrusion load can be observed. Obtained values of maximum extrusion load shows, that there is a convex die angle for which an extrusion load value, for specific composite, will be the lowest.

a) b)

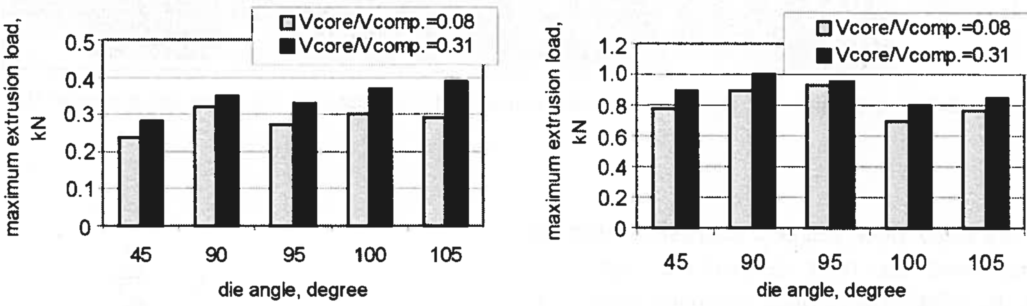


Fig. 10. Dependence of maximal extrusion load on the angle of the die, and extrusion ratio for hard core – soft sleeve system: a) λ=3, b) λ=12 (for plasticine)

The second stage of physical modeling was carried out with use of metallic materials: hard lead and soft lead. The analysis of flow of layered metal composite in the extrusion process reflects the change in character of plastic flow of composite material dependently on the kind of used die. Basing on the analysis of grid distortion observed on the longitudinal section of the billet and extrudate (to use the visioplasticity method) the identification of plastic and dead zones and distribution of relative velocities of particles have been done (Fig. 11). The improvement of flow characteristics of layered composite in extrusion with use of convex dies has been found. It was found that the radial flow of material of sleeve appears (there is no such phenomenon for extrusion using flat or conical dies) – Figure 12. Such behaviour of composed material can lead to equalization of velocities of particles in the region of the die orifice.

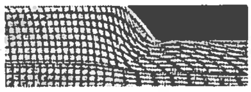
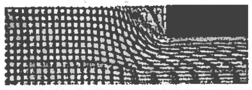
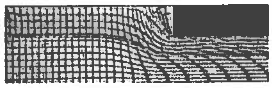
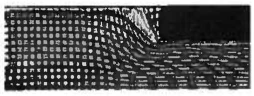
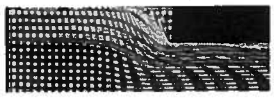
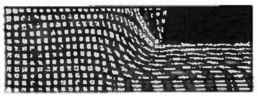
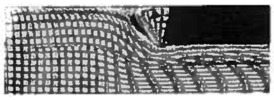
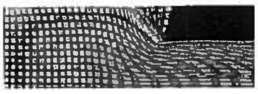
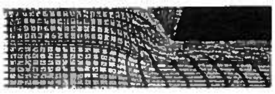
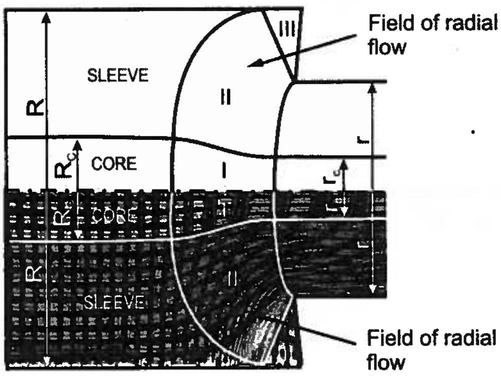
Angle of the die	hard lead (core)-soft lead (sleeve)	
	(Vcore/Vcomp.)=0.08	(Vcore/Vcomp.)=0.31
Conical die $\alpha=45°$		
Flat die $\alpha=90°$		
Convex die $\alpha=95°$		
Convex die $\alpha=100°$		
Convex die $\alpha=105°$		

Fig. 11. Grid distortion on the longitudinal section of the billet during extrusion through the conical, flat and convex dies (extrusion ratio $\lambda=3$)

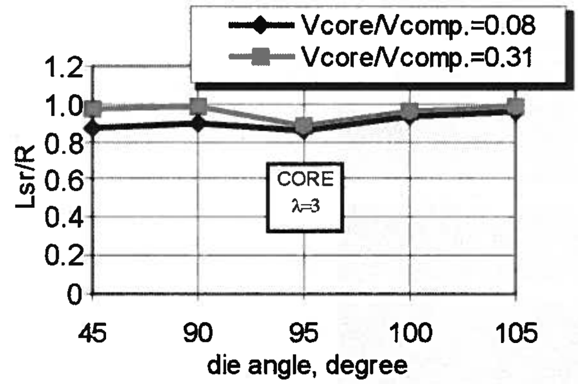


I-deformation zone of core
II-deformation zone of sleeve
III-dead zone
R, r-the radius of sleeve before extrusion and after extrusion, respectively
R_c, r_c-the radius of core before extrusion and after extrusion, respectively

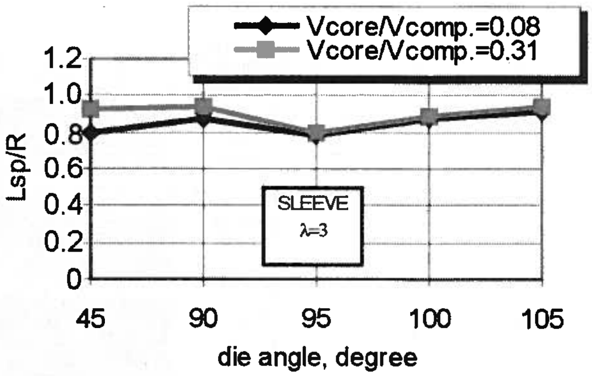
Fig. 12. The field of radial metal flow, which is unique for convex dies

Based on observation of deformed grids, it is possible to note a change of shape and size of core and sleeve zone of flow depending on die angle. It is important to define die geometry influence on deformation zone range inside the billet. It was accepted that the core deformation zone has its start between two consecutive grid lines, where distance between the two consecutive grid lines measured along the axis is larger than initial distance. Sleeve deformation zone starts at the place, where the distance between consecutive grid cracks in the area of adhering to the core is larger than for initial mesh length. Both core deformation area range and sleeve area range have the lowest value for the convex die with angle of $\alpha = 95°$ (Fig. 13 a, b). Increase of extrusion ratio (e.g. $\lambda = 12$) caused shift of lower values of composite components deformation zone range in the direction of higher die angle, i.e. $\alpha = 100°$ (Fig. 13 c, d).

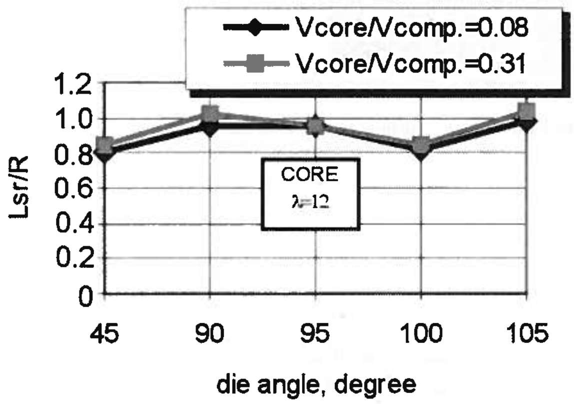
a)



b)



c)



d)

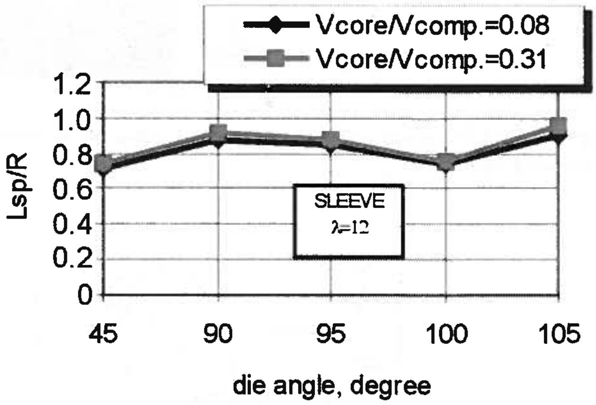


Fig. 13. Dependence of the relative range of deformation zone of the core and of the sleeve on angle of the die for two volume ratio of the core; hard core- soft sleeve system, extrusion ratio a, b) $\lambda = 3$, c), d) $\lambda = 12$

According to data presented in Figure 14, die geometry has a significant effect on particle velocity distribution in a die opening. The largest difference in particle velocity occurred during extrusion using conical die. In the case of extrusion through flat dies, velocity gradient decreases, both for a single layer and the whole composite. It is still enough significant to lead to product defect, resulting in lack of proper layer bonding or cracking of one of the components: core or sleeve. The most favorable type of extrusion considering the most uniform particle flow for each layer is extrusion through convex dies with properly selected angle of the die. Analysis of extrusion effect using all kinds of dies demonstrates that using convex die with die angle of $\alpha = (95° - 100°)$ causes reduction of difference of particle velocity.

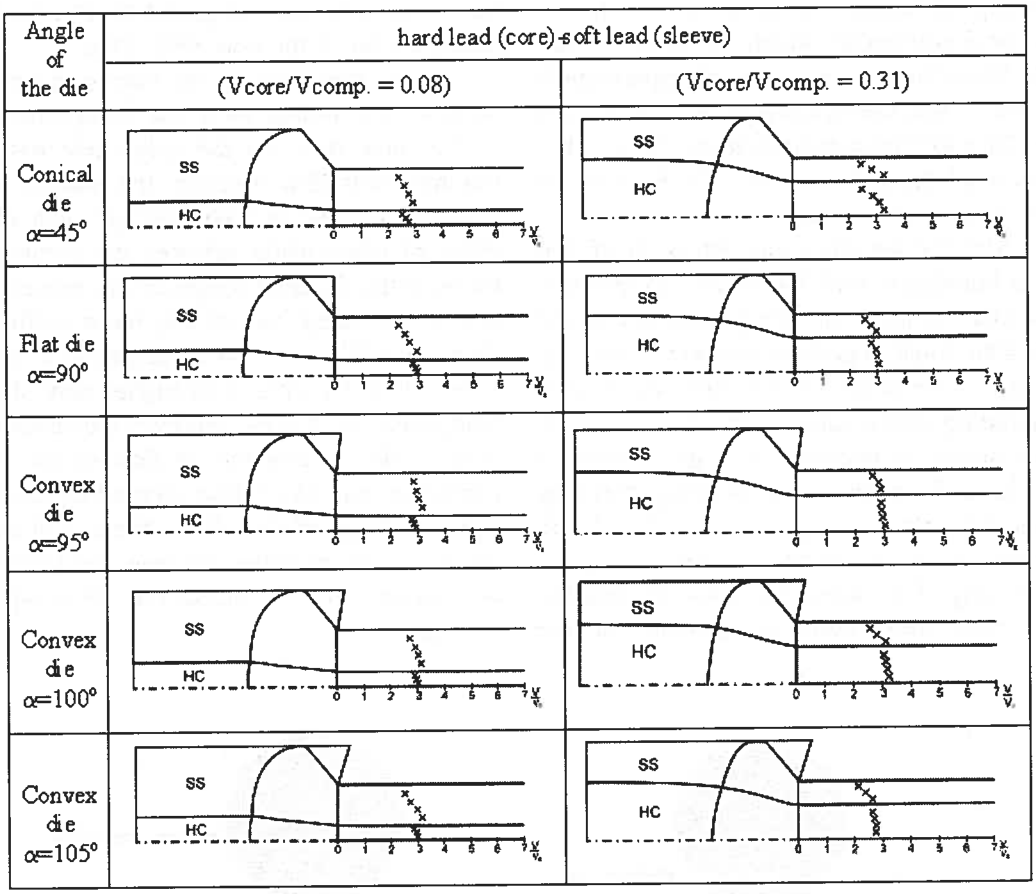


Fig. 14. Distribution of relative velocity of particles v/v_0 in the region of the orifice of the die

Analysis of obtained results of experimental investigations considering effect of the die geometry on extrusion load indicates diversity of its value depending on the die geometry. There is some minimum value of the load in the case of extrusion through convex die with die angle of α = 95° (Fig. 15a) under conditions of extrusion with extrusion ratio λ=3. Increase of extrusion ratio (e.g. from λ=3 to λ=12), causes observed minimum value to move in the direction of the die with higher die angle, i.e. α=100° (Fig. 15 b).

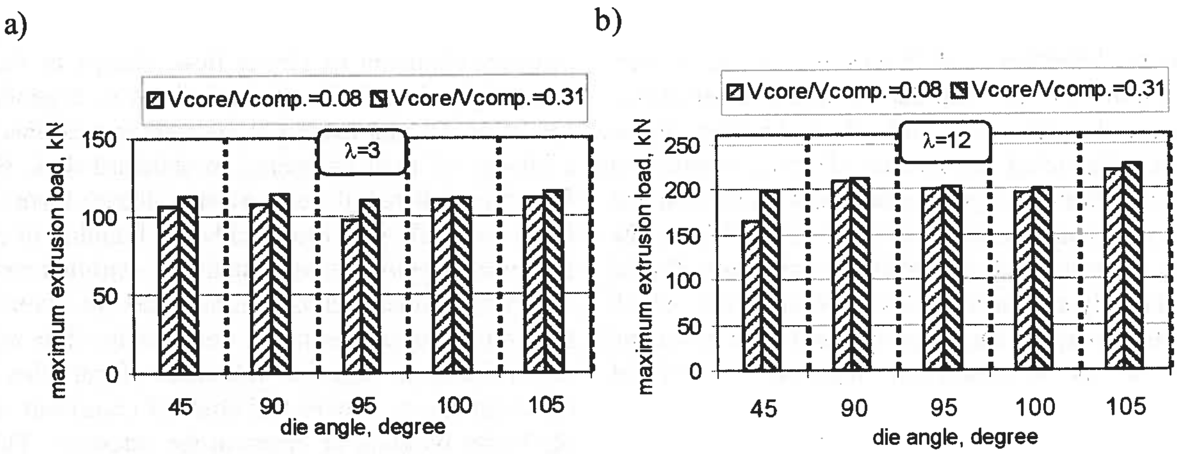


Fig. 15. Dependence of maximal extrusion load on the angle of the die, extrusion ratio: a) λ=3, b) λ=12 (for metals)

It can be accepted that there is some optimal die angle for specific layer composite, which causes the lowest extrusion load. According to the results of experimental work for hard core – soft sleeve configuration, it is most favorable to perform extrusion process using convex dies with die angles α of the (95°- -100°) – in the case of extrusion ratios from λ=3 to λ=12.

Important issue for simultaneous extrusion of two various metals is bonding of their layers. Performed analysis of influence of changing process parameters on the zone, shows that the most important parameters causing durable bonding is a die angle and deformation degree. An example of sliding effects (displacement lines of grid of core towards sleeve in interface) and good bond of component in the deformation zone (without breaking of the grid lines at interface) are presented in Fig. 16. In the case of extrusion of composite with higher volume ratio of the core (Fig. 16b) using the same die and the same extrusion ratio (λ=3), better component bonding has been observed compared to composite with lower volume ratio of the core (Fig. 16a).

At the first stage of the extrusion process, the plastic flow in components of the composite is not initiated at the same time (in the softer one first). When various materials flow together, the process becomes more uniform, but the consequence of such phenomenon is different relationship between the component's volume ratios at the different stages of the process. By retarding soft sleeve using convex die, more uniform flow of the sleeve and the core can be achieved. It will be stronger effect when the core is of higher part of volume in the composite. Next stage (uniform extrusion) characterizes more uniform velocities of flow of the components of composite but taking into account different velocities of component's particles (diversification of deformation degrees - extrusion ratios for core and sleeve separately in comparison with the global one for composite as a hole extrudate).

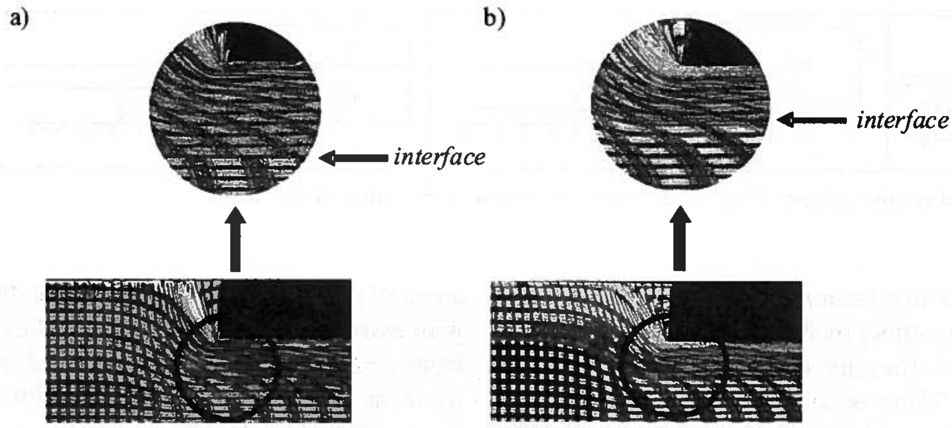


Fig. 16. View of the composite material flow with: a) the phenomenon of sliding, b) good bonding of components in deformation zone; sticking, extrusion ratio λ=3

Accurate definition of sliding or good bond of components condition is difficult, due to large number of factors affecting domination of each effect. Another important factor influencing occurrence of above mentioned effects is a friction – layer friction and friction at the tool-material boundary, component volume ratio in the billet and properties of composite components. Radial flow is relatively easy achieved using convex die, which is conductive to apply such type of the die for extrusion of composite and to obtain advantageous character of flow.

4. Conclusions

Applying convex dies with a die angle larger than 90 deg, in comparison with traditional dies has shown different character of plastic flow, change of shape and size of plastic zones and dead zones in dependence on die angle. During extrusion through convex dies there is a change of flow compared to standard dies. Effect of forced partial radial flow (mostly sleeve) favors forcing more favorable flow type and better bonding of composite layers, providing better quality of extruded composite. Applying properly chosen convex die for given type of the composite causes radial components flow and gives a possibility to equalize velocities of particles flow of the components (sleeve and core) of composite and enable better bonding of layers at the interface. This let to introduce such type of the die to the practice, though the cost of production of convex die is a little bit higher in comparison with traditional one.

The lowest range and volume of deformation zone was observed for convex dies especially for die of 95 and 100 degrees. It has been shown that use of convex dies can lead to more homogeneous flow of layers of composite material. Basing on the obtained results it has been demonstrated that optimal die angle exists for specific type of composite, which causes the lowest extrusion load and equalization of velocities of particles in the region of the plastic zone and the die orifice. Choice of adequate die angle depends on the kind of the composite materials and should be determined for specific conditions of the process.

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