FRACTURE PHENOMENON IN SIMULATION OF BIMETALLIC RODS EXTRUSION PROCESS

Grażyna Ryzińska
Rzeszow University of Technology, Faculty of Mechanical Engineering and Aeronautics, Rzeszow, Poland

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Corresponding author: Tel.:+48178651507, *Department of Metals Forming and Processing, Faculty of Mechanical Engineering and Aeronautics, Rzeszow University of Technology, Powstańców Warszawy 8, 35-959 Rzeszow, Poland, e-mail: grar@prz.edu.pl*

Abstract
Mechanical behaviour of metallic material is different during its deformation as monometallic one in comparison with deformation as a component of composite. The different flow characteristics of two materials enhance the inhomogeneity of the extrusion process. This lead to poor tolerance throughout the extrudate fracture of the core or fracture of the sleeve. The concept of FEM Marc Mode has been presented with results which may indicate the possibility of assessment of existing fracture criteria for composite material. The present study shows that prediction based on the criterion including σ_{max}, $\bar{\sigma}$, $\bar{\varepsilon}$, ε_f is reflected in experimental results. Fracture phenomena dependency occurring on geometrical arrangement of billet has been presented. The values of R_i/R_0 ratios were lower the probability of fracture occurrence was higher.

Keywords: extrusion, simulation, composite

1 Introduction
The mechanical behaviour of material in metal forming process depends on mode of plastic flow, structural and mechanical effects and factors dealing with conditions of the process. The means of controlling the material structure and determining the influence of material properties on metal flow are basic information needed to describe physical nature of plastic deformation of metallic materials. It is essential to be able to predict mechanics of plastic flow and in consequence controlling the metal forming operation. Among the simplest forms of composite materials are bimetal rods or wires, which can be obtained in the course of co-extrusion process. Even in this simple case metal flow is very complicated especially because of non-homogeneity of the initial material [1-3].
Considering the mechanical behaviour of two different materials deformed together it is necessary to take into account two possibilities in the interface core – sleeve: sticking or sliding phenomena. It depends on the conditions of the co - extrusion process. Relative thickness of layers of the composite (components volume ratio), flow stress ratio ($\sigma_{p\ hard\ component}/\ \sigma_{p\ soft\ component}$), the combination of flow types of the components and the conditions of contact and interface (core - sleeve) friction and a die shape are the main factors influencing plastic flow in extrusion. Analysis of theoretical mechanical behaviour allows to verify the features of the material under conditions of compression tests of composite initial material. It allows to define

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(for considered model of composite material) the most important material constant and evaluate other parameters e.g. the factor of friction on the contact surface metal – tool, or on the interface between the core and the sleeve. One of special criterion for prediction of the fracture of the core or the sleeve in the extrusion process of composite is Avitzur criterion [4], which has been based on assumption that product emerges without defect in the case of proportional flow only. It means that degrees of deformation of the core and the sleeve are equal. The results presented in [3] show that a composite of good quality may be obtained even when the degrees of deformation of components are not the same but different from the global degree of deformation of composite.

The forms of the plastic zones in the extrusion of layered composite of sleeve –core system are dependent on many factors and finally may lead to non-proportional flow or defective flow with sleeve or core fracture. To avoid such negative phenomenon it is important to use the theoretical method for prediction of the conditions when fracture may occur. FEM may be applied to model and control metal forming process or predict possible negative phenomena. There are numerous papers concerning such problem [5-9] but up to now there is no enough good solution taking into account the real behaviour of various materials or choice of proper criterion of fracture. There are many criteria of various formulas (**Table 1**) and their application in the modeling leads to different results.

Table 1 Chosen type of ductile fracture criterion

No	Type of criterion	Formula	
1.	Freudenthal	$\int_0^{\varepsilon_f} \sigma_H d\varepsilon = C_1$	(1.)
2.	Cockroft-Latham	$\int_0^{\varepsilon_f} \sigma_{\max} d\varepsilon_{pl} = C_2$	(2.)
3.	Brozzo	$\int_0^{\varepsilon_f} \left(\frac{2 \cdot \sigma_{\max}}{3 \cdot (\sigma_{\max} - \sigma_m)} \right) d\varepsilon = C_3$	(3.)
4.	Oyanne	$\int_0^{\varepsilon_f} \left(1 + \frac{\sigma_m}{A_4 \cdot \sigma_H} \right) d\varepsilon = C_4$	(4.)
5.	Oh	$\int_0^{\varepsilon_f} \left(\frac{\sigma_{\max}}{\sigma_H} \right) d\varepsilon = C_5$	(5.)
6.	Osakada-Mori	$\int_0^{\varepsilon_f} (B_6 + \bar{\varepsilon} + D_6 \sigma_m) d\varepsilon = C_6$	(6.)

where: σ_H – von Misses stress

σ_{max} – maximum stress

$\bar{\sigma}$ - equivalent stress,

$\bar{\varepsilon}$ - equivalent strain

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$\bar{\varepsilon}_f$ - equivalent strain of fracture
C- constant

Functioning of these criteria may be checked in the bulk forming processes for example in the co-extrusion of various metals deformed together. Well known fracture criteria [9-15] like: formula according to Brozzo, Cockroft-Latham, Ayada, Freudenthal or Clift include different factors, so indication of the moment of fracture depends on the chosen formula. Up to now there is no good enough solution, which could be applied for composite material. Existing formulae for prediction of fracture of bimaterial (e.g. acc. to Avitzur) [4] are rather complicated and based on over simplified assumptions.
A possibility of applying the finite element method (FEM) for modeling, including the plastic deformation processes, creates new possibilities for the analysis of physical phenomena based on the highly developed mathematical model. FEM methods allow, with some kind of approximation, to determine, among others, the distributions of deformations values, and thus to predict the behavior of the material in various forming processes. [16-22].

2 Experimental materials and methods

There were made experimental tests of the extrusion process of composite materials, followed by the modeling process. Forward extrusion of layered composite rods were carried out using set of tools in a hydraulic press. Conditions of the process were as follow: forward extrusion, ram speed about 2mm/s, flat face dies leading to extrusion ratios R=3, R=6 and R=12, room temperature. The initial material (billet) was composed of aluminum (the core layer) and lead (the sleeve layer) (**Table 2**).

Table 2 Some properties of materials used in investigations

Material	**Chemical composition [%]**	**Yield stress [MPa]**	**Young's modulus [MPa]**	**Poisson's ratio**	**Brinell Hardness HB**
Lead	99,98 Pb; 0,05 Ag; 0,05As; 0,01Sb; 0,05Sn; 0,05Cu; 0,05Fe; 0,05Zn; 1,0Bi	5	14000	0,43	4,4
Aluminum 1050	99,5 Al; 0,4Fe; 0,3Si; 0,05Cu; 0,07Zn; 0,05Ti	26	70000	0,33	22,4

There was obtained a series of products which were cut along to observe the phenomena occurring internally, within the core fracture in particular. There were also obtained graphs of the relation of force in the function of the punch displacement. The shape and dimensions of the composite extrusion samples and the sample products were shown in **Fig. 1**. It was also analyzed a number of fracture criteria selected as suitable for the extrusion process (**Table 1**).
In order to analyze the fracture criteria and to understand better the phenomena observed in experimental studies occurring in the extrusion process the FEM model was built by using the commercial program MSC Marc. The construction of the same as in the test FEM model of the extrusion process and simulation of the process with parameters as in the experiment allowed for the verification of this model and its modification by comparing the results obtained in the simulation with the results obtained in experimental studies. The obtained FEM model will

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allow to predict the effects resulting from the change of the input parameters in the extrusion process without the need of costy and time-consuming experiment. Consequently, this approach will allow to understand better the process of extrusion of composite materials and in the future it will give guidance for the design of such processes.

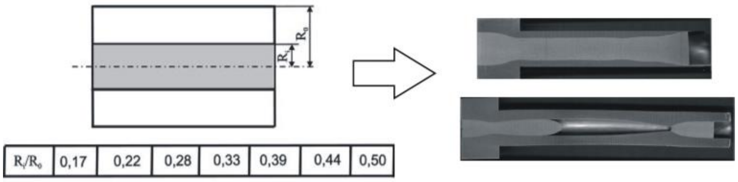

Fig.1 The shape and dimensions of the composite extrusion samples and the sample products. Material of core –aluminum, material of sleeve – lead

In order to determine the friction coefficients between the layers of the composite and tools and the interlayer friction, the friction tests were performed by using tribotester T-01M, of a pin-on-disc type (without samples lubrication). Based on measurements of pressure load F_N and circumferential force F_T in the conducted test, the values of friction coefficients were calculated according to the formula (7). The obtained results of friction coefficients values for particular pairs of metals are summarized in the **Table 3**. Boundary conditions used in modeling of the extrusion of composite materials were shown in **Table 4.**

Table 3 The obtained results of friction coefficients values for pairs of metals

Pair of metals	Friction coefficient
aluminum - steel	0,15
lead - steel	0,2
aluminum - lead	0,35

Table 4 Boundary conditions used in simulation

Yield condition	Flow rule	Friction	Stress-strain curve
Huber - Misses	Prandtl - Reuss	Coulomb friction	experiment

$$\mu = \frac{F_T}{F_N} \qquad (7.)$$

where: F_N - pressure load
F_T - circumferential force

Geometric model of extrusion tools was built on the basis of the geometry of the tools used in the experiment. The discussed process is the axially symmetrical process, therefore in this case it is not justified to build the three-dimensional model due to the high demand for computing power in case of 3D models. It was assumed that perfectly rigid tools (die, punch) enter into contact with the deformable material feedstock. For the construction of the finite element mesh of the deformable sample there were used the elements of class 4 grade 10. The numerical

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simulation was performed by using automatic remeshing, which allows to continue the calculations in case of plastic deformations resulting in a large deformation of finite elements mesh.

To describe the properties of the material as isotropic there were used the characteristics determined while conducting the test of upsetting samples with different H/D ratio.

In the tested models a number of finite elements was taken into account, since considering the same size of elements, their number in individual cases would be different, depending on the geometry of the feedstock. Because of good compatibility with experimental results Coulomb friction model was used. The verification of the model was conducted by comparing the course and the extrusion force value obtained in the subsequent simulations with the force determined experimentally. Finally there was adopted the model that showed the greatest similarity to the results of the experiment.

In order to calculate the value of individual criteria in every calculation step there were written procedures in Fortran language. Each of the analyzed criteria required a special procedure. The frameworks of PLOT-V subprogram were used.

Some part of the procedure remained constant while another one was changing depending on the type of calculated criterion. Analytical form of used procedures was shown in **Table 1**.

3 Results

As a result of modeling of the composite materials extrusion process there were obtained the courses of forces in the function of punch displacement (**Fig. 2**), as well as the distribution values of the researched function for each fracture criterion (**Fig. 3**).

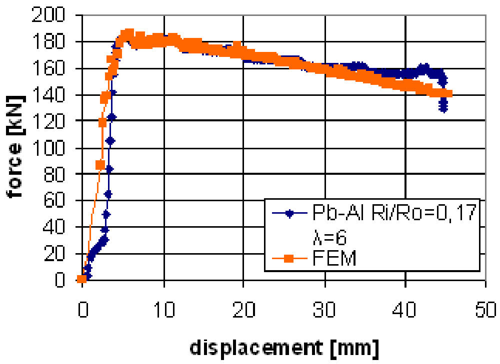

Fig.2 An exemplary courses of force in the function of punch displacement (R=6). Experiment (Pb-Al R_i/R_0=0,17) and simulation (FEM)

As the result of the extrusion experiment it was decided that the fracture of the core is initiated on average by the extrusion of 10% of the initial length of the sample. The analysis of the values of the criteria was carried out for the same conditions as in the experiment. The performed numerical analysis with an application of the appropriate procedures allowed to obtain distribution values of various criteria of fracture which facilitate an analysis of the suitability of particular solutions, e.g. in the extrusion process of composite materials. The figure shows the results for Brozzo, Cockroft-Latham, Freudenthal, Oyane Oh, Osakada-Mori criteria and the modified C-L criterion available in the standard software in MSC MARC (Fig. 3).

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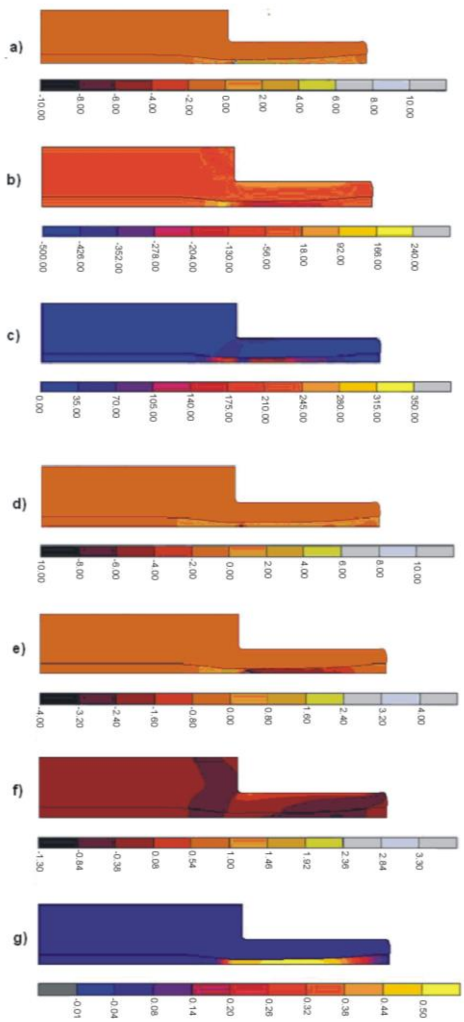

Fig.3 Numerical simulation. An exemplary distribution values of the researched function, Pb-Al (hard core – soft sleeve) R=6, Ri/Ro=0,17; a) Brozzo fracture criterion, b) C-L, c) Freudenthal, d) Oyane, e) Oh, f) Osakada-Mori, g) modified C-L criterion

Distributions shows in Fig. 3 are presented the average values of analyzed criteria. The fracture place observed in the experiment is not converged with the place of the highest values of criterion predicted by FEM.

The obtained experimental results allowed to build FEM extrusion model of composite materials with an application of flat dies. Numerical modeling allows for better understanding the phenomena observed in the performed experiment. To already made and tested FEM models there were attached the procedures which counted the values of the discussed fracture criteria at each calculation step. Such a procedure facilitates the assessment of the suitability of the fracture criteria with respect to the extrusion process of composite materials.

The choice of criteria for the analysis was dictated by the theoretical studies conducted on the

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basis of the research results published in scientific literature. There were analyzed the criteria which give the best results when applied during the extrusion process. It was also taken into account the formula of the criterion and the factors included in it.
The analysis done in case of the Freudenthal criterion (Fig. 3c), which was characterized by the simplest form, and the occurrence of fracture depends on the fracture deformation and stress σ_H indicates the correct core fracture in the given time except R=6, Ri/Ro=0,17, where the fracture exists in the experiment and the criterion value in modeling does not exceed the critical value. An exemplary comparison of Freudenthal and C-L criteria was shown in **Fig. 4**.

a) R=6, Ri/Ro=0,50, Freudenthal criterion b) R=6, Ri/Ro=0,50, C-L criterion (MSC-option)
Fig.4 Comparision of distribution of Freudenthal criterion values -(a), C-L criterion values available in standard MSC software -(b)

Values of particular criteria in the place of fracture observed in the experiment (center of the die orifice) were measured. It perform measurements in grids nodes. Values of particular criteria (FEM) after extrusion of 10% of initial billet length are shown in **Table 5-11**.

Table 5 Maximum values of Freudenthal criterion (FEM)

Freudenthal, C_1=159,06							
Ri/Ro	**0,17**	**0,22**	**0,28**	**0,33**	**0,39**	**0,44**	**0,50**
λ=3	110	110	141,15	122	124	132,15	142
λ=6	150	171	184	186	184	194	192
λ=12	260	290	309	315	308	340	353

Table 6 Maximum values of C-L criterion (FEM)

C-L, C_2=104,21							
Ri/Ro	**0,17**	**0,22**	**0,28**	**0,33**	**0,39**	**0,44**	**0,50**
λ=3	66,36	76,3	69	74	85,6	85	83,7
λ=6	75,68	107,7	124	105	116	110	112
λ=12	85,00	142,5	211,6	209,7	212,9	204,4	196

Table 7 Maximum values of Brozzo criterion (FEM)

Brozzo, C_3=0,8							
Ri/Ro	**0,17**	**0,22**	**0,28**	**0,33**	**0,39**	**0,44**	**0,50**
λ=3	0,6	0,69	0,62	0,66	0,76	0,76	0,74
λ=6	0,64	0,85	1,02	0,88	0,98	0,92	0,95
λ=12	0,69	1,11	1,60	1,60	1,69	1,59	1,49

Table 8 Maximum values of Oyane criterion (FEM)

Oyane, C_4=1,54							
Ri/Ro	**0,17**	**0,22**	**0,28**	**0,33**	**0,39**	**0,44**	**0,50**
λ=3	0,92	1,03	0,99	1,01	1,13	1,15	1,13
λ=6	1,05	1,3	1,53	1,36	1,49	1,43	1,47
λ=12	1,18	1,79	2,4	2,40	2,52	2,42	2,33

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Table 9 Maximum values of Oh criterion (FEM)

Oh, C_5=0,83							
Ri/Ro	**0,17**	**0,22**	**0,28**	**0,33**	**0,39**	**0,44**	**0,50**
λ=3	0,6	0,69	0,53	0,66	0,76	0,76	0,74
λ=6	0,62	0,9	1,03	0,87	0,98	0,91	0,95
λ=12	0,64	1,1	1,6	1,6	1,68	1,58	1,48

Table 10 Maximum values of Osakada-Mori criterion (FEM)

Osakada-Mori, C_6=-1,46							
Ri/Ro	**0,17**	**0,22**	**0,28**	**0,33**	**0,39**	**0,44**	**0,50**
λ=3	-0,46	-0,45	-0,41	-0,41	-0,38	-0,33	-0,27
λ=6	-0,09	-0,06	0,09	0,1	0,13	0,23	0,25
λ=12	0,91	1,71	2,16	2,28	2,44	2,80	3,14

Table 11 Maximum values of modified C-L criterion (FEM)

C-L (modified), C_7=0,83							
Ri/Ro	**0,17**	**0,22**	**0,28**	**0,33**	**0,39**	**0,44**	**0,50**
λ=3	0,48	0,46	0,43	0,41	0,37	0,27	0,23
λ=6	0,44	0,34	0,27	0,25	0,093	0	0
λ=12	0,29	0,21	0,02	0	0	0	0

If the value of criterion greater than value of C, then criterion indicates the fracture occurrence. The fracture occurrence in the experiment is shown in **Table 12**.

Table 12 Fracture occurrence in experiment (+ fracture occurs, - no fracture)

Fracture occurence in experiment							
Ri/Ro	**0,17**	**0,22**	**0,28**	**0,33**	**0,39**	**0,44**	**0,50**
λ=3	-	-	-	-	-	-	-
λ=6	+	+	+	+	+	+	+
λ=12	+	+	+	+	+	+	+

4 Discussion

C-L criterion, which makes the phenomenon of fracture dependent on the maximum stress on the main direction shows the fracture correctly except two cases R=6, Ri/Ro=0,17 and R=12, Ri/Ro=0,17; in all other cases the criterion value exceeds experimentally determined critical value (Fig. 3c, Table 6). Just as Brozzo criterion (Fig. 3a) where the occurrence of fracture depends on the fracture deformations and stresses σ_{max} and σ_m (Table 7) and Oh criterion (Fig. 3e, Table 9) where the occurrence of fracture depends on the fracture deformation and stresses σ_H and σ_{max}. Oyane criterion (σ_m, σ_H) indicates fracture much later for the value R=12, Ri/Ro=0.22, which is not consistent with the results of the experiment (Fig. 3d, Table 8). Osakada-Mori criterion (σ_m, $\bar{\varepsilon}$) indicates fracture in all the analyzed cases (Fig. 3f, Table 10). Thus, the modified C-L criterion indicates no fracture within the range of the analyzed options (Fig. 3g). Moreover, it indicates zero for geometrical cases in which the core diameter is greater or equal to the dimension of the die orifice (Table 11). Osakada-Mori criterion and available in standard software of Cockroft-Latham criterion gives the smallest degree of conformity with the results of the experiment (Table 12). The evaluation of the deformability of the complex material limited by fracture phenomenon, is possible thanks to the application of the checked fracture criterion implemented to the MES software, and it allows to determine the influence of

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various factors (the relative size of the core, the size of the R coefficient, friction, geometrical parameters of the die) on the fracture phenomenon. This allows to determine the range of permissible deformations required at the stage of process modeling.

5 Conclusions

1. Numerical model (FEM) which was build with the appropriate calculation procedures allowed to apply the fracture criteria and to analyze the changes in their value at every calculation step. The analyzed data allowed selection of the fracture criteria applied in the numerical model of extrusion process, which gave different results. The best agreement between the numerical and the experimental results was achieved while applying Osakada-Mori criterion and Cocroft-Latham criterion available in MSC.Marc program. Brozzo, Oyane and Oh criterion predicted the fracture with similar accuracy but their indications are different compared to experimental results. The most consistent results compared with experimental results were obtained while using Freudenthal criterion, which may prove greater importance of average stress σ_m and fracture deformation in predicting fracture phenomena in relation to the parameters contained in other criteria.
2. The evaluation of the deformability of the composite material limited by the fracture phenomenon allows to determine the influence of different factors, mainly: the relative size of the core (the volume share of the core in the composite, the value of the R coefficient , but also friction or the geometrical parameters of the die) on the nature of the fracture phenomenon. This allows to determine the range of acceptable deformations in the process of composite materials extrusion modeling and allows to adequate assessment of deformability of bimetallic rods with different characteristics of the components.

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