POLISH ACADEMY OF SCIENCES - MATERIALS SCIENCE COMMITTEE
SILESIAN UNIVERSITY OF TECHNOLOGY OF GLIWICE
INSTITUTE OF ENGINEERING MATERIALS AND BIOMATERIALS
ASSOCIATION OF ALUMNI OF SILESIAN UNIVERSITY OF TECHNOLOGY

Conference Proceedings

11th INTERNATIONAL SCIENTIFIC CONFERENCE
ACHIEVEMENTS IN MECHANICAL & MATERIALS ENGINEERING

Theoretical analysis and optimisation of parameters in extrusion process of explosive cladded bimetallic rods

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The article discusses the problem of theoretical choosing the optimal shape of extrusion die and extrusion ratio during the extrusion process of aluminium rods copper cladded with the help of explosive method to join the core and coat. Mathematical model of extrusion process based on finite elements method was worked out to attaining the objective. The model enables to carry out the analysis of mechanical state (stress and strain) on the boundary of layers for the sake of main parameters of the process. Optimal values of process parameters were obtained on the base of the mathematical analysis for bimetallic rod with outer diameter 18 mm and copper layer thickness 2 mm.

1. INTRODUCTION

Production of bimetallic rods by explosive cladding and follow that plastic working process is one of the better developing way of production such rods [1]. As it is known there are many ways to get semi-products for example by rolling, drawing, extrusion [1,2]. Only in the last one existing the general state of compressive stress which is helpful to predict the defects especially delamination. To working out the technology of getting bimetallic products it is necessary to solve the problem of optimal choice of following matters like: shape of die extrusion, extrusion ratio, type of lubricant, temperature and speed conditions, delamination. Indirectly it means that it's necessary to optimise the mechanical state in zone of contact of particular layers. In many cases the empirical way of solving this problem is very ineffective and expensive solution.

2. PURPOSE AND SCOPE OF TESTS

The analytic [3, 4, 5, 6] and numerical methods [7, 8] for mathematical description of bimetal deformation during the extrusion process it is used nowadays. First ones are characterized by quick calculations, and clarity of received expressions however this methods can't allow for difficult shapes of extrusion die, rheological properties of composite materials, boundary conditions and thermic process appeared into metal. Numerical methods (as a matter of fact it concern s the finite elements method) don't have such advantages in formal point of view but it can't be forgotten these methods are still approximated method. If need be the problem of bimetal extrusion can be solved by commercial software packet based on FEM [9]. By using commercial packets detailed analysis of results is difficult, inputting the new connections to the model of solution and controlling errors is impossible and often there is no independent system of optimisation of technological parameters but in the other hand these programmes can be used to test new models.

The aim of this article is presentation and testing the new mathematical model of extrusion of bimetal rods and also getting optimal parameters of extrusion process of Al/Cu bimetal rods with outer diameter 18 mm and thickness of copper layer 2 mm.

3. DESCRIPTION OF THE MODEL

The process of extrusion was examinated in steady-state (stationary phase). It is connected with fact that main parameters of the process like shape of die extrusion, dimensions of starting material, friction etc. can not be changed in different phases of the process so that the optimisation concerns only stationary phase. The process of extrusion was analysed as an axisymmetrical problem. To obtain the distribution of stresses and strains during process of extrusion bimetallic rods it was used the variational equation of theory of plastic flow for incompressible and non-linear, visco-plastic model with strain hardening. The testing was performed using FEM based on variational A.A. Markov equation

$$J = \int_{V} THd\mathrm{V} + \int_{V} \sigma_0 \xi_0 d\mathrm{V} - \int_{S} \sigma_\tau \Delta V_\tau \mathrm{dS} \tag{1}$$

where: ΔV_τ - rubbing speed of material related to die; **S** – contact surface between material and tool; ξ_0 – strain rate for triaxial compression, H – intensity of non-dilatational strain; σ_0 – mean stress; T- intensity of shear stresses.

Connection between stress and strain is described according to equation of theory of plastic flow:

$$\sigma_{ij} = \delta_{ij}\sigma_0 + \frac{2T(H,\Lambda,t)}{H}\xi_{ij}, \tag{2}$$

where: δ_{ij} – Kronecker delta; ξ_{ij} – components of strain rate tensor; **t** – temperature; Λ – intensity of non-dilatational strain:

$$\Lambda = \int_0^\tau H d\tau, \tag{3}$$

where τ – time of strain.

Procedure of finding the value Λ was based on integration of quantity H along the line of flow of the material in deformation zone [10].

In analogical way it was determinated the boundary between layers of bimetal in zone of plastic deformation.

Nonlinearity of rheological properties of particular components of bimetal were determined using hydrodynamical approximation method. In determination of boundary conditions was used penalty function. The tool used in experiment was impenetrable. Friction between layers and between tool and material was taken into consideration in the analysis.

Triangle elements were used in discretization procedure. To approximate the field of strain rate square function (6-nodes, triangle elements) was used and to approximate the mean stress – linear function such approximations guarantee stability of solution [11].

4. TESTING OF WORKED OUT MODEL

The test was being done in the commercial software FORGE2 which allow to input the multilayer stock with specified dimensions. This programme solves the solution in non-steady state, which is different than in worked out model (steady state) this caused that the results were compared in steady state. The experiment was carried out to testing the model, study and optimisation following parameters: die angle (α) and extrusion ratio (λ).

Al/Cu bimetal rods were considered (copper as outer layer). Outer diameter of rod-18 mm, temperature of deformation - 20 ^{o}C, ram velocity – 1 mm/s. The rheological properties of particular layers were obtain on the base of literature [12] up to the following patterns:

$$\sigma_{Al} = 67{,}7\left(1 + 1{,}13\varepsilon^{0{,}315}\right) \tag{4}$$

$$\sigma_{Cu} = 124{,}0\left(1 + 2{,}11\varepsilon^{0{,}391}\right) \tag{5}$$

where $\overline{\sigma}$ – yield stress; $\overline{\varepsilon}$ – intensity of strain $\overline{\varepsilon} = \sqrt{3}\,\Lambda$.

The testes were carried out for two different extrusion ratios (λ) 2 and 5 in conical die with angles (α) 30^0 and 15^0 and for two values of friction factor (**m**) – 0 and 0,05 to optimisation parameters (α) and (λ) the factor analysis was done. The results of calculating are presented in table 1 (for **m=0**) and in table 2 (for **m=0,05**). These tables also contains: the values of maximal tensile stresses on the boundary between layers, distribution of intensity of strain rate and mean stresses (for Table 2). For the case 4 in tables 1 and 2 was carried out more detailed analysis of stress and strain distribution (Fig. 1-2).

5. DISCUSION OF TEST RESULTS

Comparison of test was done for the carried out programme results and for FORGE2 results. In table 1 The distribution of strain rate (for carried out programme the value $\boldsymbol{H}$ was counted and for FORGE programme $\bar{\varepsilon} = \sqrt{3}H$). It can be observed the qualitative and quantitative goodness of fit of intensity of strain rate for these two analyses. It wasn't observed the considerable differences for intensity of strain. In cases 1,2,3 in table 1 for the carried out model the maximum value $\bar{\varepsilon}_{max}$ was respectively 42%, 41% and 11% smaller than obtained in FORGE2 programme whereas, in case 4 in table 1 value $\bar{\varepsilon}_{max}$ was 15% bigger.

Table 1
Results of modelling the bimetal extrusion process without friction between tool and material

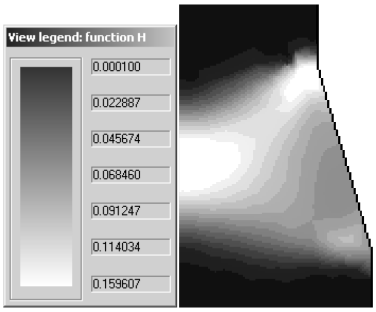
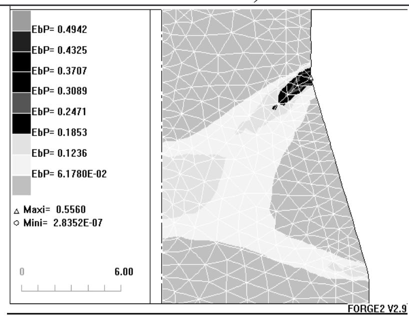
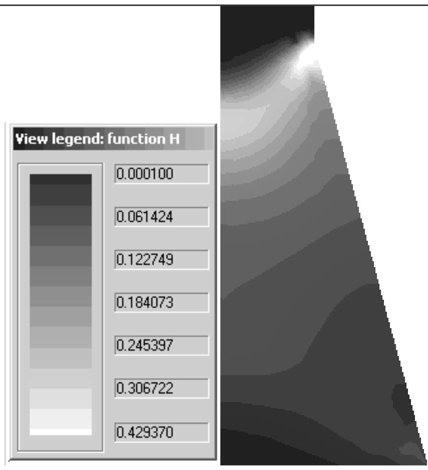
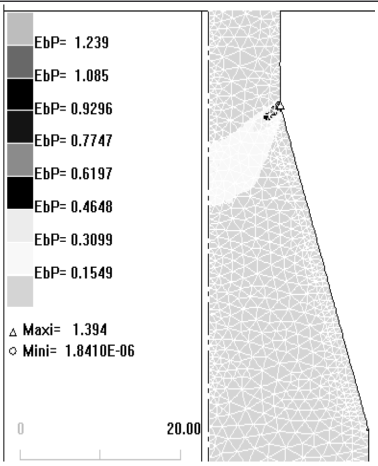
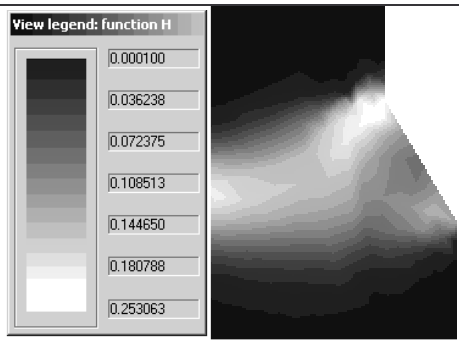
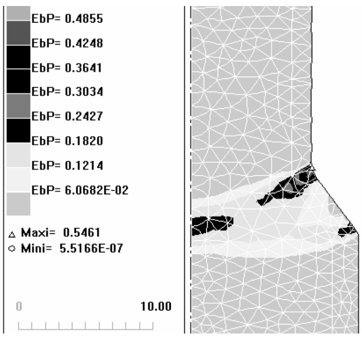
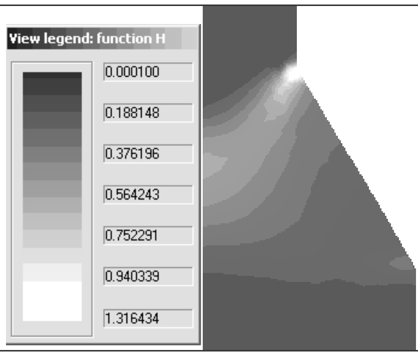
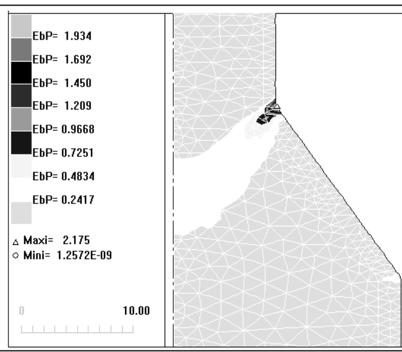
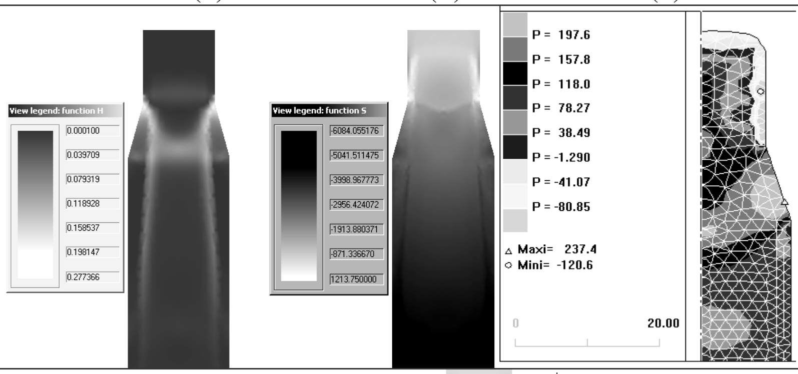
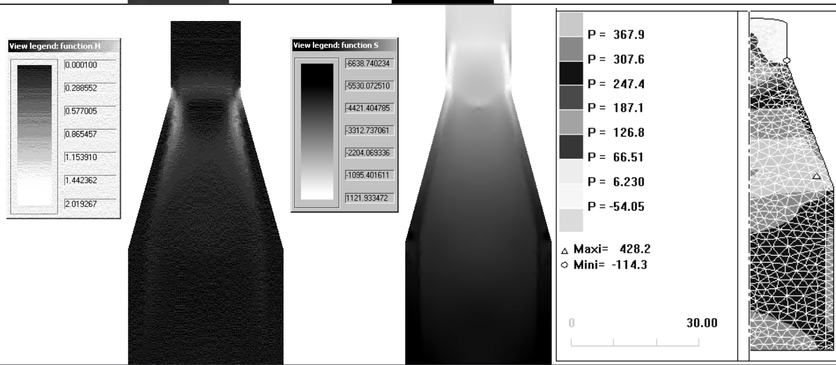
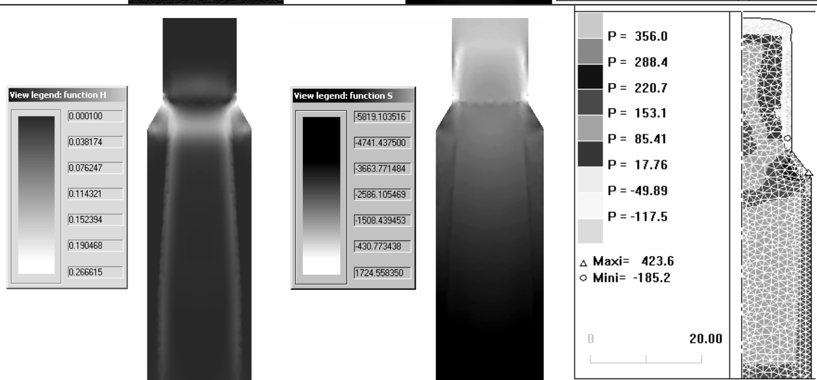
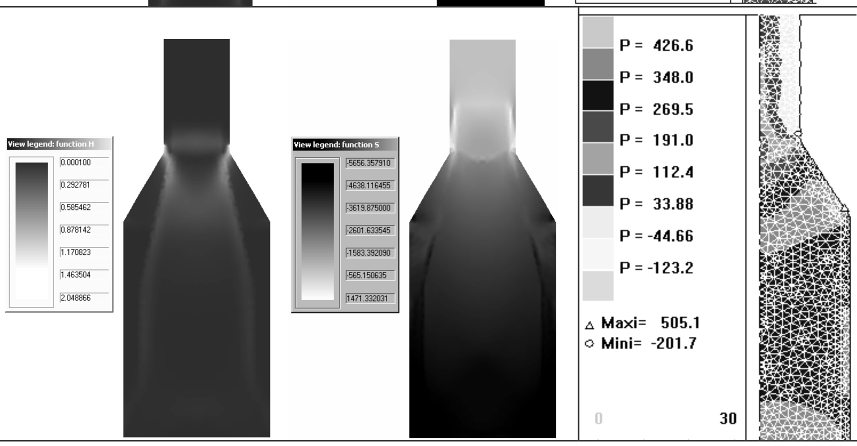
№	α	λ	σ_{xmax} on boundary of layers	Distribution of strain rate intensity, (a) – for proposed model, (b) – for FORGE2 programme a)	b)
1	15	2	289		
2	15	5	297		
3	30	2	303		
4	30	5	147		

Table 2
Results of modelling with friction between tool and material (m=0,05)

	α	λ	σ_{xmax} on boundary of layers	Distribution of strain rate intensity (a) and mean stress (b), for proposed model and for FORGE2 programme(c) (a) (b) (c)
1	15	2	788	
2	15	5	609	
3	30	2	764	
4	30	5	729	

It can be observed that the results obtained using the FORGE2 programme seemed not always be proper for example from cases 1 to 3 in table 1 the length of deformation zone decreases for the same value of total elongation and the strain rate should of course increases, but in results obtained from FORGE2 programme the strain rate decreases. Proposed model in the same conditions gives the increase of $\bar{\varepsilon}_{max}$ by 1,53 times, it corresponding with decrease of the length of deformation zone by 1,93 times. Probable reason of anomalies in range of intensity of strain rate could be caused the fact that density of mesh of finite element method in proposed model is 2-3 times bigger than in FORGE2.

Comparing the results of counting the values of mean stresses (Table 2) it could be observed that both models shows tensile stresses on the output from deformation zone in outer layer of bimetal which hasn't so big influence on large stresses in general state of compressive stress. Proposed model permit to stated that stresses are localised on the boundary between layers of bimetal. In general the distributions obtained of stresses in both models are similar. Farther analysis was carried for proposed model.

Analysis without friction proceeds the general rules for process of extrusion – strains are located in working part of die it can be seen on distribution of intensity of non-dilatational strain rate (Table 1), distribution of strain rate (Fig. 1a) and shear stresses (Fig. 1b). It can be concluded that the most non-uniform strain is obtained by the extrusion for die with angle 30^0. On the output of material from die the outer harder layer is slowed down by differences in rheological properties of the layer and influence of die. In outer layer appears tensile stresses (Table 1 shows the maximal stresses on the boundary of bimetallic layers, normal to surface of the boundary). Values of this stresses are decreases according to increase of elongation and die angle. The minimum values of normal tensile stresses on the boundary between layers were obtained for extrusion ratio 5 and die angle 30^0.

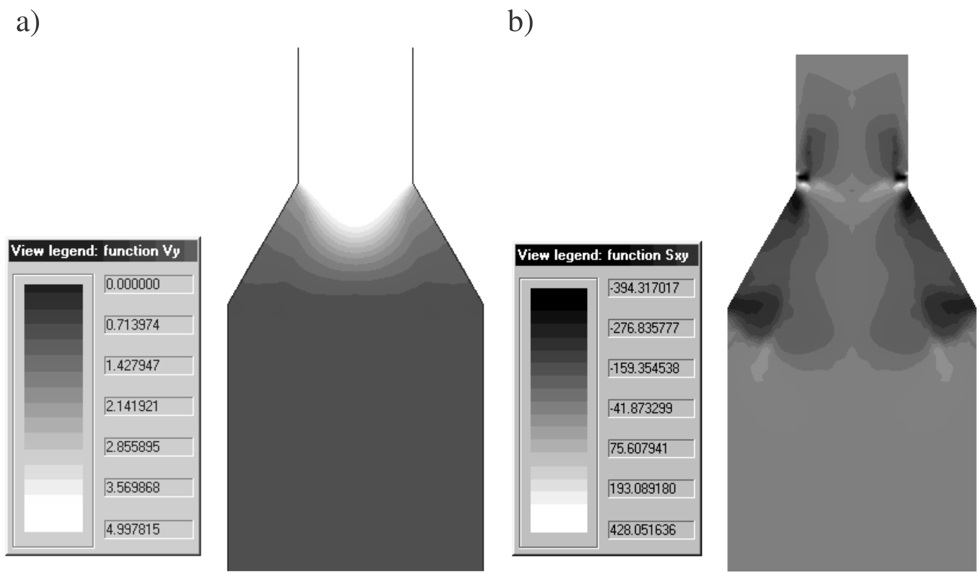


Fig. 1. Distribution of strain rate along the extrusion direction (a) and respectively distribution of shear stresses (b) without friction (case 4 Table 1)

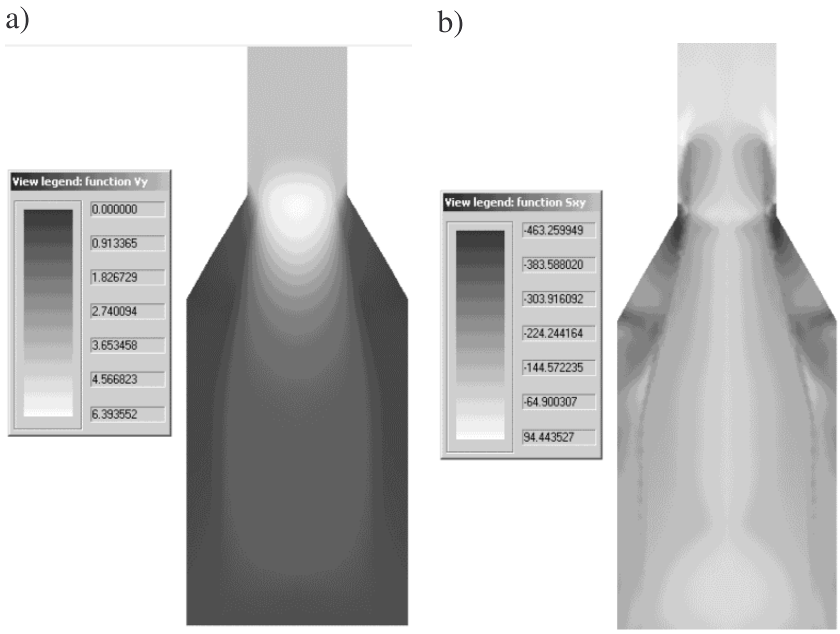


Fig. 2. Distribution of strain rate along the extrusion direction (a) and respectively distribution of shear stresses (b) with friction (case 4, Table 2)

During presence of friction the state of strain is changing considerable (Table 2, fig 2)in distinguishing from extrusion process of homogeneous material. It is caused that the outer layer is more resistant. The friction considerable reduces the strains in this layer (Deformationresistance is presented in Table 2). This reduction of strain in outer layer is compensated in channel of die when the harder layer starts intensively flowing according to constancy volume law (Fig.2a). This mechanism explains the appearing of zone of intensive strain on boundary between layers (Table 2) and manifests the high gradient of shear stresses (Fig.1b and Fig.2b). This character of strain caused appearance of considerable tensile stresses (Table 2) and shear stresses (Fig.2b). The increase of tensile stresses level was caused by increase the friction stresses 3-5 times. The influence of this stresses can be seen 10-15 mm behind the output from the tool. The increase of friction stresses changes location of minimum of tensile stresses in the range of considered parameters. Minimal tensile stresses appeared on the boundary between layers of bimetal in case 2 (Table 2 **λ=5, α=15^0**). The results approximation of mathematical experiment allowed to carry out the following equation which is very helpful to define the maximal stress σ_{xmax} on the boundary between layers of bimetal:

$$\sigma_{xmax} = C_0 + C_1X_1+C_2X_2+C_3X_3+C_{12}X_1X_2+C_{23}X_2X_3+C_{13}X_1X_3+C_{123}X_1X_2X_3, \tag{6}$$

where:

$$X_1 = \frac{2(\lambda - \lambda_{sr})}{\lambda_{max} - \lambda_{min}},\ X_2 = \frac{2(\alpha - \alpha_{sr})}{\alpha_{max} - \alpha_{min}},\ X_3 = \frac{2(m - m_{sr})}{m_{max} - m_{min}} \tag{7}$$

Table 3
Values of coefficients C:

C_0	C_1	C_2	C_3	C_{12}	C_{23}	C_{13}	C_{123}
490.8125	-45.3125	-4.9375	231.6875	-2.5625	28.9375	-8.1875	38.5625

If the criterion of optimisation is tensile stress on the boundary between layers of bimetal the best case in solution is case 3 in Table 1 and 2.

6. CONCLUSIONS

It is proposed the new model of counting stress and strain state of metal during the extrusion process of bimetallic rods based on FEM in this article.
The model carried out during the creating BimExtr programme makes possible to: analyse strain an stress state of metal on the boundary between layers of bimetal, optimization process the extrusion process with different parameters as a criterion.
The analysis of influence of: extrusion ratio, level of friction stresses and die angle has been done for Al/Cu bimetal with concrete dimensions of rod.
The comparison analysis of counted cases of extrusion technology has been done and it can be stated that the best case is extrusion with extrusion ratio 5 and in conical die with angle15^0.

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