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

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Abstract

The article discusses the problem of theoretical choice of the optimal shape of extrusion die and extrusion ratio during the extrusion process of aluminium rods copper cladded with the help of the explosive method to join the core and the coat. Mathematical model of extrusion process based on finite elements method was worked out to attaining the objective. The model makes it possible 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 basing on the mathematical analysis for bimetallic rod with outer diameter 18 mm and copper layer thickness 2 mm.

Keywords: Bimetallic rods; Extrusion process

1. Introduction

Production of bimetallic rods by explosive cladding and further 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 avoid the defects—delamination. 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 to work out the technology of getting bimetallic products. Indirectly, it means that it is necessary to optimise the mechanical state in zone of contact of particular layers. In many cases the empirical way of solving this problem is a very ineffective and expensive solution.

2. Purpose and scope of tests

The analytic [3–6] and numerical methods [7,8] for mathematical description of bimetal deformation during the extrusion process are used nowadays. First ones are characterised by quick calculations, and clarity of received expressions however this methods do not allow to use difficult shapes of extrusion die, rheological properties of composite materials and boundary conditions. Numerical methods (as a matter of fact it concerns the finite elements method) do not have such advantages in formal point of view but, it cannot be forgotten, these methods are still approximate method. If needed, the problem of bimetal extrusion can be solved by commercial software package based on FEM [9]. By using commercial packages, the detailed analysis of results is difficult and making modifications in the programme algorithm is impossible and often there is no independent system of optimisation of technological parameters but on 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 examined in steady-state (stationary phase). It is connected with a fact that main parameters of the process like shape of die extrusion, dimensions of

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starting material, friction, etc. cannot be changed in different phases of the process so that the optimisation concerns only its 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 the variational equation of theory of plastic flow for incompressible and non-linear, visco-plastic model with strain hardening was used. The testing was performed using FEM based on the variational A.A. Markov equation:

$$J = \int_V TH\,\mathrm{d}V + \int_V \sigma_0 \xi_0\,\mathrm{d}V - \int_S \sigma_\tau \Delta V_\tau\,\mathrm{d}S \qquad (1)$$

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

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

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

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

$$\Lambda = \int_0^\tau H\,\mathrm{d}\tau \qquad (3)$$

where τ the 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].

The boundary between layers of bimetal in zone of plastic deformation was determined in analogical way.

The non-linearities of rheological properties of particular components of bimetal were determined using hydrodynamical approximation method. The penalty function was used to determine the boundary conditions. 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 the model

The test was done using the commercial software FORGE2, which allows 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 test the model, study and optimise the following parameters: die angle (α) and extrusion ratio (λ). To optimise the full factorial, analysis design was done. 2^3 plan was built to carry out the statistical analysis.

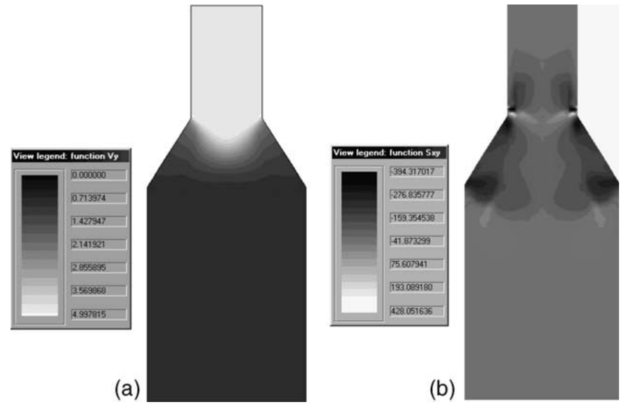

Fig. 1. Distribution of strain rate along the extrusion direction (a), and respectively, distribution of shear stresses (b) without friction.

The Al/Cu bimetal rods were considered (copper as outer layer). Outer diameter of rod was 18 mm, temperature of deformation 20 °C, ram velocity 1 mm/s. The rheological properties of particular layers were obtained basing a literature, up to the following formulae [12]:

$$\sigma_{\mathrm{Al}} = 67.7(1 + 1.13\bar{\varepsilon}^{0.315}) \qquad (4)$$

$$\sigma_{\mathrm{Cu}} = 124.0(1 + 2.11\bar{\varepsilon}^{0.391}) \qquad (5)$$

where $\bar{\sigma}$ is the yield stress; $\bar{\varepsilon}$ the intensity of strain $\bar{\varepsilon} = \sqrt{3}\Lambda$.

The tests were carried out for two different extrusion ratios (λ) 2 and 5 in conical die with angles (α) 30° and 15° and for two values of friction factor (m)—0 and 0.05 to optimisation parameters (α) and (λ) the factor analysis was done. The calculation results of are presented in Figs. 1–4 (for $m = 0$) and in Figs. 5–8 (for $m = 0.05$). These figures also contain the values of maximal tensile stresses on the boundary between layers, distribution of intensity of strain rate and mean stresses

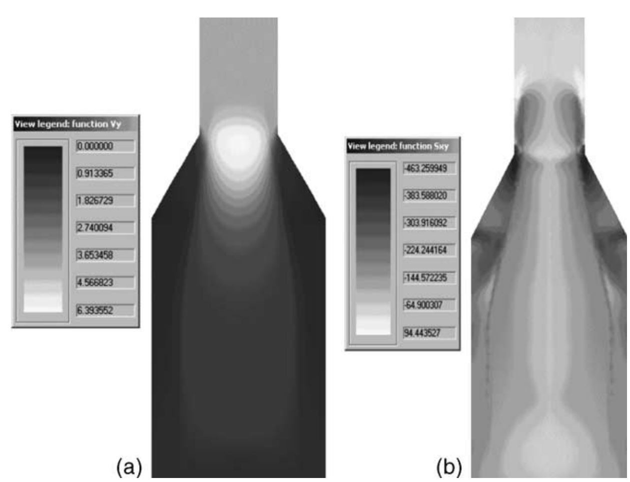

Fig. 2. Distribution of strain rate along the extrusion direction (a), and respectively, distribution of shear stresses (b) with friction.

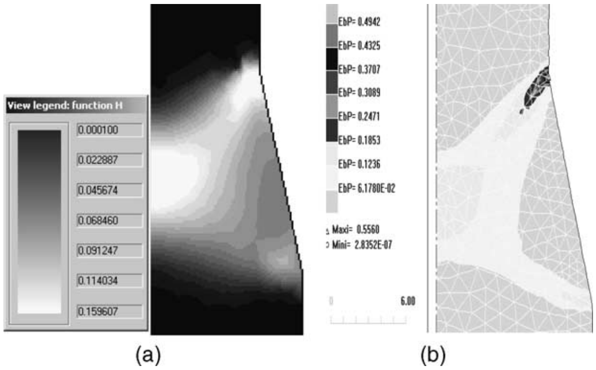

Fig. 3. Results of modelling the bimetal extrusion process with friction between tool and material. Distribution of strain rate intensity: for proposed model (a), for FORGE2 programme (b) for $\alpha = 15^{\circ}$, $\lambda = 2$, $\sigma_{xmax} = 289$ MPa.

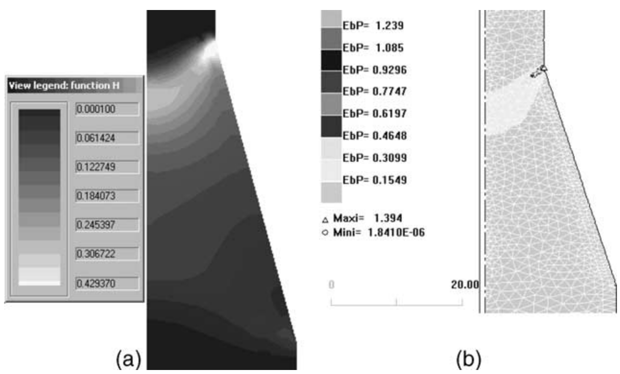

Fig. 4. Results of modelling the bimetal extrusion process with friction between tool and material. Distribution of strain rate intensity: for proposed model (a), for FORGE2 programme (b) for $\alpha = 15^{\circ}$, $\lambda = 5$, $\sigma_{xmax} = 297$ MPa.

(for Figs. 5–8). For Figs. 1 and 5 out the more detailed analysis of stress and strain distribution (Figs. 9 and 10) was carried out.

5. Discussion of test results

Comparison of test results was done for proposed model programme results and for FORGE2 programme results. In Figs. 1–4 the distribution of strain rate (for carried out programme the value H was calculated and for FORGE programme $\bar{\dot{\varepsilon}} = \sqrt{3}H$). It can be observed that the qualitative and quantitative goodness of fit of intensity of strain rate for these two analyses. There are no considerable differences for intensity of strain between the results of the analyses. In Figs. 1–3 for the carried out model the maximum value $\bar{\dot{\varepsilon}}_{max}$ was respectively 42%, 41% and 11% smaller than obtained in FORGE2 programme; whereas, in Fig. 1 value $\bar{\dot{\varepsilon}}_{max}$ was 15% bigger.

It can be observed that the results obtained using the FORGE2 programme seemed not always be proper for example from Figs. 1–3 the length of deformation zone decreases for the same value of total elongation and the strain rate should of course increase, but in results obtained from FORGE2 programme the strain rate decreases.

Proposed model in the same conditions gives the increase of σ_{xmax} by 1.53 times, it corresponding with decrease of the length of deformation zone by 1.93 times. Probable reason of the anomalies in range of intensity of strain rate could be caused by 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 calculation the values of mean stresses (Figs. 5–8) it could be observed that both models show tensile stresses on the output from deformation zone in outer layer of bimetal which does not have so big influence on large stresses in general state of compressive stress. Proposed model permits to state that stresses are localised on the boundary between layers of bimetal. In general the stress

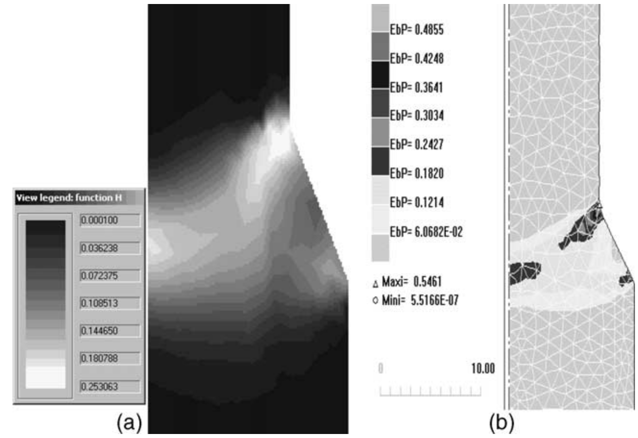

Fig. 5. Results of modelling the bimetal extrusion process with friction between tool and material. Distribution of strain rate intensity: for proposed model (a), for FORGE2 programme (b) for $\alpha = 30^{\circ}$, $\lambda = 5$, $\sigma_{xmax} = 147$ MPa.

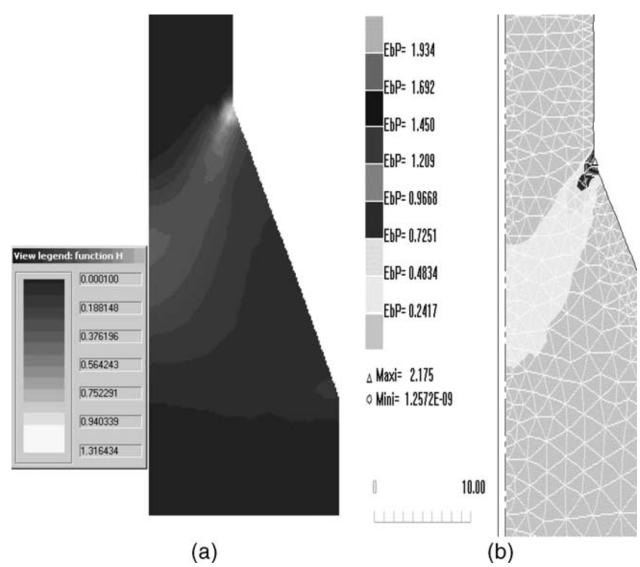

Fig. 6. Results of modelling the bimetal extrusion process with friction between tool and material. Distribution of strain rate intensity: for proposed model (a), for FORGE2 programme (b) for $\alpha = 30^{\circ}$, $\lambda = 5$, $\sigma_{xmax} = 147$ MPa.

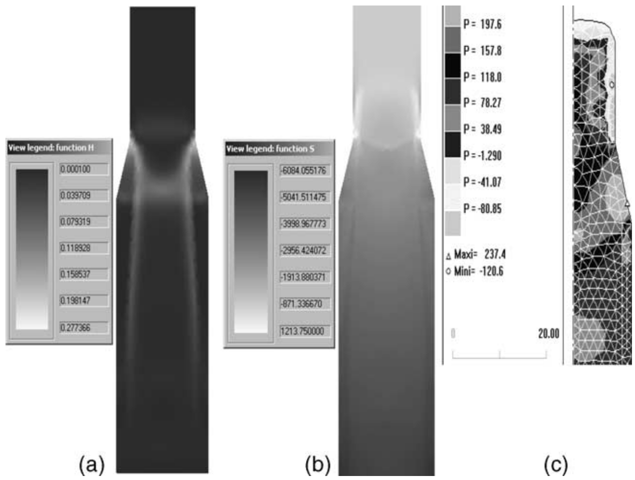

Fig. 7. Results of modelling the bimetal extrusion process with friction between tool and material ($m = 0.05$). Distribution of strain rate intensity and mean stresses (b) for proposed model (a), for FORGE2 programme (c) for $\alpha = 15^{\circ}$, $\lambda = 2$, $\sigma_{xmax} = 788$ MPa.

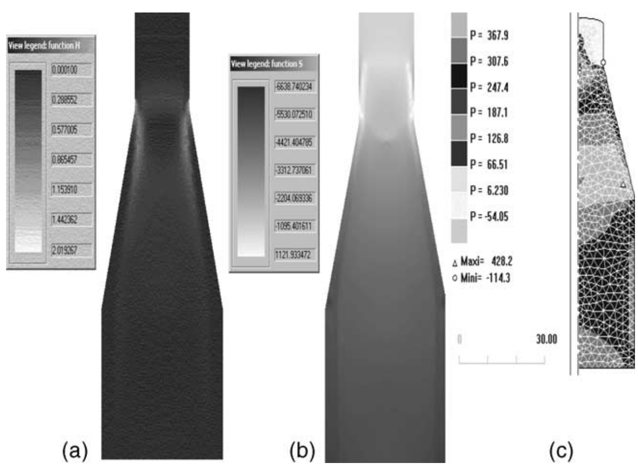

Fig. 8. Results of modelling the bimetal extrusion process with friction between tool and material ($m = 0.05$). Distribution of strain rate intensity and mean stresses (b) for proposed model (a), for FORGE2 programme (c) for $\alpha = 15^{\circ}$, $\lambda = 5$, $\sigma_{xmax} = 609$ MPa.

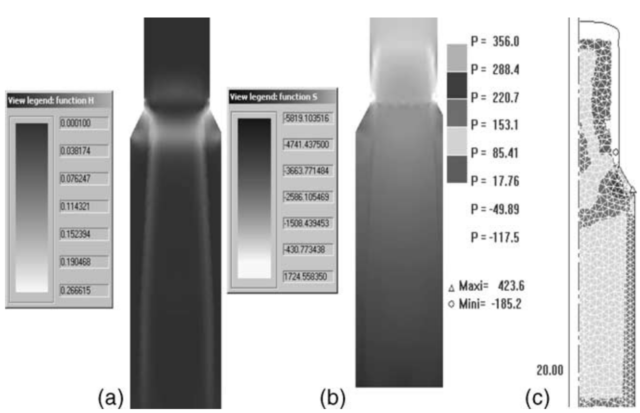

Fig. 9. Results of modelling the bimetal extrusion process with friction between tool and material ($m = 0.05$). Distribution of strain rate intensity and mean stresses (b) for proposed model (a), for FORGE2 programme (c) for $\alpha = 30^{\circ}$, $\lambda = 5$, $\sigma_{xmax} = 764$ MPa.

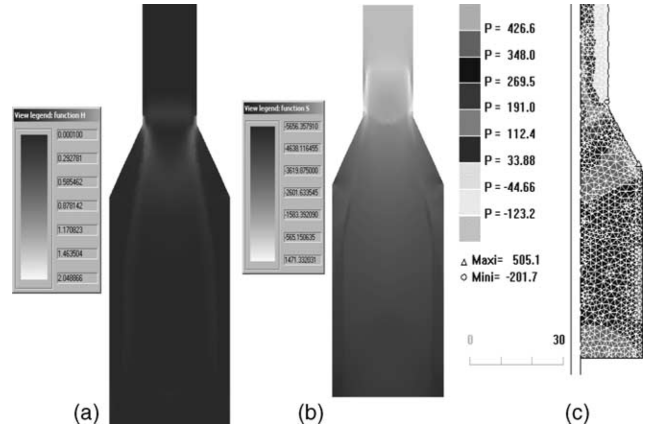

Fig. 10. Results of modelling the bimetal extrusion process with friction between tool and material ($m = 0.05$). Distribution of strain rate intensity and mean stresses (b) for proposed model (a), for FORGE2 programme (c) for $\alpha = 30^{\circ}$, $\lambda = 5$, $\sigma_{xmax} = 729$ MPa.

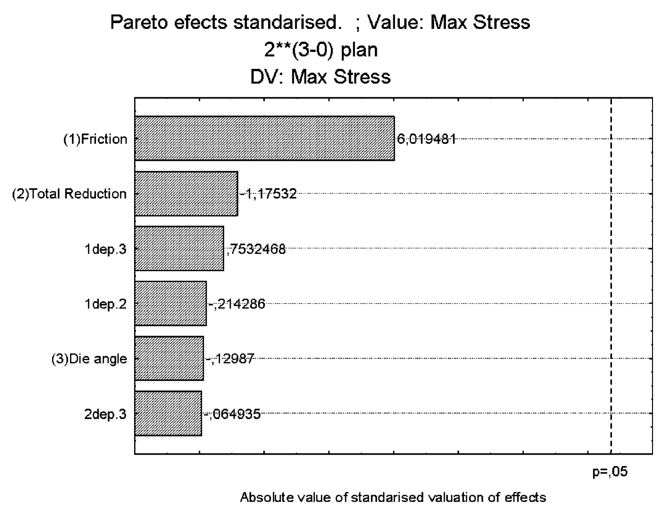

Fig. 11. Pareto effects diagram for the experiment.

distribution in both models are similar. Further analysis was carried for the proposed model.

Analysis without friction confirms 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 (Figs. 1–4), distribution of strain rate (Fig. 9a) and shear stresses (Fig. 9b).

Table 1
Values of coefficients C

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

It can be concluded that the most non-uniform strain is obtained by the extrusion for die with angle 30°. 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 appear tensile stresses (Figs. 5–8 shows the maximal stresses on the boundary of bimetallic layers, normal to surface of the boundary). Values of these stresses are decreasing 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°.

During presence of friction the state of strain is changing considerably (Fig. 10 and Figs. 5–8) in distinguishing from extrusion process of homogeneous material. It is caused by the outer layer that is more resistant. The friction reduces considerably the strains in this layer (deformation resistance is presented in Figs. 5–8). This reduction of strain in outer layer is compensated in channel of die when the harder layer starts to flow intensively according to constancy volume law (Fig. 10a).

This mechanism explains the appearing of zone of intensive strain on boundary between layers (Figs. 5–8) and manifests the high gradient of shear stresses (Figs. 9b and 10b). This character of strain caused appearance of considerable tensile stresses (Figs. 5–8) and shear stresses (Fig. 10b). The increase of tensile stresses level was caused by increase the friction stresses 3–5 times. The influence of these 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 Fig. 6. The friction also have the most significant meaning in Pareto Experiment for maximal stresses (Fig. 11). The results of mathematical experiment allowed to obtain the following equation, which is very helpful to define the maximal stress σ_{xmax} on the boundary between layers of bimetal (Eqs. (6)–(9) and Table 1):

$$\sigma_{\mathrm{xmax}} = C_0 + C_1X_1 + C_2X_2 + C_3X_3 + C_{12}X_1X_2 + C_{23}X_2X_3 + C_{13}X_1X_3 + C_{123}X_1X_2X_3 \quad (6)$$

where

$$X_1 = \frac{2(\lambda - \lambda_{\mathrm{sr}})}{\lambda_{\max} - \lambda_{\min}} \quad (7)$$

$$X_2 = \frac{2(\alpha - \alpha_{\mathrm{sr}})}{\alpha_{\max} - \alpha_{\min}} \quad (8)$$

$$X_3 = \frac{2(m - m_{\mathrm{sr}})}{m_{\max} - m_{\min}} \quad (9)$$

If the criterion of optimisation is tensile stress on the boundary between layers of bimetal the best case in solution are Figs. 4 and 6.

6. Conclusions

The new model is proposed for calculating stress and strain state of metal during the extrusion process of bimetallic rods based on FEM in this article.

The model worked out during the development BimExtr programme makes it possible to analyse strain an stress state of metal on the boundary between layers of bimetal, optimisation 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 calculated cases of extrusion technology has been done and it can be stated that the best case is extrusion with extrusion ratio 5 and in a conical die with angle 15°.

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