EUROPEAN COOPERATION IN THE FIELD OF SCIENTIFIC AND TECHNICAL RESEARCH - COST

COST 526

Automatic Process Optimisation in Materials Technology

(APOMAT)

Title:

Optimisation of tool shape in the tests aiming at identification of models describing rheological and mechanical properties of metallic alloys

Keywords: rheology, optimization, identification, tool shape design

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1. Duration / run time of the project

36 months

- Starting and finishing date

January 1, 2002 – December 31, 2004

2. Overall cost

555 000 PLN

- in kEURO

140

3. Funding situation

- Funding already assured by State Committee for Scientific Research

4. Project partners indicated to participate

- Not specified yet.

5. Project partners to be found

- Objectives of collaboration

1. Computer code for direct model
Development of rheological models for materials forming in semi-solid state. Selection of advanced constitutive laws, which account for the two-phase structure of the material and microstructure evolution models (rheocast structure, coagulation, final grain size and properties).
2. Inverse analysis.
Sensitivity analysis. Identification of parameters in the rheological, friction and microstructure evolution models. Inter-laboratory round-robin exercises for all testing methods to determine one set of real material parameters on the basis of results of tests performed for various sample geometries, methods of heating, lubrication conditions.
3. Optimisation procedures.
Sensitivity analysis. Development of optimisation technique based on genetic algorithms. Automatic selection of the optimisation techniques.
4. Experiment.
Tests of selected materials in the semi-solid state for experimental validation of the developed code in both laboratory and industrial conditions. Observing of microstructure and properties of final products in semi-solid forming processes.

- Expected mutual benefit

1. Development of constitutive models for two-phase materials in semi-solid state.
2. Development of complex thermal-mechanical-microstructure model for semi-solid forming based on the finite element code.
3. Better knowledge how to form the materials in semi-solid state and how to optimize the activities.
4. Transfer of advanced technological development combining optimum process design methodologies between partners.
5. Providing reliable, rapid and user-friendly industrialized numerical tools for optimisation of the

semi-solid forming process parameters.

6. Short description of the material process to be optimized

- Which type of process is involved (e.g. pilot process, industrial process)?

The goal of the project is to design the optimum pilot process of semi-solid forming for identification such process parameters as stock temperature, ram velocity, material dimensions, microstructure and properties. Figure 1 presents two different shapes of the dies for semi-solid forging used for searching the optimum die design during the optimisation procedure.

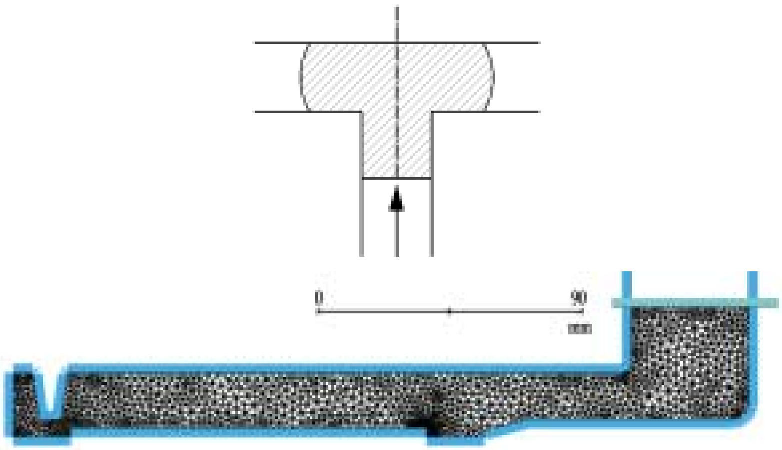


Fig.1. Examples of the pilot semi-solid forming processes: a) simple shape of the die, b) die with grooves.

- Essentials of process technology
- Economic impact

Process of forming of materials in semi-solid state is an efficient method of shaping of materials. Thixoforming, which requires special rheocast microstructure, is particularly effective semi-solid process, ant it will be the main objective of the project. This method allows forming of materials with some special useful properties and which, on the other hand, cannot be plastically deformed in the typical metal forming conditions. Figure 2 shows the results of earlier research, how the AlCu4Mg alloy formed in semi-solid state fills the grooves with complex shapes much better than in conventional forging. Figure 3 shows the rheocast microstructure for another AlSi alloy.

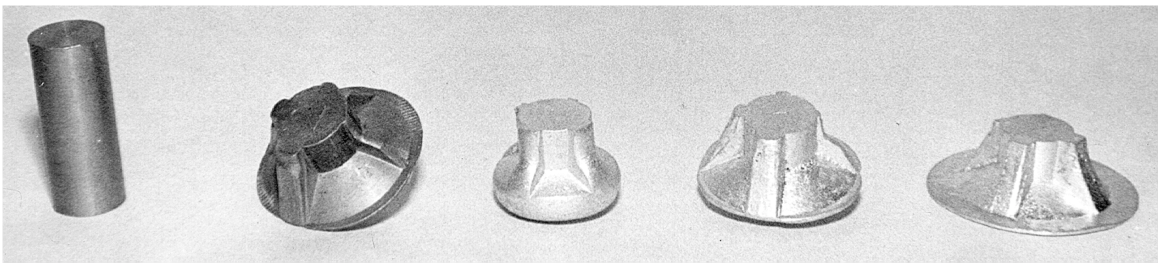


Fig.2. From left to right: stock sample, forging made of lead, forgings made of AlCu4Mg: conventional forging (load 32kN), conventional forging (load 91kN), thixoforging (load 32kN).

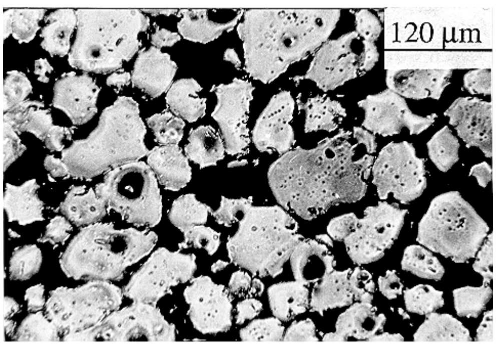


Fig .3. Microstructure of the AlSi alloy in the semi-solid state.

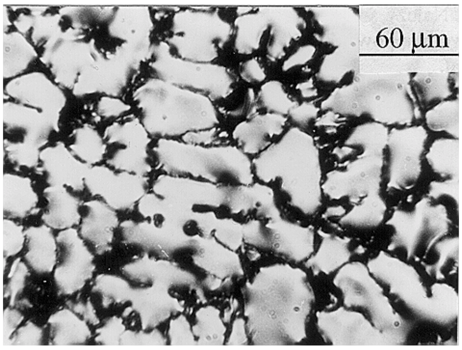
Possibilities of computer aided design of the semi-solid forming process parameters are appearing. This project was inspired by the need of methods to obtain efficient codes based on the finite element method and combined with the optimisation techniques.

7. Material(s) involved

- Material type of the product

Aluminium alloys of AlSi type in semi-solid state, see Figure 4.
Steels

AlSi4



AlSi7

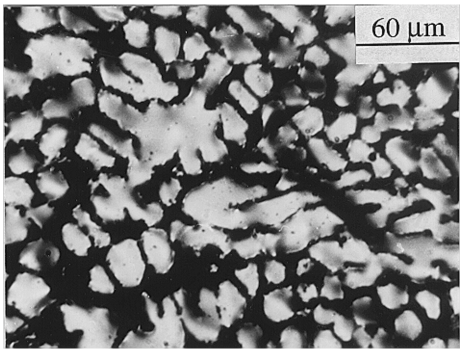


Fig.4. Microstructure at axial cross section of the stock material, AlSi type alloys

8. Optimisation potential of the process or process step

- Quantified impact on material quality, processing time etc.
- Technological feasibility

Optimisation potential: improvement of material quality, which means: homogeneity of product microstructure, uniform flow of two-phases during the process, high quality properties of products.

9. Specified material properties to be achieved

- Which material qualities are to be respected or even improved?

Material properties to be achieved

- homogeneity of structure,
- uniform flow of two-phases,
- high properties of final products.
- What are the material defects to be avoided?

Material defects to be avoided:

- separation of phases,
- improper filling of the die,
- not obtaining the required dimensional accuracy.

10. Process parameters to be optimized

- temperature distribution in the stock material,
- ram velocity,
- uniform microstructure and mechanical properties,
- die shape design,
- die filling.

- Identify process parameters related to material qualities or defects
- What are the restraints for these parameters (e.g. maximum heater temperature, maximum speed)

Sensitivity analysis of process models to materials and physical parameters.
It is important to determine the relative influence of the different material parameters on the results of the process simulations. Finite element modelling of the selected processes will be performed. The general constitutive and friction laws are implemented in the finite element codes, which are specifically dedicated to modelling of semi-solid processes, and the parameters will be varied. The objective is to determine the level of accuracy – or quality – needed for the different parameters of different forming operations. This sensitivity analysis will indicate, which aspects of parameter identification should be stressed and which refinement is needed in the identification procedures in order to reach a desired level of accuracy in the modelling of industrial processes.

Optimisation problem.
Goal of the project: search for optimum shape of the dies of semi-solid forming process for identification of such process parameters as stock temperature, ram velocity, stock dimensions, microstructure and properties.
Quality function:

$$\Phi(\mathbf{h})=\sum_{\mathbf{p}\in P}\left[\sum_{i=1}^{N}\frac{\left(F_i(\mathbf{h},\mathbf{p})-F_i(\mathbf{h},\mathbf{p}+\Delta\mathbf{p})\right)^2}{F_i(\mathbf{h},\mathbf{p})^2}+\frac{\left(W(\mathbf{h},\mathbf{p})-W(\mathbf{h},\mathbf{p}+\Delta\mathbf{p})\right)^2}{W(\mathbf{h},\mathbf{p})^2}\right] \qquad (1)$$

where *P* – space of process parameters (ram velocity, initial microstructure, …), **p** – vector of process parameters, *N* – number of steps in 3D FE simulation of the process, F_i – load in the i^{th} step of the process simulation, *W* – efficiency of die filling, **h** – *n*-dimensional vector describing shape of the die, $H\subset R^{3\times n}$ - space of possible shapes of the dies.
The optimisation problem is defined as:

$$\max_{\mathbf{h}\in H}\Phi(\mathbf{h})$$

11. Material laws including material dependent coefficients

- What quantitative laws will be applied for quality function design?
- Are coefficients / data available or to be determined?

Constitutive law formulation was developed on the basis of Authors' experience of the semi-solid forming processes. The research on semi-solid forming of materials has been carried out at AGH for several years. The rheocast structures have been obtained for various alloys. All simulations, however, used the constitutive laws for single-phase materials. Therefore, the results of simulations were not accurate enough. Thus, the new constitutive model accounting for the two-phase microstructure is proposed now. The law has been implemented in the finite element software and will further be used in the software for analysing the tests and for optimisation of the die design of the process.
Material coefficients and material data will be determined in the project using inverse analysis.

12. Simulator

- Brief description of the program system to be applied for process simulation
- Are there process specific software developments necessary?

The finite element 3D code is based on the rigid-plastic approach coupled with the solution of the heat transport equation. The approach is based on the extremum principle, which states that for a plastically deformed body of volume *V,* under the tractions **s** prescribed on the part of the surface S_t and the velocity **v** prescribed on the surface S_v, under the constraint $\dot{\varepsilon}_V = 0$, the actual solution minimizes the functional:

$$J=\int_V\left(\sigma_i\dot{\varepsilon}_i+\lambda\dot{\varepsilon}_V\right)dV-\int_{S_t}\underline{\mathbf{s}}^T\underline{\mathbf{v}}\,dS_t \qquad (2)$$

where: λ - Lagrange multiplier, σ_i - effective stress which, according to the Huber-Mises yield criterion, is equal to the flow stress σ_p, $\dot{\varepsilon}_i$ - effective strain rate, $\dot{\varepsilon}_V$ - volumetric strain rate, **s** - vector of boundary traction, **v** - vector of velocities.

In the flow theory of plasticity, strain rates ($\underline{\dot{\boldsymbol{\varepsilon}}}$) are related to stresses ($\underline{\boldsymbol{\sigma}}$) by the Levy-Mises flow rule:

$$\underline{\boldsymbol{\sigma}} = \frac{2\sigma_p}{3\dot{\varepsilon}_i}\underline{\dot{\boldsymbol{\varepsilon}}} \qquad (3)$$

The main change in the model, connected with an application to the semi-solid forming processes, is connected with an introduction of the strain rate sensitivity into the yield stress function, what allows treating the metal as liquid with non-linear viscosity. Discretization of equation (2) and differentiation with respect to the nodal velocities and to the Lagrange multiplier yields a set of non-linear equations, which is solved by the Newton-Raphson linearization method.
Complete analysis of forming processes requires a simulation of heat transfer in the deformation zone, therefore, the solution for flow formulation is coupled with the thermal model. Temperatures are calculated accounting for heat conduction in the material, heat generation due to the plastic work and friction, heat losses due to transfer to the surrounding medium. The general principles of the approach is non-steady state solution of the diffusion equation:

$$\nabla\left(k\nabla T\right) + Q = c_p \rho \frac{\partial T}{\partial t} \qquad (4)$$

where: k - conductivity, T - temperature, Q - heat generated due to plastic work, ρ - density, c_p – specific heat, t – time.

The program is being developed now in our Department and will be completed and tested before the end of June 2002. This is fully object oriented code. It means that it is divided into classes and easily accessible, therefore, introduction of new materials or new constitutive laws does not present difficulties.

13. Optimizer

• Indicate optimisation algorithms or software optimisation environments (e.g. name of a commercial optimisation software package) to be applied

The difficulties connected with selection of proper optimisation technique, avoiding the local minima and long computing times restrain development of user-friendly optimisation codes. The decision of the user is required at various stages of optimisation and fully automatic optimisation is not possible. Thus, the works in this project will focus on automatic selection of the optimisation techniques and on making the codes efficient. The following methods will be tested and used:

- conventional non-gradient techniques,
- classical gradient algorithms,
- evolution strategies, in which it is not necessary to use the gradient of the quality function with respect to input parameters but only the quality function itself. The technique is based on evaluating successively and in classifying this quality function. The set of parameters, which gives the smallest value will be the identified one.

In a very innovative part of the numerical optimisation technique we will investigate the robustness of these techniques in the frame of optimisation of the forming process parameters.
All the algorithms are implemented and are our own codes. This allows for easy modifications and linking of them to design efficient optimisation strategy.

14. Competence / activities of proposer

• With respect to material process simulation, material laws and - if applicable - to numerical process optimisation

The Department of Computational Methods in Metallurgy belongs to the Faculty of Metallurgy and Materials Science of the Akademia Gorniczo-Hutnicza. 3800 employees work at AGH. 1760 of them are involved in teaching and research, the remaining are technicians and administrative staff.
The scientific topics studied by the researchers of the department include:

- Optimisation of the tool shape in forging and extrusion processes
- The development of the internal variable models, which describe the state of material during thermomechanical processing as a function of the history of deformation. Earlier conducted research has shown that when internal variables are introduced instead of the current values of external variables, it is possible to simulate complex microstructural phenomena including dynamic and metadynamic recrystallization. It is also possible to create a constitutive law, which accounts for the current state of microstructure.
- Running precisely controlled laboratory testes for axisymmetrical compression with particular emphasis on the tests with varying strain rates and/or temperatures for some materials being of particular interest from economical point of view, like IF steels.

- Running multistage compression tests with varying strain rates and/or temperatures are planned. These are used for validation of the internal variable model.
- Determination of the inverse technique for the evaluation of material constants in the both microstructural and internal variable models. The inverse analysis can be performed for three types of tests: upsetting, plane strain compression and torsion.

Personnel : Prof. Maciej Pietrzyk, Ass.Prof. Jan Kusiak, Dr Danuta Szeliga, experts in metal forming and process optimisation. 2 Ph.D. students and 2 post-docs will be assigned to the project.

15. International state of the art and references

- State of the art of process modelling and optimisation concerning your proposal
- Relevant publications and articles

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