1. **Project Name:** **Physical and Numerical Analysis of Extrusion Process for Production of Bi-metallic Tubes**

2. **Lead Organization:**

Institute for Metal Forming
Lehigh University
5 East Packer Avenue
Bethlehem, PA 18015

3. **Principal Investigator:**

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4. **Project Partners:**

Organization	Investigator	Contact Information	Responsibilities
Lehigh University	Wojciech Z. Misiolek	(610) 758 4288 Fax: 758 4244 wzm2@lehigh.edu	Project coordination, maintaining contacts between project members and report writing responsibilities
Lehigh University	David Williams	(610) 758 6120 dbw1@lehigh.edu	Advisor on material characterization methods
Lehigh University	Pawel Kazanowski	(610) 758 4288 Fax: 758 4244 kap2@lehigh.edu	Process model development, execution of experiments and data analysis, FEM simulations
Lehigh University	Mario Epler	(610) 758 4243 Fax: 758 4244 mee3@lehigh.edu	Tube bond integrity analysis
Oak Ridge National Laboratory	Vinod Sikka	(865) 574 5112 Fax: 574 4357 sikkavk@ornl.gov	Supervising the extrusion processing experiments and coordinating the simulations performed at ORNL
Oak Ridge National Laboratory	Gail Mackiewicz-Ludtka	glm@ornl.gov	Feedback and overseeing the incorporation of project results into a related project
Altair Engineering	Robert N. Yancey	(614) 764 2277 Fax: 764 2122	Technical support for HyperXtrude software package
Dynamet Technology	Susan M. Abkowitz	(781) 272 6967 Fax 229 4879	Technology transfer
Energy Industries of Ohio	Robert M. Purgert	(216) 643 2925 Fax 643 5901	Technology transfer
Special Metals Corp.	Gaylord D. Smith	(304) 526 5100 Fax 526 5643	Technology transfer
Plymouth Extruded Shapes	Tony Esposito	(270) 866 6631 Fax 855 7034	Extrusion Practice, Die Design, Lubrication, Technology transfer

5. **Date Project Initiated and FY of Effort:** Date work began – 09/30/2001
Current year of the project – 2nd

6. **Expected Completion Date:** 09/29/2004

7. Project Technical Milestones and Schedule:

ID Number	Task / Milestone Description	Planned Completion	Actual Completion	Comments
1.1	Literature review	04/30/02	Accomplished	
1.2	Perform deformation test	10/31/02	Accomplished	
1.2.1	Deformation tests on modeling material	10/31/02	Accomplished	
1.2.1	Deformation tests on steel	12/31/02	Delayed	New date 07/31/03
1.3	Develop material model	10/31/02	Accomplished	
2.1	Analyze extrusion press characteristic	06/30/02	Accomplished	New date 08/31/02
2.2	Analyze tooling design	10/31/02	Accomplished	
3	Develop numerical co-extrusion process model	04/30/03	Accomplished	1st Generation Model
4	Perform physical modeling validation of numerical model	03/31/04	On schedule	
5	Develop powder metallurgy module for process model	03/31/04	On schedule	
6	Verify model under various conditions on a pilot press	07/31/04		
7	Analyze tube bond integrity	07/31/04		
8	Analyze tooling deflections and process control	07/31/04		
9	Implement model into industrial practice	09/30/04		

8. Past Project Milestones and Accomplishments:

The research objective of the project is to develop numerical design tools to allow for the selection of compatible metals and process parameters for co-extrusion of bi-metal tubes. Numerical tool design process was preceded by a wide and careful literature analysis. It was found that all the theoretical solutions presented in literature are valid for steady state of the extrusion process only, when the material flow is uniform. The initial and final stage of the bi-material billet extrusion process was investigated experimentally at Lehigh University. Large volumes of scrap material extruded from bi-material billet of the same length of core and sleeve material were observed. Significant reduction of scrap material volume in comparison with the existing bi-material tube extrusion process was achieved by the implementation of a newly designed "core length shortening method" that was developed at Lehigh University[1]. In some cases, the scrap volume was reduced by 18%. Energy savings generated by the new method results from better process yield and reduced costs of recycling.

A new method to evaluate the performance of bi-material samples during axisymmetric upsetting has been proposed. The aim of this investigation was to develop a material response model evaluating the compatibility of two materials for simultaneous flow under axisymmetric extrusion conditions. Results of the performed bi-material cylinders upsetting tests indicate the influence of materials sequence as well as material thicknesses ratio on the simultaneous material flow. The proposed method can be performed on all envisioned pairs of materials at room and elevated temperature.

An original approach to the development of a numerical model for co-extrusion of bi-material tubes has been proposed. A newly developed relationship between the initial bi-material billet geometry and final bi-material product geometry is based on the extrusion constant (K) concept. Extrusion constant K is a function of several parameters including material properties, friction conditions, and degree of deformation for a specific press. The degree of deformation for each material during simultaneous deformation is evaluated from bi-material cylinder upsetting. Assuming constant material properties and friction conditions during deformation and applying reverse engineering it is possible to evaluate the bond diameter between sleeve and core material within a bi-material billet. Very good agreement between experimental and theoretical results has been achieved.

Tedious and energy consuming experimental evaluation of optimal billet design can be significantly shortened by utilizing the newly developed solution. The proposed model was presented to Altair Team (Software company – project partner) and bi-material module for HypeXtrude FEM package will be created in the new software edition of their product.

9. Planned Future Milestones:

Metal flow compatibility of two materials for simultaneous extrusion has been already established. Additional modeling effort will include influence of thermal conductivity and expansion coefficients of the individual metallic elements on the bi-material tube performance. The possible applications will be evaluated based on the metallurgical and thermal compatibility of selected materials. It will have an important influence on the understanding of the interface conditions at bi-material "bond" and residual stresses.

Verification of the proposed model under various process conditions is essential for proposed numerical co-extrusion process model. The ORNL Team analyzed extrusion press characteristics and tooling design along with initial bi-material billet geometries simulating various conditions. Physical modeling to validate the numerical models is in process utilizing the billets design by Lehigh Team and manufactured by ORNL. Material and geometrical properties of extruded tubes will be evaluated at Lehigh University. Mechanical and metallurgical bond integrity is of special interest for a potential user. In order to perform accurate mechanical bond analysis the Lehigh University Team proposed several methods involving bending and compression of the bi-material product.

Tooling deflections and process controls will be analyzed at ORNL during experiments with steel tube extrusion (carbon steel/stainless steel). It is envisioned to enhance the inner and outer surface of bi-material tube by introducing straight (2nd generation of tubes) or helical fins (3rd generation of tubes). The performed research is essential in order to build a foundation necessary to develop these more complex and unique products. Fin performance is a complex function of material properties and its geometry. From heat exchange point of view helical fins are superior to straight fins[2]. The biggest challenge during extrusion of the monometallic tube with helical fins on the inner surface is understanding of the complexity of metal flow and therefore precise design of the extrusion tooling. Bond

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[1] K.E. Kloske, T. Jeong, A.R. Bandar and W.Z. Misiolek: Proc. 7th Intern. Aluminum Extrusion Tech. Seminar ET'2000 (2000) Vol. 2, p. 223

[2] F.P. Incropera and D.P. DeWitt, Fundamentals of Heat and Mass Transfer, 5th Ed., John Wiley & Sons, NY, 2002

integrity within a bi-material product may affect general tube performance. The evolution of metallurgical bond integrity will be evaluated using LOM, SEM, EBSD, EDS, and EPMA.

An approach to lower the inner material twist during helical tube extrusion is to introduce a powder layer between sleeve and core material. Careful multi-material billet design will lead to the process in which sleeve material of the tube will not rotate while the rotation of core material diminishes at a certain distance from the die orifice. The shear force between core and sleeve material will distribute the powder evenly and simultaneously achieve its full densification. The envisioned solution will yield a complex shape of unique properties and wide applicability for many DOE industries of the future (IOF) programs.

10. **Issues/Barriers:**

None

11. **Intended Market and Comme rcialization Plans/Progress:**

Foreign producers and vendors dominate the market of 1st generation of bi-material tubes without any surface enhancements. Equipment cost is also a limiting factor. Heat exchangers and boilers are widely used across many IOFs. The 2nd and 3rd generation of the bi-material tubes is envisioned to partly replace presently used bi-material tubes where a high heat exchange index is desired. In order to disseminate the information and methodology of the research, numerous different avenues can be used.

Publications in technical, scientific, and trade journals can be used to share the information with the appropriate technical audience. Presentations at industrial conferences will also provide means to share the results. Any software that is developed by the Lehigh Team as a result of this work will be provided as free-ware or source code so that it is not prohibitive to industry.

The project has a strong industry team with the focus on implementing the technology. Plymouth Extruded Shapes is our industrial partner and currently certain metal flow analysis and die design optimization are performed for their products. It is envisioned that this work will continue for more complex solid and tubular shapes in the future.

12. **Patents, publications, presentations:**

- Misiolek W.Z., Kazanowski P., Van Geertruyden W., **Merging research with manufacturing. Making technology grow through university – industry partnership**, The Tube & Pipe Journal, Vol.13, No.7, 2002, pp.20-23
- Kazanowski P., Misiolek W. Z. **Investigation of the bi-metal tube cross-section geometrical stability after extrusion with the mandrel,** XII Scientific Conference on Production Technologies for Tubes and Pipes in Non-Ferrous Metals Industry, Zakopane, Poland, 21st November 2002
- Kazanowski P, Misiolek W.Z., Sikka V.K., **Analysis of the influence of the initial billet geometry and die design on the product geometry during bi-material tube extrusion**, THERMEC'03 International Conference on Processing and Manufacturing of Advanced Materials, Madrid, Spain – to be presented in July'03

Highlight

Physical and Numerical Analysis of Extrusion Process for Production of Bi-metallic Tubes

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Goals

The research objective of the project is to develop numerical design tools to allow for the selection of compatible metals and process conditions for co-extrusion of bi-metal tubes. A new method to evaluate the performance of bi-material samples for extrusion application during axisymmetric upsetting has been proposed. A newly developed relationship between the initial bi-material billet geometry and final bi-material product geometry is based on the extrusion constant (K) concept and is shown in Figure 1.

The presented solution is a base on which a cost-effective technology for bi-material tube extrusion can be evaluated and developed.

Energy Benefits and Performance Index

The most important factor in reducing cost and energy expenditures in manufacturing is the ability to control and reduce scrap volume. When scrap is reduced, material is conserved. This translates directly into savings in material, energy needed to produce the feedstock material and then the final product. At the same time both tooling wear as well as a general wear and tear of the equipment are reduced. Additionally, much smaller amount of the scrap material needs to be recycled. A detailed model for the proposed performance index for bi-material tube has been developed.

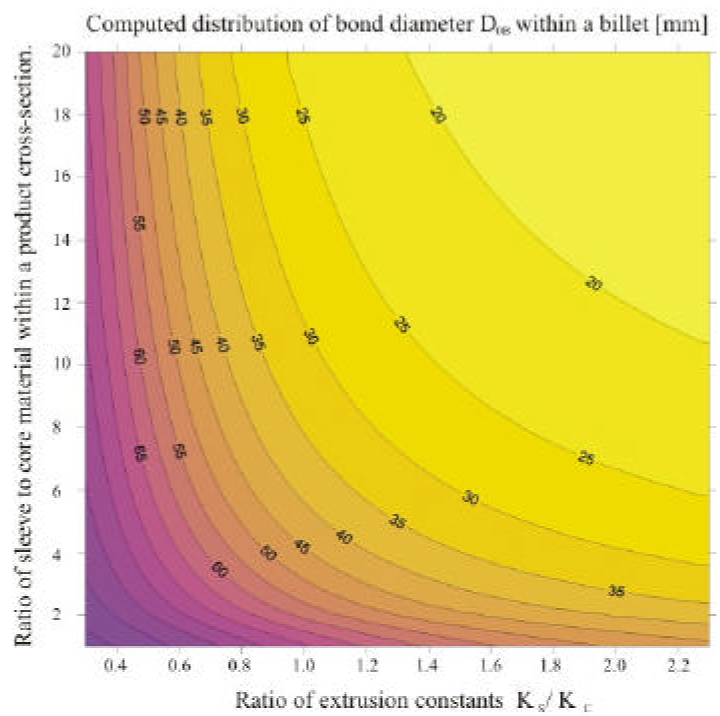

Fig. 1. Computed distribution of bond diameter within a billet using developed algorithm (extrusion ratio R = 5.33)

Applications and Commercialization Plan

Foreign producers and vendors dominate the US market of 1st generation of bi-material tubes without any surface enhancements. Equipment cost is also a limiting factor for manufacturing of these products in the US. Heat exchange units and boilers are widely used across many industries. The 2nd and 3rd generation of the bi-material tubes (See Figures 2 and 3) is envisioned to partly replace presently used bi-material tubes where a much higher heat exchange index is needed. In order to disseminate the information and methodology of the performed research results, numerous different avenues will be used. Publications will be placed in technical, scientific, and trade journals to share the information with the technical audience. Presentations at conferences will also allow to share the results and exchange ideas with technical and scientific communities. Any software that will be developed by the Lehigh Team as a result of this work will be provided as free-ware or source code so that it will not be cost prohibitive to industry. This will allow to develop new manufacturing capabilities in the US for next generations of bi-material tubes.

The project has a strong industry team with the focus on implementation of the developed technology. Plymouth Extruded Shapes is our main industrial partner and currently certain metal flow analysis and die design optimization are performed for their products. It is envisioned that this research will continue for more complex solid and tubular shapes in the future.

Fig.2. Second generation of bi-material tubes with straight outer fins.

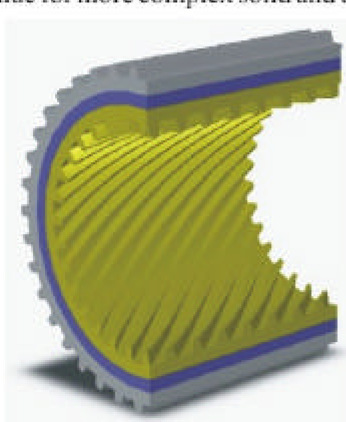

Fig.3. Third generation of multi-material tubes with straight

Future Plans

Continuation of the work on 2nd and 3rd generation of steel bi-material tubes. The input from other industries for improved tube design will be critical for successful completion of the project.

A bi-material fastener is an example of a new application for small diameter bi-material tubes.

Additionally, proposed developments can be readily applied to the medical device industry.