METAL FORMING 2004
CONFEREN CE PROGRAM

SUNDAY,  SEPTEMBER 19

9:00–18:00  SOCIAL PROGRAM – free of charge for conference participants

15:00–20:00  REGISTRATION – Fundacja KRAKUS, 15 Reymonta street

18:00–20:00  RECEPTION – Fundacja KRAKUS, 15 Reymonta street

MONDAY,  SEPTEMBER 20

8:00–17:00  REGISTRATION - Building A0

9:00  CONFERENCE OPENING (ROOM A)

<table>
<thead>
<tr>
<th>TIME</th>
<th>ACTIVITY</th>
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<tbody>
<tr>
<td></td>
<td><strong>R. Kopp, O. Hofmann, V. Honnet</strong>, (Institut fur Bildsame Formgebung, Aachen, GERMANY), <strong>C. Plociennik</strong> (SMS Demag AG, Düsseldorf, Germany)</td>
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<td></td>
<td><strong>E. Laitinen, J. Pieskä</strong> (University of Oulu, FINLAND), <strong>I. Rentola</strong> (Rautaruukki Steel, Raahe steel works, Raahe, FINLAND), <strong>V. Toivonen</strong> (University of Oulu, FINLAND)</td>
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10:40–11:00  COFFEE
<table>
<thead>
<tr>
<th>ROOM A</th>
<th>ROOM B</th>
<th>ROOM C</th>
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<tbody>
<tr>
<td><strong>EXTRUSION</strong></td>
<td><strong>MATERIAL PROPERTIES - Workability</strong></td>
<td><strong>FORGING</strong></td>
</tr>
<tr>
<td>Chairman: A. Kiet Tieu</td>
<td>Chairman: Rudolf Kawalla</td>
<td>Chairman: Jean-Claude Gelin</td>
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**ROOM A**

1100-1120

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<tr>
<td><strong>P. Skubisz, J. Sińczak, A. Solec</strong></td>
<td><strong>O.-G. Lademo, T. Berstad</strong> (SINTEF Materials Technology, Trondheim, NORWAY), <strong>O.S. Hopperstad</strong> (University of Science and Technology, Trondheim, NORWAY), <strong>K.O. Pedersen</strong> (SINTEF Materials Technology, Trondheim, NORWAY)</td>
<td><strong>F.-W. Bach, B. A. Behrens, H. Dähndel, M. Gumertz, A. Huskic</strong> (The University of Hannover, GERMANY)</td>
</tr>
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**ROOM B**

1120-1140

<table>
<thead>
<tr>
<th>A Study of the Thermo-Mechanical Response of a Die Face Pressure Sensor for Hot Aluminium Extrusion</th>
<th>A numerical tool for formability analysis of aluminium alloys. Part II: Experimental validation.</th>
<th>Numerical and Experimental Analysis of the Closed-Die Forging of Aluminium Spiders</th>
</tr>
</thead>
</table>

**ROOM C**

1140-1200

<table>
<thead>
<tr>
<th>Numerical Sensitivity Study to Determine the Effects on Transverse Welds in Direct Extrusion of AlMgSi – Alloys</th>
<th>Application of ductile fracture criteria to prediction of forming limit of high-strength steel sheets</th>
<th>Investigations on the Use of Damage Criteria under Semi-Hot Forging Conditions with FE-Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>T. Hatzenbichler, B. Buchmayr, A. Umgeher</strong> (Montanuniversität Leoben, Leoben, AUSTRIA)</td>
<td><strong>H. Takuda, T. Kanie, E. Isogai, T. Yoshida</strong> (Kyoto University, JAPAN)</td>
<td><strong>H. Just, A. Behrens</strong> (University of the Federal Armed Forces, Hamburg, GERMANY)</td>
</tr>
</tbody>
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1200-1220

<table>
<thead>
<tr>
<th>Development of Direct Extrusion Process for Al Multi-Cell Tube Using Porthole Die</th>
<th>The Influence of Interlayer Thickness and Properties on Springback of SPS - (Steel/Polymer/Steel) Laminates</th>
<th>Design of Forging Technology with Using the Cost – Volume – Profit Model</th>
</tr>
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<tbody>
<tr>
<td><strong>Jung Min Lee, Byung Min Kim</strong> (Pusan National University, Pusan, KOREA), <strong>Hyung Ho Jo</strong> (KITECH, Incheon, KOREA), <strong>Chung Gil Kang</strong> (Pusan National University, Pusan, KOREA)</td>
<td><strong>M. Weiss, B. Rolfe, M. Dingle, P.D. Hodgson</strong> (Deakin University, AUSTRALIA)</td>
<td><strong>A. Łukaszek-Solek, J. Sińczak, P. Skubisz</strong> (Akademia Górniczo-Hutnicza, Krakow, POLAND)</td>
</tr>
</tbody>
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1220-1240

<table>
<thead>
<tr>
<th>Development of Extrusion Process and Die Design for Al Speaker Body</th>
<th>Identifying the material parameters of a combined isotropic and non-linear kinematic hardening model for AISI 304 stainless steel sheet</th>
<th>Theoretical Analysis of Rotating Compression Forming of Ring Considering Constant Shear Friction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Byung Min Kim, Jung Min Lee</strong> (Pusan National University, Pusan, KOREA), <strong>Hyung Ho Jo</strong> (KITECH, Incheon, KOREA), <strong>Chung Gil Kang</strong> (Pusan National University, Pusan, KOREA)</td>
<td><strong>T. Manninen, A.S. Korhonen</strong> (Helsinki University of Technology, Espoo, FINLAND), <strong>P. Aspegren, T. Taulavuori</strong> (Avesta Polarit, Tornio, FINLAND)</td>
<td><strong>Wen-Tung Chien</strong> (Peking University of Science and Technology, TAIWAN, ROC), <strong>Gow-Yi Tsou, Ming-Nan Huang</strong> (Yung-Ta Institute of Technology, Ping-Tung, Taiwan, ROC), <strong>Wen-Hsin Tseng</strong> (Ping-tung University of Science and Technology, TAIWAN, ROC)</td>
</tr>
</tbody>
</table>
### Conference Program

#### Room A

**EQUIPMENT - MEASUREMENTS**  
Chairman: Andrzej Kocańda

- **14:30-14:50**  
  Development of Direct Drive Digital Servo Press  
  **C. Murata, T. Machida, S. Futamura** (Hoden Seimitsu KakoKenkyusho Co., Ltd., JAPAN), **J. Endou** (Kanagawa Institute of Technology, JAPAN)

- **14:50-15:10**  
  High Resolution Measurement of Large Strain with Fourier Phase Correlation Method by Image Sensing Camera  
  **T. Sawada, M. Sakamoto** (Tokyo University of Agriculture and Technology, Tokyo, JAPAN)

- **15:10-15:30**  
  Measuring of the Curvature Distribution of Bent Profiles  
  **U. Dirksen, S. Chatti, M. Kleiner** (University of Dortmund, GERMANY)

- **15:30-15:50**  
  Measuring and Calculating Flatness During Hot-Coiling  
  **A. Nilsson** (MEFOS, SWEDEN), **J. Jokisaari** (Rautaruukki OY, FINLAND), **Å. Stenström** (Avesta Polarit, Avesta, SWEDEN)

- **15:50-16:10**  
  Validation of the forward-backward extrusion test, designed for evaluation of friction coefficient and flow properties of metal alloys deformed in semi-solid state  
  **A. Zmudzki** (Akademia Górniczo-Hutnicza, Kraków, POLAND), **M. Papaj** (Non-Ferrous Metal Foundry, Starachowice, POLAND), **R. Kuziak** (Institute for Ferrous Metallurgy, Gliwice, POLAND), **J. Kusiak, M. Pietrzyk** (Akademia Górniczo-Hutnicza, Kraków, POLAND)

#### Room B

**MATERIAL PROPERTIES – Transformations**  
Chairman: Philippe Picart

- **14:30-14:50**  
  Problems and benefits of deformation in the two-phase region: metal forming application  
  **A. Bator, J. Majta** (Akademia Górniczo-Hutnicza, Kraków, Poland), **A.K. Zurek** (Los Alamos National Laboratories, USA)

- **14:50-15:10**  
  Prediction of Distortion during Cooling of Steel Rolled Rings Using Thermal-Mechanical-Metallurgical Finite Element Model  
  **F. Pascon, G. Blès, C. Bouffioux** (Université de Liège, BELGIUM), **S. Casotto, S. Bruschi** (Università degli Studi Padova, ITALY), **A.M. Habraken** (Université de Liège, BELGIUM)

- **15:10-15:30**  
  Development of the Constitutive Law for Microalloyed Steels Deformed in the Two-Phase Range of Temperatures  
  **M. Pietrzyk** (Akademia Górniczo-Hutnicza, Kraków, POLAND), **R. Kuziak** (Institute for Ferrous Metallurgy, Gliwice, POLAND)

- **15:30-15:50**  
  Mushy State Forging of Aluminum Alloy Using Resistance Heating  
  **S. Maki, T. Shibata, K. Mori** (Toyohashi University of Technology, JAPAN), **H. Makino** (Sintokogio Ltd., Toyokawa, JAPAN)

- **15:50-16:10**  
  A New Coupled Approach Between a Micromechanical and a Phenomenological Modelling of the Strain Induced Martensite Transformation Kinetics in a 304 Austenitic Stainless Steel (TRIP Steels)  
  **Z. Tourki, K. Sai** (Ecole Supérieures des Sciences et Techniques de Tunis, TUNISIE)

#### Room C

**FORGING**  
Chairman: Jerzy Gronostajski

- **14:30-14:50**  
  Development and Research on Near Net Shape Forging Technology of Round Part with Flange Made of Aluminium Alloy A95456.  
  **P. Petrov, V. Perfilov, M. Petrov** (Moscow State Technical University, Moscow, RUSSIA)

- **14:50-15:10**  
  Warm precision forging and upsetting for the extruded billet of AZ61 Magnesium alloy  
  **D.-S. Lee, M. Asakawa, Y. Tanno** (Waseda University, Tokyo, JAPAN), **M. Kobayashi** (Nagaoka University of Technology, Niigata, JAPAN), **K. Hatsukano, K. Matsuoka** (Institute of Mechanical Systems Engineering, AIST, Tsukuba, JAPAN)

- **15:10-15:30**  
  Numerical and Experimental Investigation on Hot Impression Die Forging: Flash Design Optimisation  
  **R. Di Lorenzo, S. Beccari, M. Piacentini, F. Micari** (Università di Palermo, ITALY)

- **15:30-15:50**  
  An Influence of the Selected Flash Variables on the Closed-Die Forging Processes  
  **G. Samoluyk, Z. Pater** (Technical University of Liblin, POLAND)

- **15:50-16:10**  
  An Upper Bound Stream Function Elemental Technique for the Forging of Spur Gears  
  **M. Salimi, M. Kabirian** (Isfahan University of Technology, IRAN)
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<th>Room C</th>
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<tbody>
<tr>
<td>16:10</td>
<td><strong>ROLLING - Microstructure</strong></td>
<td><strong>MATERIAL PROPERTIES</strong></td>
<td><strong>NUMERICAL MODELLING</strong></td>
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<tr>
<td></td>
<td>Chairman: Sigurd Støren</td>
<td>Chairman: Andrzej Rosochowski</td>
<td>Chairman: Gow-Yi Tzou</td>
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<tr>
<td>17:00</td>
<td>during Continues Casting of Steel LH15SG for</td>
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<td>Problem during Forming Process Simulation</td>
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<td>Shape Rolling</td>
<td>T. Śleboda (Akademia Górniczo-Hutnicza, Kraków, POLAND), J. Kane,</td>
<td>C. Pelissou, E. Massoni, J-L. Chenot, (CEM EF, Ecole des Mines de</td>
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<td>R.N. Wright, N.S. Stoloff, D.J. Duquette (Rensselaer Polytechnic</td>
<td>Paris, Sophia-Antipolis, FRANCE)</td>
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<td>Institute, Troy, NY, USA)</td>
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<tr>
<td>17:00-</td>
<td>Mechanics of Slab Edging with Friction Consideration</td>
<td>The Effects of Nb and Mo Additions on the Microstructure and</td>
<td>An Efficient Vectorized Approach for the Simulation of Metal Injection</td>
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<tr>
<td>17:20</td>
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<td>Formability of C-Mn-Si-Al TRIP-Aided Ferrous Sheet Steels with an</td>
<td>Molding</td>
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<td>Annealed Martensite Matrix</td>
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<td>17:20-</td>
<td>Effect of Rolling Condition on Mill Load and</td>
<td>Selected Properties of Ni-Al Materials after Hot Forging of PM</td>
<td>Modelling and Simulation of Precision Blanking for Very Thin Components</td>
</tr>
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<td>17:40</td>
<td>Oxide Scale Deformation in Hot Steel Rolling</td>
<td>Preforms</td>
<td>V. Lemiale, P. Picart (University of Franche Comté, Besançon, FRANCE)</td>
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<td>S. SzczepaniK, K. Piątkowska (Akademia Górniczo-Hutnicza, Kraków,</td>
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<td>17:40-</td>
<td>Shear Texture Control of Aluminum and Low Carbon</td>
<td>Application of the Control Theory Methods for Evaluation of</td>
<td>Experimental and Numerical Investigation of Miniaturization in Deep</td>
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<tr>
<td>18:00</td>
<td>Steel Sheets by Differential Speed Rolling</td>
<td>Dislocation Model Parameters</td>
<td>Drawing</td>
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<td>D. Svyetlichnyy (Częstochowa University of Technology, POLAND)</td>
<td>H. Justinger, N. Witulski, G. Hirt (Saarland University, Saarbruecken,</td>
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<td>GERMANY)</td>
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<tr>
<td>18:00-</td>
<td>Mechanical and Metallurgical Properties of Hot</td>
<td>Determination of Microscale Deformation in Hot Worked Steel</td>
<td>Prediction of Surface Layer Hardness in Hot Forging Dies by Means of</td>
</tr>
<tr>
<td>18:20</td>
<td>Rolling Ti-6Al-4V Sheets</td>
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<td>Finite-Element-Analysis</td>
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<td>J. Mei, M. Lovell, F. Pettit (University of</td>
<td>L.E. Hernandez-Castillo, J.H. Beynon, C. Pinna (IMMPETUS, University</td>
<td>E. Doege, B.-A. Behrens, F. Schaefer (University of Hanover, GERMANY)</td>
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<td>Pittsburgh, USA)</td>
<td>of Sheffield, UK), S. van der Zwaag (Delft University of Technology,</td>
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<td>THE NETHERLANDS)</td>
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**TUESDAY, SEPTEMBER 21**

**8:30 - 17:00** SECRETAIRAT (BUILDING A0)

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<th>KEYNOTE LECTURES (ROOM A)</th>
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<td>Chairman: Ian Pillinger</td>
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<td>9:00 - 9:45</td>
<td>Coupling Microstructure Models with Large Scale Forming Simulations</td>
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<td><strong>Y. Chastel, R. Logé</strong> (Ecole des Mines de Paris, CEMEF, FRANCE)</td>
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<tr>
<td>9:45 - 10:30</td>
<td>Deterministic and Stochastic Analysis of Failure in Sheet Metal Forming Operations</td>
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<td><strong>J. Rojek, M. Kleiber</strong> (Institute of Fundamental Technological Research, Polish Academy of Sciences, Warsaw, POLAND), <strong>A. Piela</strong> (Silesian University of Technology, Katowice, POLAND), <strong>R. Stocki, J. Knabel</strong> (Institute of Fundamental Technological Research, Polish Academy of Sciences, Warsaw, POLAND)</td>
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**10:30 - 11:00** COFFEE
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<th>ROOM A</th>
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<tr>
<td><strong>SHEET FORMING</strong>&lt;br&gt;Chairman: Bruno Buchmayr</td>
<td><strong>MATERIAL PROPERTIES - Microstructure</strong>&lt;br&gt;Chairman: Roman Kuziak</td>
<td><strong>NUMERICAL MODELLING - Optimization</strong>&lt;br&gt;Chairman: Tomaz Rodic</td>
</tr>
<tr>
<td><strong>1120-1140</strong>&lt;br&gt;A storage and Retrieval System for Roll-Forming Design Data Using a Neural Network&lt;br&gt;A.W. Downes, P. Hartley, I. Pillinger (University of Birmingham, UK)</td>
<td>Effects of Mg Concentration, Test temperature and Strain Rate on Serration of AlMg3 and AlMg5 Alloys&lt;br&gt;S.A. Risteska, J.K. Mickovski (The Univerzy “St. Cyril and Metodious” Skopje, MACEDONIA)</td>
<td>Bending Profile Metals in Application with Artificial Neural Networks&lt;br&gt;K.-J. Fann, J.-C. Yang, P.-Y. Hsiao (National Chung Hsing University Taichung, TAIWAN/R.O.C.)</td>
</tr>
<tr>
<td><strong>1220-1300</strong>&lt;br&gt;Springback Analysis in Drawbead Simulator Tests&lt;br&gt;A. Matuszak, D. Krecisz (Politechnika Wrocławska, Wrocław, POLAND)</td>
<td>Modelling Phase Transformation in Steels&lt;br&gt;J. Ronda (Akademia Górniczo-Hutnicza, Kraków, POLAND)</td>
<td>3D FEM Analysis and Optimization of Metal Forming and Temperature Development During Multi-Pass Rolling of the Round Shape&lt;br&gt;A. Milenin, H. Dyja (Częstochowa University of Technology, POLAND)</td>
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<tr>
<td><strong>1300-1400</strong> LUNCH</td>
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<td><strong>1420</strong> PHOTOGRAPH OF THE CONFERENCE DELEGATES IN THE BUILDING A0</td>
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Conference program,
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<tr>
<td>14:30-14:50</td>
<td><strong>ROLLING</strong>&lt;br&gt;Chairman: Daniel Yuen&lt;br&gt;Effect of Roll Edge Local Perturbation of Deformation on Thin Strip Rolling&lt;br&gt;Z. Jiang, H.T. Zhu, A.K. Tieu (University of Wollongong, AUSTRALIA)</td>
<td><strong>MATERIAL PROPERTIES Identification</strong>&lt;br&gt;Chairman: Yvan Chastel&lt;br&gt;A methodology to identify bulk behaviour of galvanised coating: An application to the skin-passed steel strip&lt;br&gt;S. Huart, M. Dubar, R. Deltombe, A. Dubois, L. Dubar (Université de Valenciennes et du Hainaut Cambrésis, FRANCE)</td>
<td><strong>DRAWING</strong>&lt;br&gt;Chairman: Junichi Endou&lt;br&gt;Prevention of Wire Breaks and Its Analysis by FEA in Superfine Gold Wire Drawing&lt;br&gt;T. Yamashita, K. Yoshida (Tokai University, JAPAN)</td>
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<tr>
<td>14:50-15:10</td>
<td><strong>Surface Profile Characteristics of Steel Strip After Hot Rolling</strong>&lt;br&gt;W. Sun, A. K. Tieu, Z. Jiang, H. Zhu (University of Wollongong, AUSTRALIA)</td>
<td><strong>A Trust-Region Algorithm for Automatic Identification of Elasto-Viscoplastic Parameters in Metal Forming Problems</strong>&lt;br&gt;P.-P. Jeunechamps, P. Duysinx, J. Walmag, V. Mathonet, E. Delhez, P. Tossings, A.-M. Habraken, J.-P. Ponhot (University of Liège, BELGIUM)</td>
<td><strong>Cold Drawing of Magnesium Alloy Wire and Fabrication of Microscrews</strong>&lt;br&gt;K. Yoshida (Tokai University, JAPAN)</td>
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<td>15:10-15:30</td>
<td><strong>Parameters Affecting Free Spread of Stainless Steel Sheet Grade 304</strong>&lt;br&gt;A. Ismail, T. El-Bitar, A. El-Morsy M. Abdel-Aziz (Central Metallurgical R&amp;D Institute (CMRDI), Cairo, EGYPT)</td>
<td><strong>An Approach for Evaluating Constitutive Models for Hot Aluminium Extrusion – Rod Extrusion of AA6060 as a Case Study</strong>&lt;br&gt;P.T. Moe, W. Wajda (Norwegian University of Science and Technology, Trondheim, NORWAY), L. Madej, D. Szeliga (Akademia Górniczo-Hutnicza, Krakow, POLAND), S. Stören (Norwegian University of Science and Technology, Trondheim, NORWAY), M. Pietrzyk (Akademia Górniczo-Hutnicza, Krakow, POLAND)</td>
<td><strong>FEM Analysis of a Multi-Pass Hydrodynamic Drawing Process of High Carbon Steel Wires With Different Drawing Directions</strong>&lt;br&gt;A. Milenin, H. Dyja, Z. Muskalski, J. Pilarczyk (Częstochowa University of Technology, POLAND)</td>
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<td>15:30-16:00</td>
<td>COFFEE</td>
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<td>ROOM A</td>
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<td><strong>SHEET FORMING</strong>&lt;br&gt;Chairman: Zbigniew Gronostajski</td>
<td><strong>MATERIAL PROPERTIES</strong> - Identification&lt;br&gt;Chairman: Erkki Laitinen</td>
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<tr>
<td><strong>1600-1620</strong>&lt;br&gt;Prevention of Wrinkling and Fracturing in Deep Drawing of Metal Foil Using Resin Dies and Auxiliary Sheets&lt;br&gt;Y. Marumo, H. Saiki (Kumamoto University, JAPAN)</td>
<td>Using Inverse Analysis to Obtain Material Behaviour for Crash Simulations&lt;br&gt;J. Mullins, P.D. Hodgson, M. Dingle (Deakin University, Waurn Ponds, AUSTRALIA)</td>
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**1930-2300 CONFERENCE BANQUET – ROYAL CASTLE WAWEL**
## WEDNESDAY, SEPTEMBER 22

### 8:30 - 15:00  SECRETARIAT (BUILDING A0)

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<tbody>
<tr>
<td>9:00-</td>
<td><strong>KEYNOTE LECTURES (ROOM A)</strong></td>
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<tr>
<td>9:45-</td>
<td><em>Metal forming technology for producing bulk nanostructured metals</em>&lt;sup&gt; наблюдающий&lt;/sup&gt;</td>
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<td><strong>A. Rosochowski (University of Strathclyde, Glasgow, UK), L. Olejnik (Warsaw University of Technology, Warsaw, POLAND),</strong></td>
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<td><strong>M. Richert (Akademia Gorniczo-Hutnicza, Krakow, POLAND)</strong></td>
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<tr>
<td>10:30-</td>
<td><strong>The Formation of Ultrafine Grained Steel Microstructures through Thermomechanical Processing</strong>&lt;sup&gt; наблюдающий&lt;/sup&gt;</td>
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<td><strong>P.D. Hodgson, H. Beladi (Deakin University, AUSTRALIA)</strong></td>
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<td>10:30-</td>
<td><strong>COFFEE</strong></td>
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<td>Time</td>
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<td>11:00-</td>
<td><strong>ROLLING</strong> Chairman: Didier</td>
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<tr>
<td>11:20</td>
<td>Farrugia</td>
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<td></td>
<td>Asymmetrical cold sheet rolling in free horizontal entry conditions</td>
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<td></td>
<td><em>M. Salimi, M. Kadkhodaie</em> (Isfahan University of Technology, IRAN)</td>
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<td>11:20-</td>
<td><strong>A study on the ski-end direction in plate mills</strong> A. Nilsson (MEFOS, SWEDEN), A. Bogdanoff, S. Niemi (Rautaruukki OY, FINLAND)</td>
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<tr>
<td>11:40-</td>
<td><strong>A Determination of the Total Roll Separating Force During Rolling Bimetal Rods in Grooves</strong> S. Mroz, A. Milenin, H. Dyja (Częstochowa University of Technology, POLAND)</td>
</tr>
<tr>
<td>12:00-</td>
<td><strong>Production of a new type of block-tram rail for European Union at Krolewska Steelworks Ltd.</strong> K. Kolodziej (Z.U.I. &quot;PRECISON ROLLING&quot;, POLAND), Z. Bigaj, R. Korzekwa (Królewska Steelworks, Chorzow, POLAND)</td>
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<tr>
<td>12:20-</td>
<td><strong>The Influence of Tool Geometry on the CWR Process of Hollowed Shafts</strong> J. Bartnicki, Z. Pater (Technical University of Lublin, POLAND)</td>
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Conference program.
### Conference Program

**ROOM A**

**ROLLING**
Chairman: Wolfgang Rasp

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<tr>
<th>Time</th>
<th>Title</th>
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<tr>
<td>14:30</td>
<td>Width Variation and Shape Attenuation in Hot Strip Rolling</td>
<td>A. Dixon, W.Y.D. Yuen (BlueScope Steel Research, Port Kembla, AUSTRALIA)</td>
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<tr>
<td>14:30</td>
<td>Minor Cyclic Deformation of AlMg0.45 Aluminium Alloy</td>
<td>Z. Gronostajski, N. Misiolek (Politechnika Wrocławska, Wrocław, POLAND)</td>
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<tr>
<td>14:45</td>
<td>Investigation of Hot Rolling Process Using Longitudinal Slitting Passes</td>
<td>S. Turczyn (Akademia Górniczo-Hutnicza, Kraków, POLAND)</td>
</tr>
<tr>
<td>15:00</td>
<td>Numerical Modeling of Stock Stability in the Roll Grooves during Shape Rolling</td>
<td>S. Mróz, A. Milenin, H. Dyja (Częstochowa University of Technology, POLAND)</td>
</tr>
<tr>
<td>15:15</td>
<td>Hot ductility of low C-Mn-B steel under continuous casting simulation conditions for metal forming applications</td>
<td>A.K. Lis, N. Piwek, J. Lis, H. Dyja, M. Knapiński, J. Markowski (Technical University of Częstochowa, POLAND)</td>
</tr>
<tr>
<td>15:30</td>
<td>Simulation of multipass hot rolling of AA 6082 aluminium alloy</td>
<td>C. Bruni, M. El-Mehtedi, A. Forcellese, F. Gabrielli, M. Simoncini (Polytechnic University of Marche, Ancona, ITALY)</td>
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**ROOM B**

**MATERIAL PROPERTIES – Resistance to deformation**
Chairman: Kazunari Yoshida

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<th>Time</th>
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<tr>
<td>14:30</td>
<td>Minor Cyclic Deformation of AlMg0.45 Aluminium Alloy</td>
<td>Z. Gronostajski, N. Misiolek (Politechnika Wrocławska, Wrocław, POLAND)</td>
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<tr>
<td>15:00</td>
<td>Comparison of the mechanical response of HSLA steel deformed under static and dynamic loading conditions</td>
<td>K. Muszka, J. Majta, T. Sleboda, M. Stefania-Kadziela (Akademia Górniczo-Hutnicza, Kraków, POLAND)</td>
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<tr>
<td>15:15</td>
<td>Electromagnetic Microforming of Metal Foil</td>
<td>I. Aoki, M. Sasada (Kanagawa University, JAPAN)</td>
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**ROOM C**

**SPECIAL FORMING PROCESSES**
Chairman: Pavel Petrov

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<th>Time</th>
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<tr>
<td>14:30</td>
<td>Die-less Forming Strategies for Non-Rotational Symmetrical Shapes</td>
<td>S. Jadhav, R. Goebel, W. Homberg, M. Kleiner (University of Dortmund, GERMANY)</td>
</tr>
<tr>
<td>15:00</td>
<td>Initial Optimization of Self-Piercing Riveting Process by Means of FEM</td>
<td>R. Cacko, P. Czyzewski, A. Kocańda (Warsaw University of Technology, POLAND)</td>
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**13:00-14:30 LUNCH**

**14:30-15:00 ROOM A**

**15:00-16:05 CLOSING OF THE CONFERENCE – ROOM A**
THURSDAY, SEPTEMBER 23

10:00-12:00 VISIT TO THE FACULTY OF METALLURGY & MATERIALS SCIENCE AGH

(Meeting in front of the Building B4 at 10:00)
Real Metal Forming and Virtual Reality
R. Kopp, O. Hofmann, V. Honnet, C. Plociennik

More and more computer technology is implemented even in the metal forming processes. Not only the construction departments or the programming of the machines work with the aid of computers. Nearly every process step is computer aided. Up to now, the single steps work with their own systems or programming, so that the use of calculated results in the next step is not possible in one tool. A solution to cope this problem is an relatively new tool, the Virtual Reality.

Virtual Reality is a tool, that is being utilized more often in the industry. Above all, the automotive industry, as well as the aerospace sector, apply this technology productively for their development processes. It offers the possibility to show a three dimensional model of an entire complex plant. Combined with results of logistic simulations, the model can be animated to show the production process. To accomplish this combination of calculations at several accuracy levels a hierarchical structure was developed by the project partners. At selectable parts it is possible to go deeper into the process (vertical) and to integrate the above mentioned single process step calculations (horizontal). This horizontal and vertical enlargement of the simulation finally leads to an overall description of the production process of a product.

The present manuscript at first describes the new medium Virtual Reality. It presents the first steps made at the IBF with this tool. The development up to the now reached state is presented, demonstrating the representation of complex production facilities in different visualization levels. The hierarchical model matrix with the interfaces is presented. A short outlook on the future and the aim of the current project as well as a view on following project end this presentation.

Quality Optimization of Steel Products in Continuous Casting Process Using Numerical Optimization and Soft Reduction
E. Laitinen, J. Pieskkä, I. Rentola, V. Toivonen

This paper considers quality improvement of steel slabs in continuous casting process. Firstly, the paper presents a 3D-model for simulation and dynamic control for the secondary cooling of continuous casting process. The control of secondary cooling has a considerable influence on the quality of the final product. Secondly, the paper shows that properly adjusted soft reduction reduces the centre-line segregation of microalloyed steel grades. The simulation results presented in this paper are verified with industrial measurements and the reduction of centre-line segregation is shown using macroetched slab samples.

Extrusion of magnesium alloy profiles
P. Skubisz, J. Slińczak, A. Łukaszek-Sołek

The paper presents results of experimental and numerical analysis of the extrusion process of solid and hollow shapes of a high-strength wrought magnesium alloys. Experimental part was carried out for various temperatures and strain rates with unchanged other variables of the extrusion process. A strong effect of temperature and extrusion speed on load was observed. The results of experiments have been compared to the results of a computer simulation. On the strength of the comparison of numerically estimated and experimental results, correctness of boundary conditions and material characteristics assumed in the analysis has been concluded. Metallographic researches of metallurgical structure of the extruded material for selected regions of extruded cross-sections were carried out to estimate effect of effective strain on grain size.

A study of the thermo-mechanical response of a die face pressure sensor for hot aluminium extrusion
P. T. Moe, W. Wajda, S. Støren

Die face pressures up to 500 MPa may cause large elastic and even plastic deformations of the tool stack during aluminium extrusion. As a result, both the die outlet and the profile shape may be significantly distorted. In the extreme case also the stability of the flow is affected, so that the profile may buckle or curve. Particularly when extruding thin-walled sections it is essential to control the outlet shape by careful die design, by introducing self-compensating mechanisms or by measuring shape or other essential parameters and correcting, preferably on-line. In order to establish a better understanding of extrusion and to improve control, it is important to study all relevant physical responses of the process. The article presents a pressure sensor that may be used to assess the pressure distribution on the die face and potentially also the stress distribution in the profile. It uses the capacitive principle for distance measurement to determine the elastic deformation of a disc in contact with the aluminium billet. The 2.75 mm thick sensor disc is an integral part of the extrusion die. The study focuses on the thermo-mechanical response of the sensor during extrusion. The disc deflection is approx 30 µm, and the linearity of the capacitive sensor is approx 1 µm. An in-situ calibration technique makes it feasible to measure pressure to an accuracy of approx ± 5 %. The most significant effect that is not captured by the calibration technique is the thermo-mechanical response of the sensor when it is heated during extrusion. One has found that thermal expansion may cause deviation in maximum response of approximately 10 %. At the same time, however, a reduction in the elastic modulus and changes in capacitance of the system due to the temperature increase, counteract the thermal expansion effect. A simple method of temperature compensation is presented as well as a rod extrusion case study of pressure measurement.
Numerical sensitivity study to determine the effects on transverse welds in direct extrusion of AlMgSi – Alloys

T. Hatzenbichler, B. Buchmayr, A. Umgeher

Billet-to-billet-extrusion of aluminium alloys is one of the most economic manufacturing processes in making semi-finished products. The mating surfaces of the billets pressed together are always oxidized and the sheared face is often contaminated with stray lubricant. Due to this the transverse welds usually show discontinuities in the final product. In structural sections, where product integrity is very important and the discontinuity associated with a line of contaminants in the transverse weld is not acceptable, the length of extrusion containing the weld line must be scrapped. Hence, the productivity of billet-to-billet-extrusion depends significantly on the length of the internal defect. Its length is a function of different process parameters like friction, initial temperature of the billet and the tools, tool geometry and geometry of the extruded section. The aim of this work is to determine the most important parameters influencing the length of the transverse weld defect in the extruded section by a numerical FE-study. In the present investigation the commercial finite element code Deform™, based on a Lagrangian formulation with automatic remeshing, is used. Verification of the simulation is done by metallographic studies. The simulations show a strong influence of the tool geometry, especially of the pre-chamber design on the length of the transverse weld defect in the extruded section. Furthermore, the friction between the face surfaces of the two billets pressed together has an influence on the prescribed defect while other process parameters like temperature, ram speed or bearing length have a neglectable effect. The work shows that it is possible to reduce the scrap of the extrusion process by proper tool geometry.

Development of Direct Extrusion Process for Al Multi-Cell Tube using Porthole Die

J. M. Lee, B. M. Kim, H. H. Jo, C. G. Kang

This paper describes a 3D FEM simulation of the porthole die extrusion process for producing multi-cell tubes that are used in the cooling systems of automobiles. The multi-cell tube is mainly manufactured by the conform extrusion method, but this process is less effective than the direct extrusion method in productivity per unit time and in the equipment investment. Therefore the conversion to the direct extrusion using a porthole die that can produce multi-cell tube competitive in costs and qualities is essential. At present, an experimental method to quantify the deformation behavior of the porthole die for multi-cell tube extrusion has yet to be devised, due to the porthole die’s complicated assembly and the complexity of metal flow. In this regards, FEM is a good alternative in evaluating the three-dimensional deformation behavior of metals in multi-cell tube extrusion with the porthole die. Especially, an understanding of metal flow in porthole die extrusion is important, because it provides necessary information for die design in high-performance extrusion. This study was conducted to evaluate material flow, welding pressure, and extrusion load in multi-cell tube extrusion with the porthole die using an FE analysis under non-steady state conditions. Also, experimentation on extrusion was performed to verify the efficiency of the analytical results for multi-cell tube extrusion with the porthole die.

Development of Extrusion Process and Die Design for Al Speaker Body

B. M. Kim, J. M. Lee, H. H. Jo, C. G. Kang

Speaker bodies with hollow sections and high complexities are generally using aluminium due to its high strength, light weight characteristics and easy production of complicated shapes, and they are manufactured by extrusion process using porthole die. At present, the design of extrusion dies and operation in extrusion companies are primarily based on trial and error. The experience of the die designer, the press operator and the die corrector determine the performance of the extrusion die and the efficiency of the process. In order to produce defect-free products of desirable quality in terms of strength, surface quality and geometrical dimensions, it is important to obtain more knowledge of the processes that occur during extrusion. Recently, to reduce the costs of designing and manufacturing of extrusion dies, and to ensure the quality of the extruded products, numerical simulation for extrusion processes such as FEM (finite element method) is applied increasingly and becomes a very important tool for the design and development of new products. However, most of the studies about FE simulation have been accomplished for simple geometry and low extrusion ratio in the filed of steady metal flow conditions. The extruded products of Al alloy in industrial practice involve complicated sectional geometry. Therefore, this study was designed to produce a part of speaker body has been produced in industrial practice, including extrusion die design, inspection of die design through the results of FE simulation and performance of trial extrusion. Estimation was carried out using FEM in the field for non-steady metal flow condition.
**Development of Direct Drive Digital Servo Press**

C. Murata, T. Machida, S. Futamura, J. Endou

Generally, in press forming, an eccentric load will occur in the left, right and front, rear directions. This eccentric load will deteriorate the parallelism between the bolster and slide and degrade the accuracy of the product and die. The authors have developed a 4-point loaded digital servo press equipped with a real time control system, which controls the slide parallel during eccentric load forming. The independently controllable 4-point loaded mechanism comprises of high precision ball screws, linear scales having a resolution of 1 µm, and high response AC servomotors. The authors have also developed software to control the system. This software was capable of controlling the slide instantaneously to its correct path at breakthrough during blanking.

The authors have set an actual die for blanking in an eccentric position. The blanking load increases rapidly at the instant the die touches the material - about 20 ms. The slide behavior without the parallel control is such that at the start of the process, the four lines, the displacements at four corners, go out of order but the four lines will coincide during parallel movement of the slide. This disorder is a displacement due to the eccentric load and the maximum tilt of the slide is 0.0002 radian. With the newly developed control system the disorder of displacements at four corners is reduced and inclination is 0.00005 radian, which proves that the effect of this control system is improved by four times compared to the press without this control system.

Thus, we were able to develop a high precision, digital servo press capable of controlling the slide parallelism within 50 µm during eccentric load.

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**High Resolution Measurement of Large Strain with Fourier Phase Correlation Method by Image Sensing Camera**

T. Sawada, M. Sakamoto

The Fourier phase correlation method is applied to the optical measurement of large strain in the specimen in tension on which circular marks are printed. It is effective for detecting the marks under dark illumination without many processes of the images, compared with the method transformed into binary code; flattening illumination, boundary enhancement and so on. In addition, the new method of moving the reference image to position the observed mark with high resolution is proposed. It can detect the observed marks within the range of ±0.1 pixel (standard deviation=0.042 pixel), by which the strain can be derived. The strain of the tensile specimen can be measured within the error of strain 0.0027 (standard deviation=0.0015, gage length=12.0mm), so that non-uniform deformation such as diffused necking is clearly measured.

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**Measuring of the Curvature Distribution of Bent Profiles**

U. Dirksen, S. Chatt, M. Kleiner

The demands on the quality of bent profiles are high and still increasing. Especially the curvature of the bent profile has to meet close tolerances if profiles are used as semi-finished products in process chains which are highly automated. To meet the high demands on the profile curvature and to keep down the manufacturing costs, the application of closed-loop controls is mandatory. At the Chair of Forming Technology the research of a closed-loop control for the three-roll bending process using methods of the Computational-Intelligence is still in progress. Part of the research is the development of a curvature sensor which measures the bending line and the unloaded radius of the profile during the bending process. Therefore, constant radii and radii distributions have to be determined. For the bending line, it is also important to know the periodic changes.

The concept of the curvature sensor is based on three laser triangulation sensors which move relatively along the profile contour while the profile is bent in the three-roll-bending machine. Due to the faster motion of the laser sensors in comparison to the profile motion the profile contour is measured as large quantity of basic points. Out of these basic points a constant radius or a radii distribution can be computed.

The paper describes the working environment and the requirements on the profile curvature sensor. Afterwards, the concept of the sensor and its components are presented. A discussion of first experimental results closes the presentation of the profile curvature sensor.
Measuring and Calculating Flatness During Hot-Coiling
A. Nilsson, J. Jokisaari, Å. Stenström

Today it is quite well known how to control the flatness in the rolling mill but the knowledge on what happens during cooling and coiling are limited. The main aim with this project has been to increase the knowledge in this area.

Full-scale plant trials were performed in the Steckel mill at Outokumpu Stainless AB in Avesta, Sweden and in Rautaruukki’s hot strip mill in Raahé, Finland. The aim with the trials were to study how the strip flatness is influenced by strip dimensions, target profile, cooling intensity and coiling tension in the hot-strip mill. The evaluation of the trials in the Steckel mill showed that the two parameters that possible could be used for adjustments; the cooling and the coiling tension affect the flatness trough interacting terms. Cooling is significant as a linear term but it also interacts with the thickness and the width. Coiling tension is not significant as a linear term but it is in the interaction with the thickness and the strip profile. The obtained statistical flatness model contained several interacting terms. From the results it was seen that a low profile-target gave worse flatness especially for the thin strips and that for a low profile target a high strip tension was favourable. Cooling had a larger impact on wide strips.

The campaign run at the Rautaruukki mill, on carbon steel, had the main aim to study the influence of coiling tension on the flatness of the uncoiled cold strip. In the tests the coiling tension was varied +/- 10%, for some strips. The trials were in line with the results from the Steckel mill showing that coiling tension did not have significant influence by itself. The reason is that the tension mainly interacts with the strip profile. The trials, however, showed that the coiling process did change the flatness of the strip. The flatness after the last finishing stand showed slightly longer edges, whereas the flatness at the pickling line showed a longer strip centre (after uncoiling). The coiling/cooling had consequently changed the flatness from long edges to long centre.

To study the process in more detail FE-simulations on one of the test strips were run. The coiling tension and shape of the lower pinch roll was varied in the simulation. The result shows that the pinch roll shape influence the flatness of the strip. In the simulation a higher strip tension in combination with a narrow cylindrical part of the pinch roll can change edge waves into centre buckles.

Validation of the forward-backward extrusion test, designed for evaluation of friction coefficient and flow properties of metal alloys deformed in semi-solid state
A. Żmudzki, M. Papaj, R. Kuziak, J. Kusiak, M. Pietrzyk

The reliable material model is necessary for the accurate computer simulation of the deformation processes. Evaluation of flow stress of materials undergoing the deformation is the prime objective of the plastometric tests, such as tension, torsion and compression. These tests are not adequate in the case of the deformation of semi-solid materials. Therefore, the main objective of the present work is the validation of the new test designed for evaluation of material properties of metal alloys deformed in mushy state. It is the continuation of authors’ earlier research on design of the optimal tool shape for material testing. The proposed new test supplies information regarding both rheological and friction models of metal alloys and the measured data can be directly used in the inverse analysis of the deformation processes. Illustration of the investigated die, which involves both forward and backward extrusion, is shown in the paper. The comparison between FEM simulations and experimental results for extrusion tests and ring compression tests is demonstrated. The proposition of extension to 3D non-axisymetrical test, as well as the sensitivity analysis and FEM simulations of this test are also presented.

Numerical Modeling of Thermomechanical Processes During Continues Casting of Steel LH15SG for Shape Rolling
A. Milenin, H. Dyja

Paper deals with problems of crystallization, uprisign and development of thermal stresses as well as bending and unbending of bloom in continues casting machine. To obtain numeric solution the finite element method is used. The mathematical model of thermal stress development in the billet during the continues casting process which takes into account the processes of crystallization, thermal volume changes and phase transformation in the viscoplastic rheological formulation for the steel in the high temperature is developed. The problem is solved in three-dimensional formulation. Constructive features of continues casting machine is taken into account, namely location and parameters of rolls, spray nozzles and cristallizator. It is shown an example of casting process for 300x400 mm blooms of LH15SG steel. The results of dilatometric and plastometric tests as well as results of temperature, strain and stresses modelling during casting process are presented in the paper.
Mechanics of slab edging with friction consideration
Z. Y. Jiang, X. M. Zhang, W. Sun, A. K. Tieu

In this paper, the authors discuss the utilisation of the slightly compressible finite element formulation to the analysis and simulation of the vertical-horizontal rolling process, employing a variable friction model. Programming was performed on computer and the dog-bone shape of the slab, roll separating force and rolling torque for slab edging are obtained. Simulation results show that when the variable friction model is considered, the computed results are in good agreement with the experimental values. Horizontal rolling process of the dog-bone shape produced from the slab edging is also simulated. The width variation of the slab, rolling force and torque are discussed and compared with the measured values obtained from experiments in the laboratory. Simulation and experiments validate that the developed numerical models are efficient and stable.

Effect of Rolling Condition on Mill Load and Oxide Scale Deformation in Hot Steel Rolling
W. Sun, A. K. Tieu, Z. Jiang

A scale layer is always formed on the strip surface during the hot steel processing. In this paper, hot steel rolling experiments have been carried out to investigate the effect of rolling parameters on scale rolling loads and deformation behaviour of oxide. Results show that lubrication reduces both roll separating force and roll torque even though the oil was burnt in the experiments. The heavier the reduction, the more significant the reduction of mill loads. Rolling speed influences mill load insignificantly under either dry or lubricated rolling condition. In the present work, both primary and secondary oxide scales are generally assumed to be plastic at the test temperatures. Although the scale deformed in a linear-like elastic/plastic manner at different reduction with the bulk materials, rolling speeds have an opposite effects to reduction on the scale thickness for most cases. Temperature plays an important role on the scale deformation behaviour while the effect of lubrication on oxide scale deformation varies when rolling temperature changes.

Shear Texture Control of Aluminum and Low Carbon Steel Sheets by Differential Speed Rolling
T. Sakai, K. Yoneda, K. Yoneme

In the present study, large shear deformation was successfully introduced throughout the thickness of commercially pure aluminum sheets and low carbon steel sheets by differential speed rolling. A 2-pass differential speed rolling was employed for introducing unidirectional shear strain almost uniform through the thickness. The rolling direction of the second pass was so selected that the direction of shear deformation introduced in the second pass is similar to that in the first pass. The effect of roll speed ratio on the variation of shear strain through the thickness of rolled sheet was investigated. Both in aluminum alloy and low carbon steel sheets, shear strain introduced by differential speed rolling increased with roll speed ratio.

In low carbon steel sheet, the shear texture of which main components are \{110\}\{001\} (Goss orientation) and \{112\}\{111\} developed throughout the thickness and conventional rolling texture such as \(\alpha\)-fiber or \(\gamma\)-fiber did not evolve even in the center of thickness. After recrystallization annealing, Goss orientation remained while \{112\}\{111\} orientation became weak. The recrystallized grain size was 3\(\mu\)m. A steel sheet having through-thickness Goss texture with small grain size was fabricated by 2-pass differential speed rolling followed by primary recrystallization.

In aluminum sheet, shear texture of which main components are \{111\}\{110\}, \{112\}\{110\} and \{001\}\{110\} prevailed throughout the thickness, and conventional rolling texture could not be detected. After recrystallization, shear texture became broad and almost random texture prevailed. The average r-value of recrystallized sheet was about 0.8 that is higher than that of the sheet fabricated by conventional rolling and annealing. The \(\Delta r\), which is the measure of planar anisotropy, was about -0.13 that is also superior to the sheet by conventional process.

Both in aluminum alloy and low carbon steel sheets, the shear texture components developed by differential speed rolling remained after recrystallization annealing, which makes the differential speed rolling useful for texture control. The differential speed rolling, by which shear deformation can be introduced throughout the thickness, is proved to be promising process for improving physical and mechanical properties of the rolled and annealed sheet through texture control and grain refinement.

Mechanical and Metallurgical Properties of Hot Rolling Ti-6Al-4V Sheets
J. Mei, M. Lovell, F. Pettit

The mechanical, chemical and metallurgical properties of intermediate and final Ti-6Al-4V sheets were analyzed to ascertain the affects of the hot rolling process on titanium alloys. Utilizing standard hardness and tensile testing procedures, the mechanical properties for intermediate ground, intermediate unfinished, and final Ti-6Al-4V alloy alloys were evaluated. After conducting metallurgical studies on the samples, the variation in material properties at each stage of the production process were found to be directly related to changes in the microstructure of the Ti-6Al-4V material. Since the existing techniques for producing Ti-6Al-4V sheet are labor and cost intensive, the experimental results were then analyzed and discussed with respect to the developing a new titanium production process that attain higher yield and improved product quality.
A numerical tool for formability analysis of aluminium alloys.
Part I: Theory.
O.- G. Lademo, T. Berstad, O. S. Hopperstad, K. O. Pedersen

This paper presents how the process of loss of stability, as described by the classical theory of Marciniak and Kuczynski (1967), can be represented in non-linear finite element analyses with LS-DYNA. As will be seen, loss of stability is strongly dependent upon proper constitutive equations and parameters for the sheet material at hand. Of this reason two user-defined sub-routines for weakly and strongly textured aluminium alloys, respectively, have been implemented. Further, a non-local instability criterion has been implemented in order to detect incipient plastic instability. In further analogy to the work of Marciniak and Kuczynski some inhomogeneity must be introduced either to the material properties or to the thickness. In order to perform the calculations in an efficient way, an automated procedure – called an FLD-calculator – has been created. In this paper, the FEM-based calculations are compared with analytical calculations based on the MK-theory, while a comparison with experimental results are to be given in Part II of this work. There is a fair agreement between the FEM-based and analytical FLD-calculations, as a strong influence of the yield surface is predicted in both cases. The advantage of the analytic approach is that it is very efficient compared to the FEM-based modelling technology, on the other hand, using FEM, physical inhomogeneity of any kind and general constitutive models can straightforwardly be represented.

A numerical tool for formability analysis of aluminium alloys.
Part II: Experimental validation.
O.- G. Lademo, K. O. Pedersen, T. Berstad, O. S. Hopperstad

In Part I of this work a numerical tool for calculation of Forming Limit Diagrams (FLDs), called an FLD calculator, has been developed for use with LS-DYNA. In this automated tool, a square patch of shell elements is considered, in which the element thickness varies randomly according to a Gaussian distribution. The patch is then subjected to a set of proportional strain paths and in analogy to the classical Marciniak-Kuczynski theory (1967), localization is assumed to occur when the local to the non-local thickness strain increment ratio becomes 'large'. The FLD calculator further relies upon two user-defined constitutive sub-routines for weakly and strongly textured materials, respectively. The main ingredients of these elasto-viscoplastic constitutive models are an anisotropic yield criterion, the associated flow rule, non-linear isotropic hardening and two ductile fracture criteria. For weakly textured materials the yield criterion of Barlat and Lian (1989) is adopted while the criterion of Barlat et al. (1997) is used for strongly textured materials. In the current work, the parameters of these models are identified using uniaxial tensile test results and, for the strong texture model, a through-thickness compression test. The total modelling approach, ranging from the material model assumptions and parameter identification tests and procedures, to inhomogeneity representation and detection of the instability is being validated based upon experimentally determined FLDs for several aluminium alloys.

Application of ductile fracture criteria to prediction of forming limit of high-strength steel sheets
H. Takuda, T. Kanie, E. Isogai, T. Yoshida

The possibility of the application of some criteria for ductile fracture to the prediction of forming limit of high-strength sheets is examined in this study. The forming limits of a few types of high-strength steel sheets under various strain paths from balanced biaxial stretching to uniaxial tension are examined by the in-plane biaxial stretching test. They are compared with those derived from the ductile fracture criteria. It is found from the comparison that the criterion proposed by Cockcroft and Latham gives the best fit to the experimental results. Then, the criterion is applied to the prediction of the forming limit in deep drawing processes. The criterion is combined with the finite element simulation of the sheet forming processes. From the distributions and the histories of stress and strain calculated by the finite element simulation the critical punch stroke and the fracture initiation site are predicted by means of the ductile fracture criterion. The comparison between the numerical and experimental results demonstrates that the criterion by Cockcroft and Latham is applicable to the prediction of forming limit of the high-strength steel sheets.
The Influence of Interlayer Thickness and Properties on Springback of SPS- (Steel/Polymer/Steel) Laminates
M. Weiss, B. Rolfe, M. Dingle

Laminated steel sheets sandwiched with a polymer core are being increasingly used for automobile applications. They have high weight-specific rigidity and good sound damping behaviour. However, Steel/Polymer/Steel (SPS) laminates have decreased formability and their forming behaviour as a function of the interlayer thickness is not well understood. The simulation of the forming behaviour of SPS laminates in sheet metal forming processes with FEA methods is difficult due to the extremely large differences in mechanical properties of the polymer core and the steel cover sheets.

This work studies the forming behaviour of SPS laminates in bending under tension using a draw-bending test. The influence of the interlayer thickness and the interlayer properties on the springback behaviour of SPS laminates is analysed. The test results show that the wall springback decreases for SPS laminates as the strength of the core material decreases and the thickness of the interlayer increases.

The bending process of the SPS laminates has been simulated by an incremental elasto-plastic finite-element method under the plane strain condition using the commercial FEM code ABAQUS. The calculated sheet geometries agree reasonably well with the corresponding experimental results.

Identifying the material parameters of a combined isotropic and non-linear kinematic hardening model for AISI 304 stainless steel sheet
T. Manninen, A. S. Korhonen, P. Aspegren, T. Taulavuori

An experimental test procedure and a numerical identification technique are proposed for identifying the material parameters governing the combined isotropic and non-linear kinematic hardening behaviour of anisotropic sheet metals. The proposed method has several advantages. The method is not limited to small strains, all the required tests can be carried out using a standard tensile testing machine and it is applicable also to very thin precision strip samples. The proposed method is applied to AISI 304-type stainless steel sheet and constitutive parameters describing the texture-induced anisotropy and combined isotropic and non-linear kinematic hardening behaviour are identified for the test material. The results confirm that this kind of austenitic stainless steel shows a considerable Bauschinger effect. Our identification results also suggest that, contrary to a common assumption, the initial values of one of the back-stress tensors are not zero in the as-received state.

Problems and benefits of deformation in the two-phase region: metal forming application
A. Bator, J. Majta, A. K. Zurek

The use of deformation in the two-phase region is widespread but several problems, as for example distribution of the strain and interaction between coexisted $\gamma$- $\alpha$ two phases are not completely understood. The phenomena of deformation in non-stable conditions are discussed in present work in various directions. Metal forming processes in the intercritical region cause an increase in loading requirement, inhomogeneity of strain distribution and microstructure. However, the improved workability because of newly formed, ductile ferrite allows to apply high strain rate to the forming process. This significantly affects the structure morphology as well as volume fraction of microstructure components for a given chemical composition of steel. C-Mn, high strength microalloyed and TRIP-aided steels were studied from a microstructural point of view in order to clarify the relationship between the microstructure evolution, flow stress and properties of final product. The effect of deformation conditions with strain rates ranging from 0.01 to 2500 s$^{-1}$ and finish deformation temperatures from austenite to austenite-ferrite region were investigated. The results indicate that both flow stress and microstructure development are clearly sensitive to deformation conditions in the austenite/ferrite region.
Prediction of distortion during cooling of steel rolled rings using thermal-mechanical-metallurgical finite element model

F. Pascon, G. Blès, C. Bouffioux, S. Casotto, S. Bruschi, A. M. Habraken

This work takes place in the framework of a CRAFT European project gathering three universities, three companies who produce rings through the ring rolling process and a manufacturer of temperature and dimension measurement devices. The final goal of the project is to develop and set up a system, integrated in the industrial process, capable of predicting the geometrical characteristics of final pieces just after the ring rolling stage and to allow the rolling process to avoid dimensional defects through online adaption. In fact, ring rolling production does not imply only the rolling process, but also the cooling and quench stages of steel rings. During all these phases, the dimensions of the pieces change dramatically. In particular, due to the lack of symmetry in the cooling conditions, ring distortions include contraction and rotation of the ring section. The modeling of the cooling phase requires taking into account a large number of phenomena resulting from the coupling of thermal, mechanical and metallurgical effects. A numerical model has been implemented in the non-linear finite element code LAGAMINE, developed by the University of Liège. Such a model can help to better understand the evolution of the geometry during the cooling phase and also the effects of each physical and microstructural parameter implemented in the model on the ring final shape. Effectively, several parameters can affect the ring distortions and the model should take them into account; in particular, the mechanical and thermal behavior of each phase present in the material (metastable austenite, ferrite, pearlite, bainite and martensite). Phase transformation modeling implies the integration of a wide data base of material properties (thermo-physical and mechanical properties of the phases, TTT and CCT diagrams, enthalpy and strain of phase transformation, strain of transformation plasticity...) but only a few of these data are available in literature. Some of them have been found for the reference material (42CrMo4 steel), but additional laboratory experiments have been performed at the Universities of Padua and Liège in order to characterize thermal, mechanical and plastic behaviour of phases. Finally, this paper presents the model validation on an industrial case (measurements of temperature and dimensions of rings have been provided by the manufacturer). Then, some applications are presented, demonstrating the importance of some factors such as some material properties, the shape of the rings, the type of cooling (and the cooling rate) or the symmetry of the cooling scheme on final ring distortion.

Development of the Constitutive Law for Microalloyed Steels Deformed in the Two-Phase Range of Temperatures

M. Pietrzyk, R. Kuziak

The objective of the present work is development of the constitutive model for microalloyed steels deformed in the two-phase region and identification of parameters of this model. This objective is reached in two steps. Dilatometric tests for steel containing an addition of niobium were performed first and parameters of the phase transformation model for this steel were determined. The phase transformation model was implemented into the thermal-mechanical FEM code for simulation of hot deformation processes. The second step included the plastometric tests, which were performed for the investigated steel in the temperature range between 550 and 1100°C. The coefficients in the flow stress model were evaluated by performing the inverse analysis of the stress – strain curves determined in the course of plastometric tests. The flow stress models were developed independently for austenite and ferrite phases. These models were combined to give the weighted average flow stress of austenite and ferrite mixture for flow stress calculation in the two-phase range of temperatures. The results of the loads predictions during compression of samples in the two-phase region were compared with the experimental data obtained from the Gleeble 3800 simulator. Good predictive capability of the model was demonstrated.

Mushy State Forging of Aluminum Alloy Using Resistance Heating

S. Maki, T. Shibata, K. Mori, H. Makino

In the mushy state forging using resistance heating devised with elimination of handling of a mushy-state billet in view and characterized by insertion of heat resistant SUS304 steel layers as thermal barriers between the billet and the copper electrodes, application of some amount of force to the electrodes is essential to insure their electric contacts with the billet with interposition of the layers. This applied force is desired to be set as weak as possible in order to realize homogeneous billet heating. However, when the force is too weak, spark breaks out in the resistance heating. Then, in this study, firstly, the requirement of the applied force for preventing spark occurrence was experimentally investigated using A357 aluminum alloy and a lower limit of the applied force was clarified as a critical contact pressure as a function of the electric current density. Secondly, in order to realize homogeneous billet heating, temperature distribution in the billet during resistance heating was calculated using an FEM, and it was found that fairly homogeneous billet heating can be realized by proper choice of the thickness of the layers and that an optimum thickness of the layers depends on both the contact pressure and the electric current density involved. Based on these findings, experimental mushy-state forging of the aluminum alloy was conducted and referring to the results a desirable operational condition of the mushy-state forging was discussed including resistance heating of the billet.
A New Coupled Approach Between a Micromechanical and a Phenomenological Modelling of the Strain Induced Martensite Transformation Kinetics in a 304 Austenitic Stainless Steel (Trip Steels)
Z. Tourki, K. Sai

The kinetic of martensitic transformation induced by plastic deformation, the microstructural characteristics and the hardening behaviour of the AISI 304 stainless steel were experimentally studied. The aim of this work consists in the modelling of the uniaxial behaviour using a crystallographic approach combined with a phenomenological model 2M2C (two criteria and two mechanisms). A good correlation between experimental kinetics in uniaxial tension and the present 2M2C model was found.

Thermomechanical processing and properties of P/M FeAl alloy
T. Śleboda, J. Kane, R. N. Wright, N. S. Stoloff, D. J. Duquette

The present study is focused on the thermomechanical processing of Fe-40Al alloy powder. The influence of powder particle characteristics on the properties of processed materials was investigated. Water atomized Fe-40Al powder was used for this research. As-received Fe-40Al powder was ball-milled in a high-energy SPEX 8000 mill resulting in significant powder particle size reduction. Both as-received and ball-milled powders were consolidated to full density by hot isostatic pressing at relatively low pressures. Consolidated P/M Fe-40Al samples were tested in compression on a Gleeble thermomechanical simulator in the temperature range of 700-1100°C at a strain rate of 0.1s⁻¹. Differences in the flow-stress curves of the compressed materials are discussed both with respect to differences in starting grain size as well as microstructural evolution during testing. It was found that differences in powder particle size and shape significantly affected the grain size and morphology of the HIPed products that were subsequently used as starting materials for hot compression tests. These differences substantially influenced the mechanical behavior and microstructural evolution during subsequent Gleeble processing. As the result of an optimal thermomechanical treatment, an ultra-fine grained iron aluminide was obtained. Room temperature compression tests revealed that grain refinement also influenced the mechanical properties of the investigated material under ambient conditions.

The Effects of Nb and Mo Additions on the Microstructure and Formability of C-Mn-Si-Al TRIP-Aided Ferrous Sheet Steels with an Annealed Martensite Matrix
K. Sugimoto, T. Hojo, A. Nagasaka, S. Hashimoto, S. Ikeda

The effects of Nb and Mo addition on the microstructure and ductility of 0.2C-1.5Mn-Si-Al TRIP-aided steels with an annealed martensite matrix were investigated for automotive applications. Nb additions up to 0.02mass% refined the prior-austenite grain size and the annealed martensite lath size and changed retained austenite from interlath to a block morphology. Also, Nb and Mo complex additions considerably increased the tensile strength of the TRIP-aided steels due to precipitation of fine NbMoC, keeping a good strength-ductility balance, particularly when austempered at temperatures above 450°C. An interesting result was obtained that excellent stretch-formability and stretch-flangeability were achieved in the TRIP-aided steels austempered at 450-475°C because a large amount of stable austenite was maintained. This may realize in-line galvanizing or galvannealing for the TRIP steels.

Selected Properties of Ni-Al Materials after Hot Forging of PM Preforms
S. Szczepanik, K. Piątkowska

The paper concerns manufacturing of products from the mixtures of PM Ni-Al. Ni-Al alloys that are the basic materials used for constructive elements which are subjected to high temperatures. However, they have small formability, which is their major disadvantage in comparison to other superalloys. Hence, research aiming at manufacturing of Ni-Al alloys from PM preforms in the process of closed-die forging and hot extrusion has been undertaken. Manufacturing of Ni78 wt%-Al22 wt% by hot forging was examined. The compacts were manufactured from PM Ni and Al mixture of specified proportions. The influence of deformation at 500, 550, 600°C on the density and mechanical properties of forged parts after forging and annealing at 600°C in 2h was determined.

As the second forming process, extrusion of Ni-Al preform was examined. The influence of extrusion at 500°C with the ratio $\lambda = 13.32$ on the structure and hardness of the material was investigated. As a result of extrusion material with higher density was obtained. The structure of the obtained material depends on the forming route and parameters as well as on heat treatment. Material after annealing has lower plasticity and greater hardness than material after forging or extrusion. Metallographic tests and rontgen phase analysis show that the intermetallics NiAl, Ni$_2$Al$_3$ and Ni$_3$Al occur in the obtained material. As a result of this research, materials with intermetallic phases from elemental Ni and Al powder were obtained.
Application of the Control Theory Methods for Evaluation of Dislocation Model Parameters
D. Svyetlitchnyy

A method of optimal control applied to evaluation of parameters of the flow stress model, based on dislocation theory, is presented in the paper. Model parameters are defined from comparison of the calculated curve with the measured flow stress curve. The integral quadratic criterion is usually used to modeling of data. Integral dependence of the flow stress on dislocation model parameters leads to the application of the integration of ordinary differential equations and non-gradient methods of minimization. If the dislocation evolution model described by differential equations is considered as a state-space model, methods of the solution of this optimal control problem could be applied directly. The solution algorithm and selected example of parameters calculations are presented in the paper.

Determination of microscale deformation in hot worked steel
L. E. Hernandez-Castillo, J. H. Beynon, C. Pinna, S. van der Zwaag

A modified microgrid technique was applied to a model Fe-30wt%Ni alloy to simulate the local state of deformation of austenite before transformation, in high strength low alloy (HSLA) steels. The distortion of the microgrid after hot deformation revealed different deformation features which can be quantified by calculation and plotting of the strain distribution, derived from the displacements of the microgrid intersections. This strain distribution can be used to study the localisation of stored energy in austenitic deformed structures, which plays an important role in the subsequent transformation into ferrite.
Reducing the Process Chain for the Production of Gear Wheels by Precision Forging – Integration of Heat Treatment and Necessary Changes of the Process Management
F.-W. Bach, B. A. Behrens, H. Dähndel, M. Gummert, A. Huskic

The conventional process chain for the production of gear wheels demands many manufacturing steps. Typically this process chain consists of cutting, heating, forging and deburring. Following, the teeth and the bores of the gears are shaped in a machining process like milling, slotting or broaching. Afterwards, a heat treatment by case hardening is applied and the gears are finally finished by grinding. This process chain is often disrupted by buffer storage and transports.

Precision forging can significantly reduce this process chain because deburring and machining steps become unnecessary. Additional advantages can be gained, if the heat of the precision forging process is used for an integrated heat treatment. Moreover, specific component characteristics can be reached by integrating the heat treatment in connection with an adapted process technology. Hot formed parts are directly hardened by using the forging heat. A new solution for a homogenous cooling consisting of a two-phase nozzle array will be introduced. The application of this technique allows the hardening of particular component regions according to typical strain profiles of this component.

Due to the demands of material properties, an even allowance after the precision forging process has to be maintained. The allowance after the forging process depends on varying alloys and the geometry of the part as well as forging the forging and related heat changes. The往前 dependent to be corrected and the component correction. The new approach for the presented process chain with new tool concepts and an integrated heat treatment using the forging heat will solve many problems. Moreover, a dramatic change in the process management is necessary. But on the other hand it offers great potential for cost reduction.

In particular high-duty automotive components offer a wide application field for the precision forging technology. Advantages like shortened production cycles achieved by eliminating machining operations and saving of raw material contribute to the ongoing cost-saving trend in the automobile industry.

Numerical and experimental analysis of the closed-die forging of Aluminium spiders
M. L. Alves, J. M. C. Rodrigues, P. A. F. Martins

This paper presents a combined numerical and experimental investigation of the closed-die forging of Aluminium spiders. The numerical analysis was based on the utilization of the finite element flow formulation in conjunction with an updated Lagrangian description of motion. The finite element computer program I-FORM3 currently being developed by authors was utilized throughout the investigation. The experimental work was performed on reduced scale prototypes that were cold-forged under laboratory-controlled conditions. Observations and quantification of data by means of appropriate measurement and data acquisition techniques allowed the comparison and assessment of computer predictions with metal forming experiments for a wide range of process variables such as material flow, geometry, forging load and strain distribution. An overall good agreement was obtained between experimental results and numerical predictions.

Investigations on the Use of Damage Criteria under Semi-Hot Forging Conditions with FE-Methods
H. Just, A. Behrens

Damage criteria are a suitable method to describe the susceptibility of steels to ductile damage in forging operations. Recent research concentrates mainly on cold forging operations as their share in the market of forging operations outweighs semi-hot forging by far. Nevertheless semi-hot forging operations are sometimes damage prone as the following example of a journal bearing will demonstrate. Thus the intention of this article is to qualify a suitable damage model, the Model of Effective Stresses by Lemaitre, for the use under semi-hot conditions in finite element simulations. We use the forging simulation software MSC.SuperForm 2004 for this purpose. An experimental validation of the damage model will be done and as a side-effect some uncommon material behaviour of the different tested steels will be described. We use an upsetting with semi-hot collar specimen, known from cold forging. Within a very small temperature interval the forging of the specimen changes from damaged to undamaged state. The location of the crossover temperature interval varies with the material used, without a direct explanation whether from chemical composition or microstructure. Finite Element Simulations serve for the validation of the chosen damage model and for the description of the thermal crossover behaviour of the different materials. The damage model shows good accordance with the experimentally derived fracture phenomenology of the collar specimen and thus proves suitable for the use in semi-hot forging simulations. The thermal behaviour of the specimen will be linked to the state of stresses in the collar specimen, indirectly influenced by the material itself but more directly by the specimen geometry. The integrated Model of Effective Stresses is used in the investigation of the damage behaviour of a journal bearing. This workpiece is forged under semi-hot conditions and shows severe surface fissures albeit the high temperature. The results are discussed on the basis of the experiments with collar specimen from the same material. An alternative process sequence, including an annealing before the critical forging stage, is suggested.
Design of forging technology with using the Cost – Volume – Profit model  
A. Łukaszek-Solek, J. Sińczak, P. Skubisz

The assessment of forging technology design correctness was done on the basis of the Cost – Volume – Profit model. The forging technology was worked out using commercial software package QForm 3D, assuming three-dimensional state of strain. The alternative variants of forging technology design were presented in this paper. The choice of optimal technology has been made on the basis of mean stresses distribution as well as elimination of defects in the form of laps that guarantee required quality of the final product. The possibility and the usefulness of practical application of the designed technology variants were confirmed using Cost – Volume – Profit model and polar diagram according to Nagashima approach.

Theoretical analysis of rotating compression forming of ring considering constant shear friction  

This study proposes a new analytical approach of rotating compression forming of ring considering constant shear friction. Two analytical models of compression forming based on the slab method are derived respectively, depending on whether the ring rotates or not. Model I takes into account the rotating effect, whereas Model II without rotation. By this approach, effects of the frictional factor, rotating angular speed of the ring, ratio of outer diameter to thickness, ratio of outer diameter to inner diameter, and aspect ratios of the ring on compression characteristics are explored effectively. Moreover, the compression pressure, radial stress, and compression force are predicted effectively. Comparisons between both models are performed in order to realize the advantages considering the rotation effect.

Development and Research on Near Net Shape Forging Technology of Round Part with Flange Made of Aluminium Alloy A95456  
P. Petrov, V.Perfilov, M. Petrov

This paper describes the development of isothermal enclosed die forging technology of an aluminium part with flange. The optimum conditions of forging were obtained by means of FEM simulation. That allowed the production of parts without defects and with defined mechanical properties. Moreover, the new technology ensures the reduction of forging force and the improvement of die filling. The dies for experimental forging were designed according to the results of FEM simulation. The presented results of experimental forging indicate that isothermal enclosed die forging allows the formation of round parts with flange.

Warm precision forging and upsetting for the extruded billet of AZ61 Magnesium alloy  
D.- S. Lee, M. Asakawa, Y. Tanno, M. Kobayashi, K. Hatsukeno, K. Matsuzaki

Alloyed magnesium is the lightest metal with high specific strength in practical use today. In current applications, the manufacturing process using the magnesium alloys is mainly dependent on casting techniques such as die casting and thixo-molding. In plastic processing, the main manufacturing methods are press forming and extrusion. Magnesium forging processes are not very common, and the investigation data on the topic of the precision forging of AZ61 extruded billet is rare.

This research aims to find the best condition for producing T-shaped precision forgings, which have broad practical applications such as automobile parts, pipe joints, valve bodies, etc., and to analyze the resultant mechanical properties and texture. Additionally, warm axial upsetability of AZ61 extruded billet is also evaluated.

The present experiments are composed of two stages; one is evaluation of production and analysis of T-shaped forgings; the other is analysis of deformation behaviour in warm axial upsetting of extruded billet using a concentrically grooved tool. From this research, the following conclusions about forgeability and upsetability were obtained.

For forgeability, utilizing a T-shaped die, conditions of the lubricant, temperature and backpressure were investigated.

a) Trial-produced lubricant X-1956 (a white liquid lubricant with dispersed solid lubricant) showed superior lubricating effects after MoS2.

b) For T-shaped forgings, satisfactory, fracture-free forgings were obtained with no backpressure at 468K. This is due to the high surface pressure applied by the tool.

c) With an applied backpressure of 250kN, fracture-free forgings were obtained at forming temperatures as low as 453K.
Numerical and experimental investigation on hot impression die forging: flash design optimisation
R. Di Lorenzo, S. Beccari, M. Piacentini, F. Micari

In forging processes, several parameters have a great influence on the quality of the final product: complexity of the product geometry, lubricating conditions, temperature, preform shape. The main objective of a forging design process is to ensure an adequate material flow aimed to obtain a defect free component minimizing material losses, forging loads and tool wear. In this paper, the problem of optimising the flash geometry in hot forging is studied with particular reference to flash thickness and flash–land width. The main goals to be pursued concern the minimization of the flash volume (i.e. the surplus of material necessary to fill the die cavity), with the aim to reduce material losses, and also the reduction of the maximum load required to carry out the process. In this way, numerical investigations and design tools have been utilized to optimise the main process parameters. Furthermore, an experimental validation of the results has been carried out with the aim to verify the numerical predictions in terms of forming loads and complete die cavity filling. A numerical design procedure was developed able to enhance the process design performances with respect to the available empirical guidelines. With the proposed methodology an effective flash land geometry was determined able to guaranteed the fulfilment of product design specifications.

An influence of the selected flash variables on the closed-die forging processes
G. Samołyk, Z. Pater

The article concerns an influence of the selected flash gap parameters and the technological variables on the closed-die forging processes. The theoretical analysis was made using commercial software package MSC.SuperForm 2002, which is based on finite element method (FEM). The results of this FEM calculation were verified by a physical experiment on the specially designed tools. In the analysis, it was assumed the geometrical model of forging process, which is assured a forming by extrusion of parts with a boss. This model represents a group of industrial components with a long axis. It is made an research of the influence of the various forging parameters on die cavity filling possible. The flash with two kinds of a land (that is flat parallel and flat wedge) was applied in the analyses. Besides, in there was taken into consideration the various lubrication conditions. The simulation was carried out in made an assumption forming on a mechanical press.

An upper bound stream function elemental technique for the forging of spur gears
M. Salimi, M. Kabirian

In this paper the upper bound dual stream function elemental technique was used to analyse the forging of spur gears and spline. In this technique, the deformation region is divided into a number of elements in the form of stream-function elements and the stream functions in each region are proposed. The stream function at each point of the element was assumed to be a function of the stream functions at nodes. Numerical calculations have been carried out to compute the total energy consumption, which consists of the energy required to overcome the internal deformation, the frictional resistance between the die and the work-piece and all the discontinuities in the field. This value is a non-linear function of the unknown stream functions, which can be optimized by minimization of the total energy. The billet was assumed to be a rigid-plastic material and the elastic deformation of the tooling was neglected. After the minimization of the unknown stream functions, the lower upper bound of power was obtained. Predicted values from the present analytical model are compared to that of the other investigators, which are shown to be in good agreement.
A mixed temperature/heat flux formulation for solving unsteady thermal problem during forming process simulation

C. Pelissou, E. Massoni, J.-L. Chenot

The thermal analysis using standard linear tetrahedral finite elements may be affected by spurious local extrema in the regions affected by thermal shocks, in such a severe way to discourage the use of these elements. The present work proposes a mixed continuous temperature/heat flux formulation to solve the unsteady thermal problem. This new numerical model should allow to improve the thermomechanical coupling effects during the simulation of 3D forming processes, and more particularly during the hot or cold forging processes and during the heat treatment. The spatial model is based on the Galerkin approach with the linear tetrahedral P1/P1 mixed finite elements. Time integration is based on an implicit scheme allowing better flexibility on the time steps choice. The performance of this method is evaluated by means of test case with analytical solution, as well as an industrial application, for which a well-behaved numerical solution is available, and by comparisons with two discontinuous Galerkin models based on the constant P0 finite element: the explicit Taylor Discontinuous Galerkin scheme (P0/P0 interpolation and third degree Taylor time integration) and the implicit Discontinuous Galerkin model (P0/P0+ interpolation with implicit Euler scheme). For this study, the 3D finite element FORGE3® software, able to simulate strongly coupled thermomechanical problems and steel quenching, is required.

An Efficient Vectorized Approach for the Simulation of Metal Injection Molding

Z. Cheng, T. Barriere, B. Liu, J. C. Gelin

The Metal Injection Molding (MIM) is a very cost effective technology for manufacturing the small intricate parts. The simulation of its injection process induces a real challenge due to the bi-phasic nature of injected mixture. The prediction of powder segregation in the injection stage requires the solution of two coupled Navier-Stokes equations for the filling process. The classic solution methods represent few values for such a complex case because of their tremendous computational cost and the difficulties for convergence. To overcome such a difficulty, the first effort is made by the authors to develop a dynamic explicit algorithm for the bi-phasic injection flow. The computation cost is significantly reduced for performing the realistic simulations. As the global solutions for pressure field are required, the cost of computation increases still strongly with respect to the increase of DOF number. Hence a purely vectorial algorithm is proposed to provide the powerful tool for prediction of the injection flow, especially the segregation effect by a bi-phasic model. This newly suggested algorithm is designed specially for simulation of the filling problems. The incompressibility is maintained by a feedback corrective scheme, instead of calculating globally the pressure fields. All numerical operations become the vectorial ones to provide the remarkable efficiency, except for the manipulations of small matrices at element level. Another remarkable feature is the use of elements with equal-order interpolations. To avoid the possibility of mesh locking, a systematic smoothing procedure is used without individual treatment at element or node level. The application of such a software becomes then more user-friendly to employ directly the commercial pre- and post-processors. Because of the uncoupling characters of newly proposed method, the so-developed software is moreover easy to be parallelized in a multi-cluster computer. For validation of the new software, experiments have been performed simultaneously with the research on simulation methods. The measurement on local densities of the molded parts permits the justification of segregation results obtained by simulation. The previously developed explicit algorithm with MINI elements allows the validations of simulation results for different physical quantities, too.

Modelling and simulation of precision blanking for very thin components

V. Lemiale, P. Picart

The aim of this work is to propose a efficient numerical tool to simulate the blanking process and predict the geometric and mechanical characteristics of the final component. This paper presents several numerical investigations about blanking process. The first part concerns the mechanical modelling of blanking in a finite element framework. A description of different approaches considered in literature to model damage processing and fracture propagation is proposed. The local Freudenthal's fracture criterion is adopted here. Two different strategies to simulate the fracture propagation have been implemented, first, a finite element elimination method and second, a finite element separation method. The efficiency of these methods to predict a realistic cut edge profile is analysed. The load-penetration punch curves obtained by the fracture propagation methods are compared to the experimental one. Numerical results in term of equivalent plastic strain, shear stress and damage distributions are also presented.
Experimental and Numerical Investigation of Miniaturization in Deep Drawing  
H. Justinger, N. Witulski, G. Hirt  

Micro deep drawing of metallic parts with a diameter of one or only a few millimetres and a typical wall thickness below 300 µm is in many cases a reliable mass production process today. However, the process layout is mainly based on experience. Numerical process design tools like FEM, which are extensively used for process planning in deep drawing of large parts, are rarely used for micro deep drawing applications. Accordingly, further miniaturisation as well as the development of process chains for new and more complex geometries is characterized by extensive trial and error procedures. A first step to address this problem was made by basic experimental and numerical work to study the influence of size effects in miniaturisation and to validate FEM procedures. At least the following effects must be considered: (1) in micro deep drawing the strain rate is significantly higher than in conventional drawing; (2) the grain size may be large compared to the foil thickness; (3) geometric tolerances of the tool are larger compared to the tool size; (4) the process often includes ironing for calibration. Deep drawing experiments to produce round cups ranging from 8 mm to 1 mm diameter were performed using a drawing ratio of 2. All geometric measures were adequately scaled to maintain similarity. The tests with CuZn37 foils (fine grained and annealed, thickness 300 µm to 40 µm) showed the following results: (1) high similarity of the load stroke curve; (2) little influence of the tool velocity in the range of 0.01 mm/s to 10 mm/s; (3) a large number of very small “ears” around the boundary of the cup and (4) differences in the wall thickness distribution when fine grained material is compared to annealed material. Axisymmetric implicit FEM simulation using linear 4-node volume elements could fairly well reproduce the load stroke curve for the deep drawing and also for the ironing part of the process. Variations of the geometric parameters of the process indicate the high importance of very small geometric deviations from the ideal tool geometry. Variations of the material parameters and friction conditions were used to identify their influence on the process result. For future work, which should then include planar anisotropy effects, a 3D explicit FEM model has been established and initially validated in comparison to the axisymmetric model.

Prediction of Surface Layer Hardness in Hot Forging Dies by Means of Finite-Element-Analysis  
Eckart Doege, Bernd-Arno Behrens, Falko Schaefer  

The Finite-Element-Analysis (FEA) is of major importance for the design and improvement of forging processes. In this field, FEA is used to predict die fill, residual stresses and forming forces traditionally. The intention of the work presented in this paper is the development of an advanced simulation model for the reproduction of the die surface layer. In consequence of the thermal and mechanical interactions the die surface layer is heated up. Due to this changes of the microstructure can take place. These microstructure changes lead to a changing of the surface layer hardness and have an effect on wear performance of the dies. The presented simulation model based on FEA enables the prediction of the hardness of the surface layer. The knowledge of the surface condition is essential, because it has an important impact on the die wear. The numerical simulation based on FEA will be carried out considering a precision forging process. To represent the interactions between the work piece and the tools as well as the mentioned microstructure changes adequately, the thermal-mechanical Finite-Element (FE) model includes meshed tool components. The modelling is characterised by a high level of geometric discretisation. Especially the tool surface layer is meshed with a very large number of elements. Temperature distributions in the surface layer at various work piece temperatures, die temperatures and tool velocities will be shown. If the temperature distribution is computed with the FEA, hardness properties of tool materials determined in experimental investigations can be assigned to the surface layer of the modelled dies. The developed simulation concept allows the computation/prediction of die wear with consideration of temperature dependence of the material hardness.
Coupling microstructure models with large scale forming simulations
Y. Chastel, R. Logé

Today there is a growing need for accurate predictions of the metal flow during forming operations and of the final microstructure in a workpiece. Numerical models are now used on computer platforms which are powerful enough to reach a very high level of numerical accuracy in terms of temperature and macroscopic mechanical fields calculations. The quality of the modelling results is mostly limited by the accuracy of the material and metallurgical models and parameters. Since industrial problems are complex and diverse, different approaches for coupling microstructure evolution and mechanical behaviour have been developed. Forming operations may be steady-state or non steady-state processes, and typically include multi-stand forming and heat treatment steps. Several strategies are reviewed for computing microstructure evolutions in metal forming processes with large spatial heterogeneity of strain rate, strain and temperature fields. Applications are presented for describing recrystallisation, phase change and texture evolutions. The final microstructure dictates the in-use properties of the part. Therefore, one can aim at using predictions of the microstructure after forming as an input for any subsequent life analysis of the part. So, once such models are validated, they can be used in a global optimisation loop which includes forming operations and in-use loadings.

Deterministic and stochastic analysis of failure in sheet metal forming operations
J. Rojek, M. Kielber, A. Piela, R. Stocki, J. Knabel

Numerical simulation can be successfully applied to evaluate product manufacturability and predict possible defects. Material breakage, wrinkling and shape defects due to springback are most frequent defects in sheet metal forming operations. In this paper we shall deal with prediction of sheet breakage during stamping process. The breakage possibility in our study is evaluated using Forming Limit Diagrams (FLD) commonly used in industrial practice. Typically deterministic analysis of sheet forming process is carried out. The first part of the paper includes an example of such simulation. Sheet forming operations, however, are characterised with a significant scatter of the results. This can be caused by differences that can occur in forming of each part. The second part of the paper presents a stochastic approach to assessment of sheet metal failure during forming operation. Methodology developed is based on the application of reliability analysis of structures to estimate probability of sheet breakage in metal forming operations. Numerical examples illustrate the stochastic approach to failure analysis in sheet forming processes.

Use of the modified maximum force criterion for necking analysis during sheet bulging
M. Ben Tahar, E. Massoni,

In sheet metal forming, the accurate prediction of necking remains an important issue in order to reduce the number of experimental trials. Necking models can be implemented in FEM code and are useful in numerical simulation of a wide range of sheet metal processing applications. These include stamping, and the hydroforming technology which is creating an increasing interest in the industrial environment, particularly due to the weight reduction and uniform thickness distribution that can be achieved by this technology when compared to the standard stamping process.

This paper concerns material data characterisation for double sheet hydroforming simulation. First, a circular bulge test is analysed in order to obtain reliable stress-strain curves for large deformations. Then elliptical bulge tests are used to draw a forming-limit diagram for the stretching strains. The instantaneous strain path as well as major and minor strains are recorded in real time during the trials using an optical correlation system.

The limit strain states are then calculated according to a new formulation of the Modified Maximum Force Criterion by means of step integration of the measured strain rate following the experimental strain paths. The effect of the strain rate sensitivity was introduced within the formulation of the necking criterion. The predicted FLC are compared to experimental results. The effects of strain path, and the strain rate sensitivity are discussed.

A storage and retrieval system for roll-forming design data using a neural network
A. W. Downes, P. Hartley, I. Pillinger

Cold roll-forming is a sheet metal forming process that incorporates sequential sets of rotating profiled rolls. An inherent feature of the forming process is the generation of longitudinal and transverse strains in the sheet that may result in geometric defects. Designers in industry today are largely dependent on empirical observations that have been acquired over a period of many years. When beginning a new tool design it is helpful to study existing designs for similar sections. If many hundreds of designs have been recorded, stored in chronological order, searching for a similar design can be a time-consuming and tedious task. This paper describes the application of an artificial neural network (ANN) that can be used to construct a library of existing designs on a computer disc, with an efficient and accurate method of information retrieval.
Estimation of hole flangeability for AW5754 aluminium alloy sheets
M. Sitek, F. Stachowicz

Hole flanging is a common sheet forming operation to produce structural sheet metal components. Flanges are used for appearance, rigidity, hidden joints, and strengthening of the edge of sheet metal parts. Trial-end-error is the most common approach for tooling and process design in flanging operations. This paper presents some experimental results of hole flanging process performed on flat AW5754 aluminium alloy plates with circular hole drilled in the centre. Three different punch geometry i.e. cylindrical, hemispherical and conical were used in this experiment. The effect of both the punch geometry and material mechanical parameters (especially strain hardening and plastic anisotropy) on the limit expansion of the hole was determined.

Improvement of Roughness of Inner Surface in Multi-Stage Deep Drawn Stainless Steel Cups by Inner Ironing
Y. Abe, K. Mori, T. Murao, F. Okubo

To finish the inner surface of deeply drawn stainless steel cups, an inner ironing process is introduced. In the inner ironing, the inner surface roughness increased by the multi-stage deep drawing is improved by ironing the cup set in the container with a punch having a diameter larger than the inner diameter of the cup. The effects of the ironing ratio and punch shape on the improvement of the roughness are examined in the experiment. Although the outer surface roughness is improved by the conventional outer ironing, the reduction in inner surface roughness by the inner ironing is considerably larger than that by the outer ironing. Furthermore, the inner ironing process is applied to the engine part of cars to reduce the roughness of the inner surface.

Springback Analysis in Drawbead Simulator Tests
A. Matuszak, D. Krecisz

A springback analysis of sheet metal subjected to bending-unbending under tension is made. Bending-unbending under tension was carried out on strips of three sheet materials in a drawbead simulator. The drawbead simulator, built according to H.D. Nine’s idea, consists of three fixed pins. The fixed pins were replaced with rollers to perform frictionless tests. Friction was additionally modified by using lubricated or not lubricated pins. The experimental results are compared with the calculated ones. The comparison shows that the sheet restraining force significantly contributes to a reduction in springback. The drawbead simulator has proved to be a useful tool for the experimental verification of virtual data obtained in FEM simulations of deep drawing processes in cases when drawbeads are used.

Effect of roll edge local perturbation of deformation on thin strip rolling
Z. Jiang, H. T. Zhu, A. K. Tieu

The edge contact force between the upper and lower work rolls will change with the rolling conditions in cold rolling of thin strip, which has not been clarified before. In this study, an influence function method and its numerical simulation code have been developed based on the deformation compatibilities in rolling and lateral directions between the backup roll and work roll, the work roll and strip and the two work rolls for roll edge local perturbation of deformation. The rolling force, intermediate force between the work roll and backup roll, work roll edge contact force, strip shape after rolling and the length of the edge local perturbation of deformation are obtained from the simulation. The calculated rolling forces for various strip width are in good agreement with the measured values. Simulation results also show that the strip width and transverse friction have a significant influence on the shape of the rolled strip.

Surface profile characteristics of steel strip after hot rolling
W. Sun, A. K. Tieu, Z. Jiang, H. Zhu

In this paper, both the as-rolled and hydrochloric acid pickled surfaces of hot-rolled strips were measured by a Surtronic surface profilometer. The hot rolling of the steel strip were carried out on mild steel under oil-lubricated and non-lubricated conditions at 850 to 1025 degree C respectively on an experimental Hille-100 Rolling Mill under different reduction and designated rolling speeds. Results show that reduction has a significant effect on the as-rolled strip surface roughness for both the non-lubricated and oil-lubricated conditions while the influence of rolling speeds on the surface roughness is less significant. The roughness of the pickled surface increases slightly with the rolling speed at reduction 15.8% reduction of the bulk materials. This is opposite to the trend for the as-rolled strip surface. However, surface roughness value for the strip under oil-lubricated condition become larger than those without lubricated condition in any case. On another hand, with higher reduction the effect of temperature on surface roughness becomes smaller for oil-lubricated condition rolling than dry rolling condition. Influence of rolling temperature on surface characteristics is also investigated in 2-Dimensional Power-Spectrum Density analysis from Nanoscope IIIA AFM images on the oil-lubricated samples.
Parameters Affecting Free Spread of Stainless Steel Grade 304
A. Ismail, T. El-Bitar, A. –W. El-Morsy, M. Abdel-Aziz:

This paper investigates the effect of deformation temperature and velocity on the free spread of austenitic stainless steel. Different approaches of prediction the free spread of carbon steel were developed originally by Tselikov, Tafel, Bakhtinov, Siebel and Zolotnikov are applied to predict the free spread of austenitic stainless steel. Experiments were carried out and experimental design technique was developed in this paper to study the deformation parameters and their effect on the free spread of austenitic stainless steel. Carbon steel approaches include temperatures, coefficient of friction and dimensions of roll gap while the experimental design technique developed in this work considers also the deformation parameters in addition to the geometry of roll gap. Carbon steel formulas provide very small deviations for austenitic stainless steel. The experimental design technique leads to even smaller errors as compared due to the five traditional formulas.

Prevention of Wrinkling and Fracturing in Deep Drawing of Metal Foil Using Resin Dies and Auxiliary Sheets
Y. Marumo, H. Saiki

Deep drawing of 15µm-thick stainless steel foil, 20µm-thick pure nickel foil and 40µm-thick pure copper foil has been conducted. In the deep drawing, auxiliary sheets of nylon66 and polyethylene and in part a die of polytetrafluoroethylene (PTFE) were used. The effects of the resin auxiliary sheets and resin die on the deep drawability of foil blanks were investigated. Three arrangements of a foil blank and resin auxiliary sheets were examined. In mode (A), a foil blank was sandwiched between two auxiliary sheets. In mode (B), an auxiliary sheet was placed on the blankholder side of a foil blank. In mode (C), an auxiliary sheet was placed on the die side of a foil blank. The easy formation of wrinkles due to a decrease of foil blank thickness and nonuniform blankholding pressure along the circumference reduced the deep drawability. In addition, a large increase of the necessary blankholding pressure with the decrease of blank thickness also reduced the deep drawability. The region of the loading paths of blankholding pressure along which both wrinkling and fracturing were prevented became narrower with a decrease of blank thickness. These problems were overcome by using the nylon66 auxiliary sheets and PTFE die. In the cases of 15µm-thick stainless steel foil and 20µm-thick pure nickel foil, wrinkling and fracturing were prevented by the use of nylon66 auxiliary sheets in mode (A). In the case of 40µm-thick pure copper foil, the use of a PTFE die and nylon66 auxiliary sheets was very effective for the prevention of wrinkling. In deep drawing, the diameter of the die cavity was selected such that the tool clearance between the punch and die was less than the total thickness of the auxiliary sheet and pure copper foil blank. In the die throat during deep drawing, the auxiliary sheet on the blankholder side was ironed and the PTFE die wall was deformed elastically. Therefore, the copper foil blank was effectively constrained within the region from the flange to the die wall through the die shoulder. Furthermore, the increase of the sliding frictional resistance due to the strong contact in the die shoulder and die wall was restrained by the good lubricity of the PTFE die. These effects improved the deep drawability of pure copper foil.

Multi-point die support system controlling deep-drawing die deformation
T. Ohashi

This paper presents a new structure of a die set. The author has developed a multi-point support structure for the die, which enables a user to adjust its deformation after the trial process in deep drawing, instead of correcting the surface post-trial. The die is supported at multiple points by elastic cylindrical cells with ball contact. A cell has strain gages on its surface and works as both the structural part of the die set and the load cell. Therefore, the user can inspect change of load and displacement (representing the elastic deformation of the cell) at each supported point. The user can change the distribution of these supporting points with regard to the trial process result and measured load.

A study on the influence of waiting time between forming steps on the form accuracy of a three stage formed deep drawn product made of Sandvik Nanoflex™
G. Klaseboer, J. Post, E. Stinstra, J. Huétink

Sandvik steel Nanoflex™ combines good corrosion resistance with high strength. The steel has good deformability in austenitic conditions. This material belongs to the group of metastable austenites; during plastic deformation a strain-induced transformation to martensite takes place. After deformation, the transformation continues as a result of internal residual stresses. Depending on the heat treatment, this stress-assisted transformation is more or less autocatalytic. Both transformations are stress-state and temperature dependent. The martensite phase of Nanoflex™ can be aged.
The influence of tool design on the development of localised regions of plastic deformation in cold roll forming

J. Collins, M. Castellucci, I. Pillinger, P. Hartley

The structural performance of sheet metal formed products relies on maintaining the maximum stiffness of the section while economic viability requires a minimisation of the amount of material used. A balance between these conflicting requirements can be achieved through the introduction of bends in the profile to 'stiffen' the section. Further enhancements in performance can be obtained by plastically deforming the material surface prior to the metal forming operation. This deformation can be achieved by means of surface texturing. The effect of this is two-fold, firstly it changes the section structural properties (e.g. section modulus), and secondly the sheet is work-hardened around the texture.

Previous research into the production of sheet metal formed products gave some insight into the amount and distribution of work-hardening. Finite-element simulation revealed patterns of work-hardening that contributed to the structural performance for steel [1]. Models for the development of areas of high localised plastic strain have also been presented [2]. Simple bending tests showed a correlation between the increased work-hardening and resistance to bending [3].

In the work described in this paper, the effect of changing the geometry of the sheet metal tooling on the plastic strain distribution and material thinning is investigated using finite element simulation. Tool parameters are fine-tuned to maximise the areas of increased plastic strain whilst minimising material thinning. The effect of radical tool shape changes is established, with known tool manufacturing limitations considered at all times. The impact of an entirely new tooling geometry is discussed.
Microstructural studies and flow stress modelling in a Ni-base superalloy
C. Bruni, M. Cabibbo, A. Cruciani, A. Forcellese, F. Gabrielli

The hot workability behaviour of NIMONIC 115 alloy was investigated in extended ranges of temperature (1100-1180°C) and strain rate (0.01-5 s⁻¹) by means of torsion tests. The microstructure evolution was investigated by means of LM and TEM inspections in order to understand the mechanisms occurring during hot deformation. The highest ductility level has been reached at 1140°C-0.01 s⁻¹, where the alloy exhibits a flow behaviour typical of materials undergoing dynamic recrystallisation, confirmed by LM inspections. With increasing strain rate, the ductility peak shifts towards higher temperatures, if the true temperature is taken into account. TEM inspections highlighted the effect of the dissolution of γ' phase in secondary and tertiary γ' on the high ductility levels. The activation energy values, evaluated at the yielding point, at the peak of the flow curves and at the beginning of the steady state regime, obtained in the range 1100-1140°C are higher than those found between 1140 and 1180°C. The flow curves have been modelled by means of constitutive equations for both ranges of temperature 1100-1140°C and 1140-1180°C.

Effects of Mg Concentration, Test temperature and Strain Rate on Serration of AlMg3 and AlMg5 Alloys
S. A. Risteska, J. K. Mickovski

The paper presents and elaborates the results of experimental tests on discontinuities at deformation reinforcement during the deformation by compressing of AlMg3 and AlMg5 depending on deformation temperature and rate. The experimental data for deformation initiating the discontinuities of deformation reinforcement, by application of Cotrell's model, after which the vacancies diffusion in metal is responsible for processes of dynamic relaxation, meaning that with the initiation of discontinuities on the deformation curve, the type of discontinuities has been determined depending on Mg concentration in Al alloys, temperature and deformation rate. The temperature dependency at initiation of discontinuities, determines the activation energy for the process of dynamic relaxation. It was estimated that increased concentration of pairs Mg / vacancies is responsible for process of deformation relaxation although the processes that influence the mobility of the dislocations, can have an influence, which can not be confirmed by the experiments from this research.

The Influence of the Extrusion Temperature of PM Al-Cu-Si Alloy Preforms on the Structure and Properties of the Products
S. Szczepanik, M. Wojtaszek, B. Wisiiewski

The paper discusses problems connected with the influence of the extrusion temperature of PM preforms from Al8.4%Cu6.3%Si0.6%Mg alloy on the structure and mechanical properties of the products. Changes of the structure in dependence of heating conditions of the preforms before extrusion have been examined as well.

From the heating curve the temperature of solidus was determined as 508°C for the researched alloy. Metallographical research of PM preforms at the room temperature after heating at 510 and 530°C during 15 min or 30 min and cooling in water has shown that the liquid phase occurs, and its content depends more on the heating temperature than the heating time. The material obtained from the powder is characterised by finer grain of solid phase and even distribution of liquid phase around it. The grains of solid phase are irregular and separated with the products of solidification of the liquid phase which appeared at heating.

Extrusion was carried out at 510, 520, 530°C after the preforms had been heated during 15 or 30 min. The influence of temperature and heating time of PM preforms before extrusion on the properties of the extruded products was determined. Taking this range of temperature, it was possible to elaborate its influence and, indirectly, the influence of liquid phase content on the force and its magnitude during extrusion and determine the mechanical properties obtained without and after heat treatment.

Grain Size Optimization of Single Hit-Hot Compressed Nimonic 80A Super-Alloy Using Experimental Design Technique
T. El-Bitar, A. -W. El-Morsy, M. Abdel-Aziz, A. Ismail

Nimonic is one of the Ni-base super-alloys which exhibits austenitic (γ phase) matrix and contains a wide variety of secondary phases. During forging or hot rolling, the alloy is usually subjected to severe deformation conditions. These conditions create different grain sizes with different mechanical properties. This work aims to clarify the mutual effects of the strain, temperature, and strain rate on the created grain size of Nimonic 80A super-alloy. Hot compression tests were conducted on axisymmetric specimens by using a servo-controlled, computerized hydraulic machine. The specimens were subjected to single hit tests at temperatures ranging from 800 to 1200°C for different amounts of strain and at constant strain rates of 0.1 and 1.0s⁻¹. An experimental design method is used on the bases of the laboratory hot compression testing results taking into account the influence of amount of strain and deformation temperature. Particular interest was paid to the effect of strain rate and accumulated strain on the created grain size.
A methodology to identify bulk behaviour of galvanised coating: An application to the skin-passed steel strip

S. Huart, M. Dubar, R. Deltombe, A. Dubois, L. Dubar

Skin-pass is a cold rolling process. It is used to obtain good aesthetic and mechanical properties on galvanised coated strip. The low reduction allows a roughness transfer from the work-roll to the strip, and reduces the yield point elongation. It is performed after cold rolling and before the painting of the strip. The control of contact conditions in skin-pass is critical to ensure quality and final aspect of the strip surface.

The stress and strain distributions at the roll/strip interface are determined by the galvanised layer behaviour. The bulk behaviour law of the galvanised layer is then required to improve the finite element simulation of the process and optimise industrial skin-pass.

The identification method of strip coated is based on an inverse method. Spherical indentations are performed on coated strip under increasing load. Micro-indentation tests on galvanised strip are simulated with a finite element model and are compared to experimental data. The stress-strain curves of the coating and its neighbouring substrate are then plotted from inverse method procedure.

The bulk behaviour law of the galvanised layer is used in the finite element computation of the skin pass test (SKURT). Comparison between numerical results and a skin-pass experimental test is achieved. A good correlation is obtained. At a global scale, skin-pass loads calculated via the simulation are correlated to the experimental measurements. At a microscopic scale, the roughness transfer is studied with the numerical model and is compared to the physical data. The validity of the identified bulk behaviour law is checked.

A Trust-Region Algorithm for Automatic Identification of Elasto-Viscoplastic Parameters in Metal Forming Problems


Simulation of manufacturing processes, here metal forming, has made major progresses during the last years. The virtual simulation of the manufacturing process being now quite well established, a natural step ahead consists in trying to find automatic procedures to optimize it. Another perspective is also to take care of the influence of the manufacturing constraints upon the design, which is the long term objective of the present research project. It aims at optimizing the design subject to both service constraints (stiffness and strength) and manufacturing constraints. A preliminary stage is to be able to build high fidelity digital models. Complex models require more and more material parameters for behavior laws (e.g. material constitutive and friction laws), which have to be identified numerically from experimental data.

In this material parameter identification process, three steps can be identified. At first, an experimental testing is carried out. The second step consists in building a simulation model of the experiment. Finally, the unknown model parameters are determined to match the experimental data. A standard identification procedure consists in minimizing a given norm (here the Euclidean norm) of the error between the model predictions and the experimental results.

Even if the identification problem is generally quasi-unconstrained, it has the same complexity as structural optimization problems because of the highly nonlinear and implicit character of the functions, which is especially amplified by the large deformation simulation analysis.

In this paper, we use an approach of elastoplastic calculation by finite elements combined with two optimization algorithms: a Levenberg-Marquardt algorithm, which is rather classical in the literature for solving identification problems (see [2]) and a trust-region one (see [1]), which is a rather novel approach at least for structural problems. The results obtained with these two methods are then compared and discussed on two test cases. The first application is an academic test case to validate the identification method. The second one, the compression of a cylinder, takes into account an actual experiment. In this application, the material is assumed to be elasto-viscoplastic and described by a Norton-Hoff behavior law and an isotropic strain hardening law. The parameters to be identified are the coefficients of the Norton-Hoff law.

An approach for evaluating constitutive models for hot aluminium extrusion – Rod extrusion of AA6060 as a case study

P. T. Moe, W. Wajda, L. Madej, D. Széliga, S. Støren, M. Pietrzyk

Constitutive relations are approximate mathematical descriptions of fundamental material behaviour and essential parts of all continuum models of physical systems. Testing and documentation of the accuracy and limitations of material models is a prerequisite for successful simulation. Although many material models may be given mechanistic interpretations, the primary source of knowledge is empirical data from well-defined representative experiments. The current article discusses constitutive modelling of flow in extrusion of aluminium. The complexity of the material deformation complicates both experimental and numerical studies. Conventional materials testing procedures for metal forming cannot fully reproduce extrusion conditions i.e. high strain rates, large strains, large temperature changes and high hydrostatic stresses, while high rate testing techniques do not give complete insight into the deformation history of material elements flowing through the system. Rod extrusion in carefully controlled laboratory conditions appears to be a simple method for testing the ability of flow rules implemented in a modelling tool to predict system responses during
extrusion, such as the ram force, the outlet temperature and the die face pressure. The article presents comprehensive results from such experiments with AA6060 as well as compression testing experiments performed in order to establish material data for the same alloy. An evaluation is performed of the deviation between results from extrusion experiments and from simulations with the Zener-Hollomon constitutive relation and material data from the compression tests. Simulations with the Arbitrary Lagrangian-Eulerian code ALMA produce estimates of force in fair accordance with measured results, but somewhat too high temperatures. It is shown that better estimates of temperature can be obtained without considerably altering the ram force estimate. Yet, proper control of temperature before and during extrusion is essential if the verification of models is to be trusted. Differences between experimental and simulated data may at least partly be explained by errors in the measurement of input or output parameters. Furthermore, the error plots reveal that the non-linear and coupled extrusion system is such that equally acceptable estimates of the output parameters may be produced when extruding with a different sets of material data.

Using Inverse Analysis to Obtain Material Behaviour for Crash Simulations

J. Mullins, P. D. Hodgson, M. Dingle

Finite element crash simulations require material data that is relevant for strain rates ranging between $10^{-4}$ and $10^3 \text{s}^{-1}$. Obtaining this data can be a challenging task that requires tensile testing on high speed apparatus. In this work, a different approach is investigated. The work presented highlights the benefits of using novel tensile specimens, together with inverse analysis, to predict material behaviour for vehicle crash simulations.

Non-standard, curved-gauge sheet specimens were tested in tension, at two rates of loading. In addition, notched specimens were tested at one rate of loading. The experimental results were used to drive a series of inverse analyses that estimated the parameters of a rate sensitive material model. The results showed that a single test could be used to predict material behaviour for strain rates spanning three orders of magnitude. In addition, the strain rates achieved in the analyses were greater by a factor of twenty than those achieved in comparable standard tensile tests.

Identification of the Hardening Curve Using a Finite Element Simulation of the Bulge Test

A. Chameck, H. Belhadj Salah, A. Gahbiche, A. Benamara, A. Dogui

The numerical simulations are a useful tool for controlling and optimizing the forming processes. The quality of these simulations strongly depends on the efficiency of the behaviour models of the deformed materials. In order to identify such models, experimental tests must be used. In this work, the bulge test with circular and elliptical dies are considered. During the bulge test, the displacement of the central point and the pressure were continuously monitored and recorded. The numerical simulations of this test are carried out using ABAQUS software. These current simulations, the behaviour of the specimen are assumed to be elastoplastic. The Hill's criterion (48) and the isotropic hardening are considered. An inverse modelling based on the finite element computations and experimental data is made in several situations. The aim of this analysis is to identify the parameters of the hardening curve and the Lankford's coefficients. Several sets of results are presented and discussed.

Various Plastometric Tests for Semi Solid Materials and Their Numerical Simulations

A. Żmudzki, M. Pietrzyk, P. Kotrbáček, J. Horský

The evaluation of flow stress of materials undergoing the plastic deformation is the prime objective of the plastometric tests, such as tensile, torsion and compression tests. These tests are not adequate in case of the deformation of semi-solid materials. Therefore, the main objective of the present work is the review of various plastometric tests, like hot upsetting test, ‘needle’ test, ‘U-tube’ test and ‘double cup’ extrusion test, for evaluation of material properties of metal alloys deformed in semi-solid state. Analysed tests can supply information regarding both rheological and friction models of metal alloys in semi-solid state and the measured data can be directly used in the inverse analysis of the deformation process. The comparison between FEM and experimental results for these tests is presented and discussion regarding their applicability to semi-solid materials testing is presented, as well.
The Effect of Additional Shear Strain Layer on Mechanical Properties of Fine Drawn Wire


Fine wires on the order of 100 µm in diameter have become popular for mechanical and electrical applications, such as micro springs, micro pins, printer mesh, cutting wire for Electrical Discharge Machining (EDM), and wire for cutting silicon, quartz, and other semiconductor materials. In general, fine wires produced by the drawing process are required to have both high strength and high ductility, and indeed, the fine wire drawing process seems to induce exceptional properties in the product. An objective of the present study is to ensure that superior mechanical and metallurgical properties are induced via the fine wire drawing process, and to determine precisely what factors of the process contribute to these superior properties.

In the fine wire drawing process, a large shear deformation zone with a hardened layer, referred to as the “additional shear strain layer”, is generated beneath the surface layer of the wire. Our study clarified that the depth of this additional shear strain layer was about 40 µm, and was constant for different diameter fine wires with the same reduction. For a wire of 100 µm diameter, this layer represents upwards of 80% of the cross-sectional area. Hence, the additional shear strain layer presumably comprises most of the improvement in high strength and ductility of the wires.

The chief purpose of this paper is to clarify the effect of the additional shear strain layer on fine diameter wire quality, and to apply it to further increase the strength and ductility of fine wire and other products. Work hardening of the wire is generated by the additional shear strain deformation between the die and the tool material. For starting material of constant grain size, and assuming a constant sub-surface friction layer at the die face, the strain gradient in small diameter wires is higher than that of large diameter wires. The grains are then forced to refine and rotate into the drawing direction due to the high amount of shear deformation. Therefore, it is determined that the strength is improved while the ductility remains the same – the material work hardens (increasing material strength), yet the grain size is refined (maintaining good ductility).

Tensile tests of fine wires with and without the additional shear strain layer prove that the additional shear strain layer affects the strength and ductility of the wire. In order to investigate the metallurgical effect of the shear strain, the grain orientations were observed via the Electron Back-Scatter Diffraction (EBSD) method. Grain maps and pole figures are presented. The grain aspect ratio and the angle to the drawing direction were measured as well. It is confirmed that the grains of the fine wire are more oriented to the drawing direction and are smaller than those of the large sized wire. For the large sized wire, pole figures of the surface are different from those of the center. However, for the fine wire, there is little difference in the pole figure between the surface and the center, and the slip plane of the material is parallel to the drawing direction in these pole figures. Therefore, the grains of the wire easily rotate into a textured orientation as a result of the large shear deformation throughout the surface to the center.

In summary, the additional shear strain layer improves the mechanical properties of fine wires. This layer is large, representing 80% of the volume of the wire, and results in refined grain size throughout. In addition, as the wire size decreases, the area exhibiting the shear strain increases. Therefore, it is expected that the strength and ductility of fine wires improve dramatically as the diameter drops. This result will be applied not only to the drawing process but also to other die contact deformation processes, such as forging, shearing, straightening, etc., of micro-formed products.

Deep processing of acid resistant steels – flattened strips
A. Skolyszewski, M. Rumiński

The paper presents the experimental analysis of some aspects of multi-stage deep processing technologies of producing the flat products of AISI 301 acid resistant steel, which can be used as semi-finished products for manufacturing high-quality springs. Special emphasis is put on the strip obtained in the round wire flattening process, and the strip obtained by cold rolling and slitting is discussed for comparison. The strip after each pass was subjected to mechanical testing and hardness measurements. The structure micrographs were made on the cross-sections of both flattened and cold-rolled strips, in order to observe the differences in material flow between these two processes. The results of hardness measurements and metallographic examination allowed to conclude that the strain is localized in the central region of flattened strip cross-section, unlike strip rolling, where the strain concentration is observed in the central area of the cross-section of the strip, but it distributes uniformly along the strip width. The problem of fatigue testing of the analysed products is taken into consideration and the flattened strip is presumed to show higher fatigue strength. The choice of the most suitable measure of deformation, describing that occurring in the flattening process, is also discussed.
Finite element modeling and optimization of powder segregation during metal injection molding

G. Ayad, A. Lejeune, T. Barrière, J. C. Gelin

The metal injection molding (MIM) technology is becoming a very active research field. MIM combines the well-known polymer injection molding and powder metallurgy technologies, resulting that parts with very complex geometry can be shaped as in traditional polymer injection molding. This technology is especially suitable to produce small and intricate metal parts in large batch under low cost. Compared to traditional powder metallurgy methods, one can obtain much more complex parts with better surface quality and higher mechanical properties.

Segregation is one of the major defects observed in metal injection molding and the objective of the paper is to minimize it by optimization. The use of standard optimization methods like Gauss-Newton or Levenberg-Marquardt needs to calculate the second derivative of the cost function. This derivative calculation is very difficult due to the fact that the cost function is obtained by the MIM simulation (i.e. Finite Element calculation). On the other side, the use of a stochastic algorithm, like Genetic Algorithm, needs large computing time. So an optimization methodology has been developed using an approximation of the cost function. At first, one uses a Design of Experiments to find the most influent parameters, in order to reduce the number of optimization parameters. Four significant parameters are found: powder volume fraction, interaction coefficient, powder density and binder density. Then, to reduce computing time a surface response method, using the Moving Least Square Approximation (MLSA), is used with an approximate cost function. Furthermore a genetic algorithm is coupled with this surface response approach to obtain the optimal values in reasonable computing time.

The optimization strategy proposed in this paper has been applied to minimize segregation during injection of a tensile test and wheel parts.

Optimization results are compared to MIM simulation coupled with optimization through Genetic Algorithm, and a good compromise is found in terms of optimised parameters for an acceptable computational costs.

Bending Profile Metals in Application with Artificial Neural Networks

K. -J. Fann, J. -C. Yang, P. -Y. Hsiao

Close control of spring back is essential for bending profile metals. Thus this study designed a bending process prediction system based on the error back propagation of artificial neural networks using an available database of numerous profile metal bending results as the learning samples, with the quantities of spring back being fully considered. Using this system, only data describing the shape of the bent profile metal is inputted and then a bending sequence suggested by this system is created, including the punch position, travel stroke and direction. After bending with the suggested procedure, the similarity between the bent profile metal and the desired shape is confirmed. To prepare the bending procedure database, this study performed numerous simulations of the multi-bending process using the finite element method. Additionally, a semi-automatic machine for bending profile metals is build to examine the process initiated by this study. Experimental results for bending 16 mm × 16 mm rectangular stainless steel 304 profiles into S-, U-, and W-shaped forms demonstrate that the process presented in this study can provide a good reference for engineers for bending profile metals.

Implementation of a Nonlocal Damage Model – Mesh Dependence in Sheet Metal Forming

N. Pernin, J. Chambert, P. Picart

The aim of the present work is to propose a micromechanical nonlocal damage model in order to predict the damage evolution in metal forming processes, especially in cold forging of small components. The modelling considered here is based on a Gurson model [1] modified by Tvergaard and Needleman [2], where the nonlocal damage has been defined in the same manner as Pijaudier-Cabot and Bazant [3]. The nonlocal void volume fraction is determined from an average of the usual local porosity at the neighbouring points using a weighting function. Two different weighting functions are used, the first one is defined by a Gaussian distribution function, the second one is defined in the same manner as Tvergaard and Needleman [4] ; the use of these two different functions is compared. The neighbourhood is determined by a material length $\ell_c$. The influence of the value of the parameter $\ell_c$ is studied. The ability of such nonlocal damage modelling to reduce the mesh-size dependency is investigated for the case of a 2D tensile specimen with a centred hole. Numerical results show that nonlocal extension trends to lower the mesh dependence.

Mesoscopic Model – Simulation of Size Effects in Microforming

S. Geißdörfer, U. Engel

Continued miniaturization as well as increased production numbers in the field of microelectronics production demands for a better understanding of micro forming processes. In this area of forming technology, the large ratio between mean grain size of the material and workpiece dimensions causes an increasing influence of single grains on the forming process. This effect can be visualized by the analysis of the local work hardening of the specimen measuring the micro hardness distribution. Moreover, some correlation between the integral flow stress of the workpiece and the scatter of the
process factors on the one hand and the mean grain size and its standard deviation on the other hand is detected in experiments. Conventional simulation which is by its nature size independent, is not able to consider the size effects observed in scaling down the process namely the reduction of the flow stress, the increasing scatter of the process factors and the local material flow being different to that obtained in the case of macroparts. Therefore, a new simulation model has been developed in order to take into account the detected effects and to determine the scatter of the process factors. The so-called mesoscopic model enables the discretization of the simulated material into individual objects which represent the grain structure of the real material. To each object – which represents a single grain – an individual flow curve is assigned, which is calculated on the basis of metal physics given by Hall-Petch and Ashby's theory. The computational grain structure generation is based on the Monte-Carlo-Potts model.

The presented paper deals with the theoretical background of the new mesoscopic model, its characteristics like grain structure generation and the calculation of micro material properties - based on conventional material properties. The simulation is computed by a commercial FE program MSC Superform 2003. To verify the simulation model, various experiments have been carried out with different mean grain sizes and grain structures but the same geometrical dimensions of the workpiece. It can be shown that the results obtained by these experiments compared to the results of the simulations are in a good agreement.

3D FEM Analysis and Optimization of Metal Forming and Temperature Development During Multi-Pass Rolling of the Round Shape
A. Milenin, H. Dyja

A mathematical model of three-dimensional non-isothermal metal forming during multi-pass rolling is proposed. To obtain numeric solution the finite element method is used. With the purpose of the account of processes relaxation of stresses occurring during deformation and pauses between passes the equations based on the dislocation theory are used. The problem of rolling of the round shape in 11 passes of LH15SG steel is considered. Multiple-path analysis of technology with different inter-pass cooling conditions is performed. Thermal distribution of deformation and forces in the passes are shown. The optimal technological variant is obtained from the criteria of final temperature and minimum power consumption.

Prevention of Wire Breaks and Its Analysis by FEA in Superfine Gold Wire Drawing
T. Yamashita, K. Yoshida

To connect IC chips with an external electrode, such as the lead frame of a semiconductor package, wire bonding using superfine gold wires is a mainstream process. Along with the advancement of electronic/electric apparatus and IT technology and the increase in the number of applications of IC cards, the miniaturization of semiconductor devices has been advancing; moreover, there is a strong demand for superfine wires for wire bonding. The price of semiconductor devices has been decreasing yearly, regardless of the demand for higher performance. Therefore, it is essential to produce superfine wires at low cost for wire bonding. In this study, wire breaking during superfine gold wire drawing, which leads to a decrease in the yield of superfine gold wires and an increase in production cost, has been examined, and its causes were analysed in order to take preventive measures against it. In examining the wire breaking observed in superfine gold wires drawn by conventional methods and conditions, the fracture surfaces of wire breaks were observed. The result indicates that wire breaking is mainly caused by inclusions in the wire. It was also found that most of such inclusions are oxides of aluminium or silicon with particle sizes of approximately 25µm in diameter, as determined by qualitative analysis. The fracture surface of wire breaks were observed in detail and the wire breaking process was analysed by FEA. By applying countermeasures devised on the basis of the previous discussions, a considerable increase of approximately 1.4-fold for the wire break length, which is calculated by dividing the total length of the drawn wire by the total number of wire breaks, was obtained for superfine gold wires with diameters of 20-30µm, compared to wires drawn by the conventional method.

Cold Drawing of Magnesium Alloy Wire and Fabrication of Microscrews
K. Yoshida

Recently, light magnesium alloy with superior heat radiating ability has been attracting attention in the fields of small digital electronic appliances, such as laptop computers, digital cameras, mobile phones, and automobiles. However, plastic working of the alloy is difficult, making warm or hot working necessary. Furthermore, the production of products with complicated shapes using the alloy is difficult, the processing cost is high, and the applicability of the alloy is limited. In this study, a technique for obtaining fine wires by cold drawing is examined to obtain wires with high strength, quality and surface morphology, while decreasing production cost. It was demonstrated that 60% or greater reduction of the cross-sectional area was realized during cold wire drawing by optimizing the drawing conditions. During the drawing process of the magnesium alloy wire, wire breakage occurred more easily when one-pass reduction was small, 10%. This is because, under a small-one-pass-reduction condition, the amount of shearing deformation of the wire surface increases during
drawing, and since the deformation ability of the magnesium alloy is low, cracks are generated, leading to wire breakage. In this study, the shearing strain of magnesium alloy wires drawn under various drawing conditions was calculated by FEM analysis. In addition, using the magnesium alloy fine wires obtained in this study, microscrews with M1.7 were fabricated by heading and form rolling processes. Since cracks were generated in the screw head formed by cold forging, a warm process was carried out at approximately 200°C. For forming the screw parts, the use of conventional cold form rolling was examined. By optimizing the processing conditions, the production of microscrews was possible. The dimensional accuracy and surface morphology of the microscrews produced were superior to and within the range of the standards of screws produced using commonly available materials.

**FEM Analysis of a Multi-Pass Hydrodynamic Drawing Process of High Carbon Steel Wires With Different Drawing Directions**

A. Milenin, H. Dyja, Z. Muskalski, J. Pilarczyk

In this paper steady-state wire hydrodynamic drawing processes were investigated by using the 2-dimensional rigid-plastic finite element method. The multi-pass hydrodynamic drawing technologies with different drawing directions were analyzed. The finite element method calculations resulted in obtaining the distributions of strain tensor components, effective strain and temperature. The joint deformation-temperature problem is considered. The thermal part is solved by reducing of the two-dimensional task to sequence one-dimensional tasks. Warming up of the metal deformation, heat conduction in the metal and also heat transfer to the drawing die and the air are taken into account.

A phenomenon of the occurrence of maximal strain values not at the wire surface but at certain distance from its conventional and hydrodynamic drawing, were also confirmed with a suggested model. As a result of the application of the changing of a drawing direction in the last three passes (in six passes drawing from 4.0 to 1.7 mm) a significant decrease in non-uniformity of a strain distribution on the cross section of the wire were noticed.

**Application of a fundamental friction model to the hot rolling of steel**

S. P. Jupp, J. Talamantes-Silva, J. H. Beynon

Friction is one of the most significant physical phenomena influencing the rolling processes, yet in comparison with metallurgy, heat transfer and mechanics it remains the least understood, since friction during rolling cannot be directly measured and the effect of friction is not immediately obvious. A fundamental friction model was developed based upon the simplified adhesion theory by Straffelini (Wear, 249, 79-85, 2001), which is an extension of Bowden and Tabor's adhesion theory that accounts for variations in surface energy between the contacting surfaces. This model was applied to the hot rolling of steel via a fully coupled 2-D finite element (FE) model and validated against literature experimental data. With the FE model, the friction coefficient, normal and shear stresses were predicted through the roll bite.

One of the assumptions of the FE model is a relatively thin, adherent scale layer. As such, an experimental programme was designed to provide this scale layer with the following approach: the sample was rolled with a small reduction, flaking the scale off of the sides, whereupon the sample was rotated 90° and rolled in the opposite direction. A time lag was observed in the temperature measurement as a result of the experimental technique, thus requiring the FE model to be validated against literature data.

**Through Process Characterization of Frictional Conditions for Long Product Hot Rolling**

C. Fedorciuc-Onisa, D. C. J. Farrugia

During multi-pass hot rolling of long products, the magnitude of the coefficient of friction within the roll bite is variable, affecting spread, rolling loads and torque as well as surface state, and is strongly dependent on inter-pass and in-pass rolling and cooling processing parameters. The need of shaping out the desirable or undesirable frictional conditions with the direct aim of controlling those outputs requires developing a more physical friction model.

The present paper describes the application, for specific long products and bar sections, of a newly developed Coulomb – Norton friction mathematical model, coded as a VFRIC subroutine within ABAQUS/Explicit. Its purpose is to study the influence of a range of rolling conditions such as, for example, roll velocity, roll surface roughness, thickness of secondary oxide scale, stock temperature, inter-stand and contact time, flow stress, slip rate etc. on the coefficient of friction, pinpointing, eventually, those circumstances where extreme friction conditions may occur.

The results derived from drawing up regime maps are aimed to study conditions and regions in the roll bite where shear stress could be reduced for improving product surface quality, where selective lubrication could be applied, but also for better predicting and optimising roll wear, lowering rolling power/load where applicable.
Monitoring of Process Variables and Friction During Cold Rolling
J. Larkiola, J. Nylander, M. Verho

The discontinuous cold rolling process has some major disadvantages compared to continuous / coupled cold rolling mills. The usual bottle neck of the process is linked to the amount of the strip thread-in/out, so rolling efficiency is mainly controlled by the success in threading control. Setup calculation models should also be able to calculate accurate values into the wide range of steel grades in different velocity phases and process conditions. To reach better rolling stability and product consistency, lubrication aspects appear to be a key issue which is necessary to control better in order to prevent abnormal working conditions in the roll gap.

In this work, a monitoring system for the 4 stand cold rolling process is created. The program reads strip related data from the automation system after the coil has finished in the exit section of the tandem mill. This input data is used, e.g. to calculate material flow stress curve and friction values of the stands. Furthermore, different velocity phases including threading in, low speed, acceleration, run speed and deceleration are taken into account during the analysing process. Results are stored in the database and by utilising the query options of the monitoring system the user can get a graphical view of the desired outputs. The monitoring system is used to improve pass schedule calculations by solving required process parameters. In addition, the processibility of the new steel grades can be predicted more accurately by utilising monitored results of the material flow stress curves. This speeds up, e.g. the development work of the new steel product and shortens the time from enquiry to trial and further on to the customer delivery. Also, dimensional ranges can be extended using more exact process parameters defined by analysing system.

Determination of the Coefficient of Friction in Partially Penetrated Draw Beads
M. Nanayakkara, G. L. Kelly, P. D. Hodgson

In the draw die process for stretch formed sheet metal parts, control is achieved partly by drawbeads placed in the flanged section of the blank. A draw bead is said to be fully penetrated when the sheet metal conforms fully to the geometry of the bead and the strip covers a total angle of wrap of 360° around the male and female beads. In many real forming applications partial penetration of draw beads occurs where the wrap of the sheet metal does not reach 360°. Therefore the standard equation by H D Nine [1] for fully penetrated draw beads may not be appropriate for partial penetration and it is shown that reduction in the angle of wrap with partial penetration is not taken into account in this equation. An equation is developed giving a weight factor which accounts for the change in the actual angle of wrap for the partial penetration of the sheet surface by the bead. By considering the equilibrium of forces on the bead, the strip tension, contact pressure and friction effect can be determined approximately. Constant Coulomb friction was assumed to prevail during the forming. Changes in the strip thickness in passing through the drawbead were neglected and the radius of curvature to thickness ratio was assumed to be constant. Drawbead experiments were performed for a range of bead depths. The friction coefficients as calculated by each of the equations were compared with the coefficient measured in a Flat Face Friction test. The analysis appears to represent the process for partial penetration in an acceptable manner provided the bead depth is greater than about a half that of full penetration.
Metal forming technology for producing bulk nanostructured metals.
A. Rosochowski, L. Olejnik, M. Richert

This paper reviews severe plastic deformation (SPD) technology used to convert common bulk metals into nanocrystalline metals (nanometals). The place and context of this technology in the nanotechnology revolution is discussed. The mechanics of SPD and its effect on the grain structure of metals is briefly explained. The indication of known and predicted properties of nanometals is given and envisaged applications discussed. Main SPD processes such as equal channel angular pressing (ECAP), high-pressure torsion (HPT), cyclic extrusion compression (CEC), multiaxial forging (MF), accumulative roll bonding (ARB) and repetitive corrugation and straightening (RCS) are described. New developments of ECAP, including a new 3D-ECAP, are presented. Future research and commercialisation prospects are discussed.

The Formation of Ultrafine Grained Steel Microstructures through Thermomechanical Processing
P. D. Hodgson, H. Beladi

The formation of ultrafine grained steels is an area of intense research around the World. There are a number of methods to produce grain sizes of approximately 1 µm, ranging from extreme thermal and deformation cycles to more typical thermomechanical processes. This paper reviews the status of the production of ultrafine grained steels through relatively simple thermomechanical processing. It is shown that this requires deformation within the Ae3 to Ar3 temperature range for a given alloy. The formation of ultrafine ferrite involves a dynamic transformation of a significant volume fraction of the austenite to ferrite. This dynamic strain induced transformation arises from the introduction of additional intragranular nucleation sites. It is possible that the deformation also hinders the growth or coarsening of the ferrite and may also lead to dynamic recrystallization of the ferrite. The most likely commercial exploitation of ultrafine ferrite would appear to rely on the formation of a critical volume fraction of dynamic strain induced ferrite followed by controlled cooling to ensure this is maintained to room temperature and to also form other secondary phases, such as martensite, bainite and/or retained austenite to improve the formability.

Asymmetrical cold sheet rolling in free horizontal entry conditions
M. Salimi, M. Kadkhodaie

Based on the slab method of analysis a model is proposed for the plane strain asymmetrical sheet rolling. In this model the normal stress across the thickness and in the rolling direction is linearly distributed. The shear stress distribution through thickness direction is assumed to be a second order polynomial with respect to the distance from the centreline and hence its coefficients are functions of the horizontal position of element. The frictional stresses are considered to be proportional to the mean yield shear stress of material. In deriving the governing equations, the mean value of the shear stresses across any section is required. Considering the flow rule the Von-Mises yield criterion was used. Effects of the shear stresses all around the vertical element were considered in the equilibrium equations and in the yield criterion. This model can predict the amount of deflection at entry to the roll gap in free asymmetrical rolling condition. It is also possible by this method to predict the condition at which the horizontal entry of the plate is occurred. However, the horizontal entry can be established by applying external loading to the plate at entry. In this paper setting of the rolling characteristics for free horizontal entry of the sheet is considered. The analytical results were compared with the experimental data. Numerical and experimental results are shown to be in good agreements.

A study on the ski-end direction in plate mills
A. Nilsson, A. Bogdanoff, S. Niemi

Unwanted asymmetric rolling conditions often cause ski-ends (front-end bending) in plate mills. Even though the roll speed is set equal on top and bottom roll there might be speed differences during speed up between the work rolls. Other asymmetries are different sized work rolls that will influence the contact length and the rolling level (table position) that will make the plate enter from below in an asymmetrical manner. The geometry in the roll gap is important for the development of a ski-end. The geometry can be described by the ratio of contact length and average plate thickness in the roll gap. Principally this means that for low values of the shape factor (early passes for thicker plates) the plate follows the slower roll. For higher shape factors (late passes) the plate follows the faster roll. The aim with this work is to study the interaction between the shape factor and various asymmetries. For this purpose finite-element simulations are used.
A Determination of the Total Roll Separating Force During Rolling Bimetal Rods in Grooves

S. Mroz, A. Milenin, H. Dyja

The proper design of the rolling process of the bimetal rods in the grooves requires taking into account many constraints affecting the process. During the technology design the rolling separating force is a parameter among many others, which should be determined.

In this paper a theoretical formula to determine the roll separating force during the bimetallic rods rolling in grooves, is proposed. It is obtained by analysis of the computer modeling results of stress distributions in the deformation zone as well as the results of experimental rolling. The rolling process in the passes round–horizontal oval is studied. Rolling force obtained from the proposed formula is compared to modeling by the SortRoll program that uses the full 3D plasticity solution of the finite element method (FEM).

In the theoretical and experimental research, bimetallic specimen with the different ratio of the soft clad layers to hard core as well as the different flow stress ratio are used.

Production of a new type of block-tram rail for European Union at Krolewska Steelworks Ltd.

K. Kolodziej, Z. Bigaj, R. Korzekwa

The production process of a new type tramway block rail is presented in article. A unique feature of the process is that it is implemented in three-high rolling mill that is not technologically suitable for the rolling of this type of rail. In the past this rail rolling was performed on the universal mills. As a consequence of this feature a lot of problems have been identified in connection with the rolling technology. For this reason, roll pass design has been improved several times and once modified. The reason for production process modifications at Królewska Steelworks Ltd. was associated with the necessity of reduction the number of turning-up of workpiece and free cross-flowing of metal in the chambers. Turning up number was limited by the available rolling mill equipment. The shape of rail caused the unconstrained metal flow in the part of the grooves where chambers were present. Consequently, the free cross flowing effect in the chambers was much more intensive than expected. Simplified method was developed to estimate the cross flowing of metal in the chambers. As a result roll pass design was developed, enabling the complicated rail shape rolling without using the universal stands and special tackle.

The Influence of Tool Geometry on the CWR Process of Hollowed Shafts

J. Bartnicki, Z. Pater

In order to extend the scope of knowledge concerning the cross-wedge rolling technology of hollowed shafts, numerical calculations of this process were conducted. In this example the software MSC.SuperForm2002 was used. On the basis of the calculations it was found that the stability of the CWR process of hollowed shafts may be distorted by slip and squeezing, irremovable ovalization of the cross section of the sample or by necking. Depending on the wall thickness of the rolled charge and the assumed rolling reduction ratio, the conditions in which there is no distortion or stability were determined. Moreover, the scope of the process parameters, at which the appearance in the initial phase of forming ovalization of the cross section is effectively removed and the sample free from defects, was established. The results of calculations were compared with the results of CWR experiments with the use of hollowed charges conducted in laboratory conditions. In this article, guidelines for the designing of wedge tool segments for the cross-wedge rolling of hollowed shafts are provided.

Width Variation and Shape Attenuation in Hot Strip Rolling

A. Dixon, W. Y. D. Yuen

Width changes occur as the strip is processed through the finishing train of a hot strip mill. Causes of this change include lateral spread during rolling as well as necking under tension between stands due to high temperature creep. Shape defects may also be attenuated between stands from creep. This paper is concerned with the modelling of these effects. This is carried out by coupling a model that predicts the lateral spread and generation of shape defects during rolling to that of an elasto-plastic inter-stand creep model.

The development of the Lateral Spread Model is outlined, where from physical principles an approximate lateral equilibrium equation is developed in terms of the downstream shape defect induced stresses and the lateral component of the roll gap friction. This method implicitly accounts for the effects of strip thickness, strip width and thickness reduction in the estimate of lateral spread. From the lateral strain the width change may be calculated, together with the shape defect corresponding to a non-uniform thickness reduction across the strip width.
Providing the strip does not buckle this shape defect causes a lateral variation in the normal stress in the rolling direction. It is possible for the shape defect to be appreciably attenuated between stands by plastic creep. The degree of plastic strain is predicted by a Creep Model. Expressions for the local stress are derived under the condition that the total tension force across the strip width is held constant by the tension control system. The reduction in the shape defect along the rolling direction may be calculated as well as any change in the strip width. Conditions where the strip remains flat, as well as when the strip buckles, are considered.

The combined model is successfully used to predict the trends in width change over the entire product range of a hot strip mill. It is also shown that the effects of inter-stand creep must be accounted for in the prediction of the final strip shape. In particular the onset of strip buckling, either from low inter-stand tensions and/or thin strip, will greatly reduce the degree of shape attenuation.

Investigation of hot rolling process using longitudinal slitting passes
S. Turczyn

Modern technology of bar rolling in many cases is based on the application of single or multiple longitudinal slitting, so-called Slit Rolling (SR) and Multi Slit Rolling (MSR). The slitting process uses special passes and guides to prepare, shape and separate the incoming billet into two or more individual strands, which will then be further rolled into finished sizes. The essence of this method is the application of two or three consecutive cutting-in passes, in which deformations of metal considerably differ from those occurring in conventional stretching passes.

In order to assess metal flow in the slitting passes, finite element method (FEM) was selected to be applied in the essential part of the analysis. The computations were based on the assumption of thermomechanical and viscoplastic model of deformation. The analysis of the influence of shape and width of slitting "knives" was performed with varying technological parameters. In particular, in case of three values of relative height of slitting "knife", three different shapes of "knife" as well as three different widths were analysed. Furthermore, physical modeling of the process of deformation in both slitting passes was realized with application of Gleeble simulator. The stress-strain characteristic of steel at relatively height strain rate condition was obtained. As a result of calculations, the complete metal flow patterns in the slitting passes were determined. The graphs presenting the distributions of stresses, strains and temperature in the deformation zone allow direct analysis, which gives better information about the phenomena in the roll gap. The obtained results allowed, in consequence, to design slitting passes more precisely and to apply slit rolling method in rolling mill for production of ribbed bars.

Numerical Modeling of Stock Stability in the Roll Grooves during Shape Rolling
S. Mróz, A. Milenin, H. Dyja

Stability of stock in the roll grooves depends mainly on its accurate entrance into the grooves and its support by rolling fittings. The loss of the stock stability in the grooves leads to changes of groove filling, and consequently to the appearance of product defects.

In this paper the mathematical model of the automated computer program SortRoll is used to theoretical study stock stability. The program is based on three-dimensional solution by the finite element method which allows calculation of metal flow features in the whole rolling deformation zone and accounts for stock shape and position, its temperature, velocity, rheological properties and friction condition. Regarding all those parameters allows an evaluation of stability of shape rolling in the grooves. Sensitivity analysis of final shape and rolling stability to the stock entrance angle is fulfilled.

Simulation of multipass hot rolling of AA 6082 aluminium alloy
C. Bruni, M. El- Mehtedi, A. Forcellese, F. Gabrielli, M. Simoncini

Multipass hot rolling of AA 6082 aluminium alloy were investigated by means of the simulative technique based on multistage hot torsion tests, performed on a hydraulically powered servo-controlled torsion machine. Three different test procedures, characterized by a linear decreasing temperature (from 525 to 300°C), a constant time between two subsequent deformations (20, 60 or 300 s) and a cumulative strain of 6.4 (number of passes equal to 16 or 32), were used: a) with constant strain rate on the specimen surface and constant strain per pass, b) with a linear increasing strain rate with a strain rate jump after each pass and constant strain per pass, c) with linear increasing strain rate and decreasing strain per pass. This allowed to simulate the rolling schedules for many combinations of process parameters. The influence of static and dynamic control parameters on the flow behaviour of the alloy was investigated in detail by analysing the flow curves. In particular, the envelope curves are influenced by the interpass time even if, at high temperatures, no significant effect is observed. The effect of the strain per pass differs from the one expected due to the strengthening effect produced by the static precipitation of second phase particles that is more enhanced as pass strain decreases. The strain rate path affects the envelope curves due to the strong influence of temperature on the constitutive parameters; finally, a more pronounced effect is produced by the strain path since early stages performed with larger pass strain values, owing to the more effectiveness of the dynamic restoration processes, lower the envelope curves.
Peculiarity of the Interaction Between Material Properties and Deformation Conditions during Sheet Hydroforming

R. Kawalla, S. Gouk

The interaction between microstructure constituents and local material flow were investigated at deep drawing of cold rolled sheet steels. Hydraulic bulge test, stretch forming with semicircular punch test and tensile test have been included in studies of local flow and phase deformation at DP, TRIP and ULC steels. Microstructure distribution and orientation changes of structural components were determined metallographically by optical and scanning electron microscopes (SEM), in situ tensile tests, as well as the determination of the texture by EBSD and X-ray diffraction methods.

As expected, different local deformations and variations of the microstructure in the investigated steels were found. Adequate diversifications in the material flow were the result of different forming processes. It can be associated to a fact of macro heterogeneity. The macroscopic modifications of the constituents in the microstructure are the results of the deformation (elongation) and orientation of hard structural components. This can be related to the macro and micro heterogeneity.

Computer Aided Design of Reshaping Process of Circular Pipes into Square Pipes

M. Tajdari, H. Moslemi Naeini, M. Kiuchi, A. Sanati, S. E. Hosseini Mehraban, D. Rezaee

Square pipes (pipes with square cross sections) are being used for various industrial objectives, such as machine structure components and housing/building elements. The utilization of them is extending rapidly and widely. Hence, the out-put of those pipes is increasing and new application fields are continually developing.

Due to various demands in recent time, the products have to satisfy difficult specifications with high accuracy in dimensions. The reshaping process design of pipes with square cross sections; however, is performed by trial and error and based on expert’s experience.

In this paper, a computer-aided simulation is developed based on the 2-D elastic-plastic method with consideration of the shear deformation to analyze the reshaping process. Effect of various parameters such as diameter of the circular pipe and mechanical properties of metal on product dimension and quality can be evaluated by using this simulation. Moreover, design of reshaping process includes determination of shrinkage of cross section, necessary number of stands, radius of rolls and height of pipe at each stand. All these points are investigated. Further, it is shown that there are good agreements between the results of the design method and the experimental results.

Innovative Semi-Finished Steel Tubes with Variable Cross-Section for Hydroforming

R. Shankar, S. Chatti, R. Göbel, W. Homberg, M. Kleiner

Structural parts, tubular by nature, could have been produced earlier directly by hydroforming due to simplicity in form and shape. For the present day components with complex design, particularly when the formability is limited, it is difficult to achieve the required shape directly by hydroforming. The formability in hydroforming mainly depends on the material used and the ratio between initial tube diameter and the final workpiece cross-section. The scope of this joint project, conducted at the Chair of Forming Technology, University of Dortmund, in association with several industrial partners, is to investigate the production of a complex structural component. A process chain consisting of the processes spinning, bending, and hydroforming was used instead of forming directly by hydroforming. The basic feasibility was first tested by a series of experiments in all the three processes individually. Subsequently, a demonstrator workpiece was passed through the processes spinning and bending. Semi-finished steel tubes were manufactured which fulfil the hydroforming requirements. To judge the behaviour of the pre-formed workpieces in the hydroforming process, burst tests have been carried out confirming the feasibility of the process chain.
Optimization and control of flange and tube hydroforming processes  
C. Labergère, A. Lejeune, J. C. Gelin

In the hydroforming processes for tubes and flanges, the research on the determination of process parameters especially loading and pressure curves as well as blankholder or axial punch ones is often long and tiresome. One proposes a numerical control methodology, based on an approximation per pieces of the objective functions and constraint ones compared to the control variables. This method allows the step by step construction of the main driving process parameters with respect to the required objectives in terms of shape and also thickness contours. One also compares this numerical control methodology with an optimisation methodology that is used to find the optimal process parameters. This approach is based on the parametric discretization of the objective function vs. process parameters to be optimized. Such a methodology needs to perform sensitivity analysis, i.e. the derivation of the cost function relatively to process parameters. One introduces the Finite Difference Method (FDM) and the Direct Differentiation Method (DDM) to perform such an analysis. Then the paper compares the results obtained from the control algorithm (CA) and the optimization one (OM).

FE Analysis of Spontaneous Axial Shortening of Tubes under Free Hydraulic Bulging  
A. Shirayori, S. Fuchizawa, M. Narazaki

The lengths of tubes spontaneously shorten during hydraulic bulging processes when only internal pressure is loaded on the tubes without longitudinal constraints at the tubes’ ends. This shortening behaviour has a potential to put forward suitable loading paths (hereafter referred as LPs) in tube hydroforming (hereafter THF). LPs are the relationships between internal pressure and axial feeding on the tubes and they are designed to obtain tubular products in sound condition without any failure such as bursting and buckling. Adequate axial feeding, which correlates with internal pressure, can be estimated by analyzing the spontaneous axial shortening. In this study, the shortening behaviours of straight tubes in free hydraulic bulging were investigated by use of FE analysis (hereafter FEA). It must be a fundamental approach to study the cases of free hydraulic bulging because its simplicity is expected to clarify the effects of material characteristics of tubing on the spontaneous axial shortening. Barlat & Lian’s anisotropic yield function that was proposed in 1989 was used in the FEA. This function can be same as Hill’s quadratic yield function and Mises’s yield function by changing some constants in the function. The effects of the parameters i.e. bulged length $L_b$, anisotropic coefficient $r$, the coefficient $m$ that characterizes the type of the yield function, $n$-value of $n$-th power hardening law and friction coefficient $\mu$ on the spontaneous shortening were investigated. The initial contact length $L_c$ between the tube and the supporting dies, which can be included in the parameters, was set at a constant value. It was clarified that $r$-value, friction coefficient $\mu$ and bulged length $L_b$ always affect the spontaneous shortening in this study. Greater $r$-value, less friction coefficient, and longer bulged length lead to greater amount of shortening no matter what values the other parameters were. By contrast with those three parameters, the effects of $n$-value and $m$ were relatively limited, i.e., the effect of $n$-value was small in the cases of shorter bulged length and the effect of $m$ was small in the cases of smaller $r$-value.

Minor Cyclic Deformation of AlMg0.45 Aluminium Alloy  
Z. Gronostajski, N. Msiolak

Intensive research on the development of energy-saving plastic forming processes has been conducted in several major scientific centres. The research is based on findings indicating a potential for a considerable reduction in flow stress, and consequently in deformation work, through a change in the strain path. In the early works of authors, it has been found that aluminium bronzes with low stacking fault energy (SFE) at small cyclic torsion amplitudes reduces the amount of energy accumulated in the material so much that the energy nowhere reaches the critical value needed to initiate dynamic recrystallization and the recovery process take place only. The main aim of the work is to investigate the effect of minor cyclic deformation on the flow stress, limit strain and structure in the case of material with high SFE, for that purpose the aluminium alloy AlMg0.45 was chosen. The alloy was subjected to symmetrical cyclic torsion with strain rate of $0.1 \, \text{s}^{-1}$ and different total amplitudes. For comparison, the torsion monotonic test was applied. The temperature was changed in the range of $20-550 \, ^\circ\text{C}$. For microstructure observation, optical, scanning and transition electron microscopes were used. At ambient temperature the effect of strain amplitude can be ascribed to the restoration of the deformed structure through reverse deformation. The flow stress for monotonic torsion at higher temperature of $400 \, ^\circ\text{C}$ is with fall typical for dynamic recrystallization. However structural studies carried out to confirm this, showed that no dynamic recrystallization occurs in material. The research has shown that the stress-strain curves with the fall in the case of aluminium AlMg0.45 deformed at $400 \, ^\circ\text{C}$ is due to the high heterogeneity of strain and its localization in shear bands in which very intensive dynamic recovery takes place as a secondary process. At $550 \, ^\circ\text{C}$ for monotonic torsion and minor cyclic torsion are similar to the ones obtained at $400 \, ^\circ\text{C}$, but in this case structural investigation confirmed the changes of flow stress in monotonic torsion are caused by dynamic recrystallization, but in the case of minor cyclic torsion by dynamic recrystallization and in some amount by recovery. From the research one can conclude that minor cyclic deformation intensifies strain heterogeneity and recovery. The fall in stress after its rise, characteristic for dynamic recrystallization, in materials with high SFE can be caused by dynamic recrystallization as well as by strain heterogeneity and strain localization in shear bands.
Comparison of the mechanical response of HSLA steel deformed under static and dynamic loading conditions

The need to understand and consider explicitly the microstructural and mechanical effects evoked by differences between static and dynamic loading is well recognized in engineering. In this paper, the dynamic mechanical behavior of a high strength low alloy (HSLA) steel was investigated by both quasistatic and high strain rate compression loadings. The tests were conducted in austenite, ferrite and intercritical regions. Microstructural and mechanical properties after plastic deformation under static and dynamic loading conditions were compared. It is confirmed that ferrite exhibits much higher temperature and strain rate sensitivity than austenite. Furthermore, the flow stress of samples annealed and deformed at room temperature becomes similar to these pre-strained, when higher strain and strain rate were applied. Different chemical composition of investigated steels allows to compare the effects of basic mechanisms controlling microstructure development (recrystallization, precipitation and austenite decomposition processes) under static and dynamic loading conditions. It is observed that these effects are the major factors determining the microstructure and mechanical properties of final products, also in the case of high strain rate deformation.

Hot ductility of low C-Mn-B steel under continuous casting simulation conditions for metal forming applications
A. K. Lis, N. Piwek, J. Lis, H. Dyja, M. Knapiński, J. Markowski

Continuously cast C-Mn-B steel has been chosen to study an effect of deformation temperature and strain rates under continuous casting simulation conditions and rolling processes. It has been found that hot ductility increases with increase of strain rate from $10^{-2}\text{s}^{-1}$ to $6,5 \text{s}^{-1}$. The higher strain rate; the bigger reduction of area values. Region of low ductility level was dependent both on temperature of deformation and strain rate. Surface cracking, especially the transverse cracking problem of continuously cast billets, is attributed to low ductility of steel. The flow stress equation from Forge 2 program used in FEM analysis was compared to real flow curves achieved from experiments with Gleeble 3500 apparatus.
Effects of Idealized Surface Geometry on Lubricant Entrapment during Plane-Strain Upsetting – An FEM Study.
W. Rasp, C. M. Wichern

During metal forming processes lubrication plays an important role in controlling friction and other forming parameters. The entrapment, entrainment and redistribution of lubricants during cold rolling or other forming processes are dependent to a large extent on the nature of the surface of the work piece and the tool. One important characteristic of the workpiece is the void volume of the surface. At lubricant film thicknesses that are of the same order of magnitude as the surface roughness, individual isolated pockets of lubricant can be formed on the surface. These pockets trap lubricant and transport it into the interface between the tool and the workpiece.

Previous work performed by the authors indicated that both the diameter of lubricant trapping pockets at the sliding interface during upsetting and the ratio of the diameter to the depth of the pockets are important. Experimental and preliminary FEM results showed that the pockets with a very small diameter, and thus a very low diameter-to-depth ratio, behaved much more rigidly than pockets with larger diameters. The more rigid pockets were found to retain their shape better during deformation and thus possibly affecting the lubrication condition at the sliding interface. Pockets that retain their shape during deformation do not redistribute lubricant back to the die-workpiece interface. Pockets which become highly distorted and very shallow after forming are much more effective at lubricant redistribution. The current work examines this behaviour via the modelling of idealized lubricant pockets with various diameter-to-depth ratios in order to ascertain whether there is a critical value for this ratio. This critical value is meant to indicate the ratio below which the pockets, due to their rigidity, are unable to supply lubricant to the sliding interface during deformation.

Influence of Parameters of Hydraulic Descaling on Temperature Losses and Surface Quality of Rolled Material
P. Kotrbáček, J. Horský, M. Raudenský, M. Pohanka

Hydraulic descaling is a process of removing the oxide from the hot steel surface. Surface quality after descaling is fundamental for the final surface quality of a roll product. Aspect of heat extraction, as a part of descaling process, is not usually seriously considered. Surface sub-cooling can negatively influence the demanded temperature field in the rolled material. The main goal of the paper is to show how the setting of hydraulic descaling parameters can influence heat transfer and the final temperature field in the rolled material.

Experimental work was concentrated on the study of descaling in relation to heat transfer and the quality of scale removing from the surface. Two types of measurements were implemented. The first one is a measurement of temperature drop when a product is passing under the nozzle (heat transfer test). The second type is a study of the surface quality where a defined layer of oxides is sprayed and its remaining thickness is evaluated. The heat transfer test is evaluated by inverse task and the results are prepared in a form of boundary conditions suitable for using in the numerical model.

The computation done by numerical model of descaling demonstrates the influence of various parameters on the process efficiency. Understanding of the hydraulic descaling mechanism enables the optimization of spraying parameters and its influence on the rolling technology.

A roll surface topography change during temper rolling
M. Burdek

The surface topography of work rolls during temper rolling was analyzed. 3D measurements of work roll surface before, during and after rolling were carried out using Rank Taylor Hobson TalyScan.

Two topographies of roll surface, which differ mainly in peak count number (SPc), were studied. The EDT machine was used to produce roll surface texture.

The change of some 3D parameters was analyzed. It was confirmed that the most popular roughness parameter SRa was decreased during the time of rolling.

It was found that there was a difference in manner of surface roll wear. The topography with a greater peak count deteriorated faster than the other, because peaks were sharper and a skewness was positive. Some other parameters like bearing ratio (SReduce), average material volume (Smvrbearing index (Sbi) were analyzed.

Use of Ceramic Inserts for Reduction of Wear in Forging Tools
B. A. Behrens, L. Barnert, A. Huskić

Tool life of hot forging is very short compared to other processes in massive forming. Reasons for this are the high thermal loads during hot forging, which lead to annealing effects on the surface of hot working steels, which are used for of hot forging dies. Therefore, new materials for tooling, which do not suffer hardness reduction due to annealing effects, like ceramic materials, have to be investigated. At IFUM the use of ceramic inserts on a basis of silicon nitride for wear reduction has been investigated. In the centre of the investigation were the joint of ceramic inserts and hot working steel dies, the behaviour of the composite in use and the wear of the ceramic.
In forging with flash a cone-shaped ceramic inserts from silicon nitride and sialon were fitted into steel dies by thermal shrinking.

The inserts showed a low probability of fracture at forging temperatures from 900°C to 1250 °C. Compared to steel dies, wear is reduced up to 6 times. A monolithic die made from silicon nitride with an adapted pre-stressing has been successfully tested in forging operation.

In a collective-research project the use of ceramic material for hot extrusion tools has been examined. Low breaking strain of ceramic materials was compensated in this application by a special design of tool and reinforcement. To compare wear on ceramic inserts from newly developed materials on basis of silicon nitride, a standard silicon nitride tool and steel tools (hardened and nitrided) have been investigated, too. Already with standard silicon nitride wear is reduced by 60 percent. Lowest wear is measured with a new variant of silicon nitride with improved high-temperature-characteristics. This ceramic variant shows wear 5 times less than the hardened and nitrided tool made from steel.

Another approach to join ceramic insert in steel dies is active brazing. This procedure was used to manufacture different types of dies to investigate the suitability. Upsetting tests proved a promising behaviour of the ceramic-metal composite. With the cone tool for forging with flash, where the cone was replaced by a ceramic insert a sufficient stability of the joint was found. For preliminary tests for precision forging of gears, ceramic cylinders were brazed to a model tool. After 100 forging cycles cracks appeared. These cracks did not lead to a failure of the die. The method of active brazing needs further investigation and forging tests.

**Some Issues about Tools and Friction in the Negative Dieless Incremental Forming Process**

M. Strano, L. Sorrentino, L. Carrino

In negative dieless incremental forming, a small punch plastically deforms a sheet metal, by following spiral-like or concentric trajectories, in contact with the concave side of the desired part geometry, while the sheet is clamped at the periphery onto a support frame. It is well recognized that severe deformations can occur before fracture, with negligible necking, thanks to the local shear state of strain induced by the process. The occurrence of fracture and the quality of the part mainly depend on the part geometry (particularly on the vertical inclination of the part wall α and on the feed rate fző) but they are also affected by the design of the punch. The simplest and most common design for negative incremental forming is a rigid tool with spherical contact surface and given radius r. However, several other alternative tools have been proposed in the technical literature: cylindrical punch, double punches spherical roller punch, etc.

The purpose of the present study is to investigate the effect of alternative tooling designs, with special reference to the effect of different punch radii r and the effect of friction on part quality.

It will be shown that formability may increase if using a nearly cylindrical punch, instead of a spherical punch. Besides, a moderate change in friction forces does not significantly influences formability, whereas a relevant increase in the friction makes formability significantly decrease.

The study is carried out by analyzing the results of several incremental forming experiments, executed with a robotic incremental forming cell. Most experiments have been executed with 3-axis spiral-like trajectories, but the effect of 4-axis interpolation (X, Y, Z plus Z-rotation) has been evaluated. Some FEM simulations have been run with a commercial code in order to further understand the results of the experiments.

**Die-less Forming Strategies for Non-Rotational Symmetrical Shapes**

S. Jadhav, R. Goebel, W. Homberg, M. Kleiner

The conventional metal forming processes need dedicated tooling, which costs in terms of both time and money. The "die-less" forming is one of the emerging technologies that can form a shape without using a die that conforms the desired shape. Due to the elimination of the die, the process offers higher flexibility that reduces product development time greatly, and makes it very suitable for rapid prototyping, research and development, and low volume production. At the Chair of Forming Technology (LFU), the "die-less" process research started using a die that conforms the shape or using a part specific support tool on a conventional CNC milling machine. The aim is to develop a process for the flexible production of sheet metal parts using minimum tooling. To realize maximum process flexibility, the forming was carried out with an unspecified support tool, revealing that the forming of non-rotational symmetrical shapes need different tool path and forming strategies. The paper focuses on the strategies established to form non-rotational symmetrical shapes using unspecific support tools and accuracy enhancement. Besides this, preliminary study on the forming of 3D surfaces and complexities involved to form these shapes without compromising process flexibility are presented. Apart from the improvement in forming accuracy, the result of the established strategies proved a substantial reduction in manufacturing cycle time and advancement in flexibility.
Initial Optimization of self-piercing riveting process by means of FEM
R. Cacko, P. Czyzewski, A. Kocańda

Although the importance of Self Piercing Riveting (SPR) as a joining technique of sheets constantly increases, especially in the automotive industry, there is still a lack of analytical description of mechanism of forming a joint. The reason is very simple: it is very difficult to get insight into the joint during forming process and following that to evaluate how stress field develops. The only way to analyze SPR joint during forming is to perform physical and numerical modeling. However the problem is not trivial because of high level of localized deformation combined with material separation. In detail, there exist some unknown parameters like beginning of separation of the upper sheet. These effects significantly influence reliability of analytical techniques. So far, preliminary simulations have been carried out using simple assumptions but without or with limited relation to real processes. Hence stress field after unloading, which determines strength of a joint, still remains generally unknown. In this paper initial trials carried out to optimize the SPR process using special algorithms implemented into commercial FEM codes are presented. Optimization of the FEM model refers to both real shapes of a joint and force history. They are crucial at the beginning of implementation of more sophisticated model taking into account complex stress state in the joint and relation with material separation. Commercial FEM codes: Abaqus, MSC/Marc-Mentat and MSC/SuperForm have been used for the SPR process simulation.

Electromagnetic Microforming of Metal Foil
I. Aoki, M. Sasada

In this study, experimental and analytical investigations were conducted on applying electromagnetic forming for the microforming of thin parts. Generally, electromagnetic forming (hereafter referred to as direct forming) of thin parts is difficult. Results of analysis on electromagnetic force indicate the reason to be a decrease in the electromagnetic force when the workpiece thickness becomes thin, demonstrating that direct forming is not appropriate for the microforming of thin parts. The indirect forming method described below was therefore attempted. The conductive plate and polyurethane resin adhered on the conductive plate are accelerated together. As a result, the polyurethane resin receives kinetic energy, and the elastic strain energy presses in the workpiece (sheet metal) into the die to mold it. The results of experiments confirm that indirect forming is more advantageous than direct forming. The influence of the diameter, thickness, and hardness of urethane were also investigated.

Towards a Fundamental Understanding of the Stretch Levelling Process
M. Lovell, P. Deshmukh, N. Yavelak

Sheet metal processing costs represent an enormous investment by manufacturers each year. Since the aesthetic and tolerance requirements of modern high-speed, automated sheet metal forming processes are continuously increasing, there is a substantial need for the flatness control of sheet metal products. In the present investigation, an innovative metal coil ‘stretch levelling’ process is introduced for improving the formability of sheet metal parts. To study the physical behaviour involved in the process, advanced numerical analysis techniques are utilized. After being validated by comparison to actual industrial stretch levelling experiments, the numerical results are then utilized to obtain a basic model for predicting conditions that lead to failure in stretch levelling.