Process and die design for square tube extrusion

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In this study, die profile of the square tube extrusion process is optimized to produce microstructurally sound product at maximum production speed and minimum left out material in the die. The design problem is formulated as a nonlinear programming model, which is solved using genetic algorithms (GA). Selection of the processing parameters is carried out using dynamic material modeling (DMM). Using this approach a square tube extrusion process is successfully designed.

Keywords: Microstructure; Die profile; Simulation, Processing parameters; Extrusion; Genetic algorithms

Extrusion die profile plays an important role on material flow, microstructural evolution, speed of production and left out material in the die. Conical dies, designed using conventional methods, suffer from two major drawbacks. First, the formation of dead metal zone and secondly large amount of left out material in the die cavity. Samanta\textsuperscript{1} proposed an approach for convex shape die profile for axisymmetric extrusion and drawing using upper-bound theorem. Efficiencies of these dies exceed those of conventional conical dies. Reddy \textit{et al.}\textsuperscript{2,3} reported die profile design for hot and cold extrusion using upper bound method and FEM. Jou and Hwang\textsuperscript{4} attempts shape optimal design of tube extrusion using sensitivity and rigid visco-plastic finite element approach. Kim \textit{et al.}\textsuperscript{5} optimized die profile of axisymmetric extrusion of MMCs using FEM in order to obtain uniform strain rate profile. Ponalagusamy \textit{et al.}\textsuperscript{6} attempts to design streamlined dies using Bezier curve and upperbound theorem. Lee \textit{et al.}\textsuperscript{7} optimized the die profile using Bezier curve to get uniform microstructure in hot extrusion. Neural networks are used in die profile design by Yan and Xia\textsuperscript{8} and Mehta\textsuperscript{9}. Genetic algorithms are also applied for die profile design by Wu and Hsu\textsuperscript{10}, Chung and Hwang\textsuperscript{11} and Narayanasamy \textit{et al.}\textsuperscript{12}

Although large amount of literature is available on die profile design, it can be observed that they address specific aspect of manufacturing. It is very rare to find literature, which address metallurgical and manufacturing aspects altogether. To overcome this issue, a holistic approach of die profile design using power law equation is proposed here. The important features of this are: (i) selection of processing parameters using DMM for microstructurally sound product and (ii) maximization of the speed of production at minimum left out material in the die cavity.

The design problem is formulated as a non-linear constrained programming problem, which is solved using genetic algorithms (GA). A tube extrusion process is successfully optimized using the proposed approach. Designed parameters are further used for computer simulation.

Dynamic Material Modeling (DMM)

DMM is based on relationship between the deformation induced visco-plastic heat generation and the energy dissipation associated with the micro-structural mechanisms occurring during deformation. DMM uses a non-dimensional iso-efficiency index ($\eta$) and it is given as\textsuperscript{13}

$$\eta = \frac{m}{1+m}$$  \hspace{1cm} (1)

where $m$ is the strain rate sensitivity of the material. The plot of iso-efficiency ($\eta$) values on the temperature-strain rate axes with the interpreted deformation mechanism mapped on to the plot constitute the ‘processing map’. The regions of high efficiency regime are the desirable region for the processing. The true stress-plastic strain values, at
different strain rates, are required for computing the efficiency factor ($\eta$). The procedure of constructing the map is presented elsewhere. In Fig. 1, processing map of 304 LN is shown. It can be observed, maximum iso-efficiency is about 29% and corresponding strain rate and temperature are 0.1 and 1100°C respectively. The highest efficiency will correspond to dynamic recrystallization which in turn will ensure good workability. DMM has been successfully used for designing of metal forming processes.

**Genetic Algorithms**

Genetic algorithms are computerized search and optimization algorithms based on the mechanics of natural genetics and natural selection. The operation of GA's begins with a population of random strings or decision variables. Thereafter, each string is evaluated to the fitness value. Three main operators, viz., reproduction, crossover, and mutation are used to create a new population of points then operate the population. The population is further evaluated and tested for termination. If the termination criterion is not met, the population is iteratively operated by the above three operators and evaluated. This procedure is continued until the termination criterion is met. One cycle of these operations and the subsequent evaluation procedure is known as a generation in GA's terminology.

The basic difference of GA’s with most of the traditional optimization methods are that GA use a coding of variables instead of variables directly, a population of points instead of a single point, and stochastic operators instead of deterministic operators.

All these features make GA search robust, allowing them to be applied to a wide variety of problems. The advantage of using GA over other gradient based methods, is that the latter can be mapped on local minima whereas, GA predicts global minima which may be hidden between several local minima (Fig. 2). In recent years GAs have been successfully applied to die design problems.

**Formulation of Design Problem**

A schematic of the die for square tube extrusion is shown in Fig. 3. Let $D_b$, $D_e$, and $D_m$ be the dimensions of billet, extruded rod and mandrel respectively and
Material volume required to fill the die cavity is:

\[ V = \frac{(D_b^3 - D_m^3) - 3D_m^2(D_b - D_e)}{6 \tan (\alpha)} \] ... (2)

If \( v \) is the ram velocity then time to fill this volume will be

\[ T = \frac{V}{(D_b^2 - D_m^2) \times v} \] ... (3)

Now strain rate can be calculated by

\[ \dot{\varepsilon} = \frac{\ln R}{T} \] ... (4)

where \( R \) is the extrusion ratio given by

\[ R = \frac{(D_b^2 - D_m^2)}{(D_e^2 - D_m^2)} \] ... (5)

Selection of strain rate and temperature can be carried out via the processing map to meet out metallurgical aspects. Using thus selected process parameters, ratio of velocity to cavity volume can be maximized to result in faster production at minimum wastage of material. The whole design problem can be put into following optimization problem:

Max \( \frac{v}{V} \) ... (6)

Subject to \( \dot{\varepsilon}(v, \alpha) = c \)

\( v_{\text{min}} \leq v \leq v_{\text{max}} \), \( \alpha_{\text{min}} \leq \alpha \leq \alpha_{\text{max}} \)

\( v, \alpha \geq 0 \)

Here \( c \) is the strain rate obtained from the processing map. ‘Min’ and ‘max’ are the limits of different parameters. This constrained optimization problem is solved using GA. The flow chart of the design process is shown in Fig. 4.

**Numerical Example**

A square tube extrusion process considering 304LN steel is designed using the proposed approach. External and internal dimensions of the tube are 20 and 16 mm. Outer dimension of the billet is 80 mm and mandrel dimension is 16 mm. Extrusion ratio is 42.67. The minimum and maximum limits on velocity (\( v \)) and die angle (\( \alpha \)) are 0 and 1 mm/s, 40° and 80° respectively. Processing map of 304L is shown in Fig. 1. The maximum iso-efficiency is about 29% and corresponding strain rate and temperature are 0.1 and 1100°C respectively. Using these parameters the optimization of the above mentioned objective function is carried out using GA. The GA parameters adopted in this study are given in Table 1. The

<table>
<thead>
<tr>
<th>S. No.</th>
<th>GA parameter</th>
<th>Value</th>
</tr>
</thead>
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<tr>
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<td>Population</td>
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<td>2.</td>
<td>Generations</td>
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<td>3.</td>
<td>Reproduction type</td>
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<td>4.</td>
<td>Selection type</td>
<td>Sigma Scaling</td>
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<td>5.</td>
<td>Mutation probability</td>
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<td>6.</td>
<td>Reproduction probability</td>
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</tr>
<tr>
<td>7.</td>
<td>Selection probability</td>
<td>0.85</td>
</tr>
</tbody>
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Fig. 4— Flowchart of the proposed methodology

Fig. 5— Flow curve of 304 LN
optimized ram velocity and die angle come out to be 0.315 mm/s and 49.13° respectively. Computer simulation on the optimized die is carried out using MSC. Superforge software, which is based on control volume method\textsuperscript{18}. The material model is carried out using rate power law:
\[
\sigma = K \dot{\varepsilon}^n
\]
where $K$ and $n$ are the coefficients of rate dependent flow curve\textsuperscript{19,20}. The flow data for this material is given elsewhere\textsuperscript{21}. The coefficients $K$ and $n$ of the rate flow curve for the given temperature and strain rate are 141.3 and 0.17 respectively. Yield stress is taken as 141.3 MPa. Flow curve of 304 LN is shown in Fig. 5. The optimized die profile has been used for the computer simulation. A typical CAD model showing die, punch and the mandrel is given in Fig. 6. Length
of the billet is 200 mm and Coulomb friction is 0.1. Von mises stress, effective plastic strain and strain rate contours obtained from the simulation are shown in Figs 7-9. Maximum stress is 141.3 MPa, which indicate the yielding of the billet during deformation. Maximum strain is 2.118, indicating considerable deformation during extrusion. Average strain rate in the deformation zone is 0.1, which will ensure good microstructure evolution. The load stroke curve is shown in Fig. 10. It can be observed that maximum load requirement will be 22.33 MN.

Conclusions
In this study, die and process for square tube extrusion is optimized to meet out microstructural criteria at maximum production speed and minimum left out material in the die cavity. The extrusion process design is formulated as a constrained non-linear programming problem, which is solved using GA. An extrusion process is successfully design based on this approach. Computer simulation is also carried out on the optimized design to obtain stress, strain and strain rate distributions and load requirement. It can be observed that proposed approach provides a total solution for extrusion process design of the square tube.

Acknowledgement
Permission of ASM International to reproduce processing map of 304 LN is gratefully acknowledged.

References