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ORIGINAL RESEARCH

Process and die design for rod extrusion of γ iron

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Abstract This study is related to materials modeling and die and process design of rod extrusion of γ iron. Strain dependent rate power law is used for materials modeling whose coefficients are arrived at through genetic algorithm (GA). Die profile of the rod extrusion process is optimized to produce products of desirable microstructure at maximum production speed and minimum left out material in the die. The design problem is formulated as a nonlinear programming problem which is solved using GA. Selection of the processing parameters is carried out using dynamic materials modeling (DMM). Using this approach rod extrusion process of γ iron is successfully designed. FE simulation on the optimum profile is also attempted to study deformation behaviour and load requirement.

Keywords Gamma iron · Extrusion · Die profile · Dynamic materials modeling · Genetic algorithm

Introduction

Gamma iron is a form of austenite steel used for making cutlery, hospital and food-service equipments, tableware and the like. These steels are mainly processed using bulk forming methods like rolling, forging, extrusion etc. Bulk forming is considered as primary processing technique as the major microstructural change occurs during this step. In this regard proper design of the forming processes are very important in manufacturing. Conventional approach of metal forming process design is based on trial and error methods. Such approach is costly, time consuming and hardly optimal. In recent years computer simulation based approaches such as finite element analysis are being excessively used for such applications due to their ability to provide realistic design data in short span of time. In finite element analysis of metal forming process, a suitable material model is a prerequisite. Tomov et al. [1] have shown that proper material model is a key factor for realistic FE simulation. These models are in the forms of certain mathematical equations whose coefficients are arrived by data fitting obtained from experiments. Conventional data fitting techniques are mathematically simpler and can't handle large number of coefficients. Most often, strain independent material model is adopted in finite element simulation of hot deformation processes but it has been observed that strain also affects the flow stresses. In this study, strain dependent rate power law model has been used for materials modeling of the gamma iron. Materials modeling is proposed as an optimization problem which is solved using genetic algorithms. Resulting coefficients will make out the best fit model which will also take into the account the inherent errors in the experimental data.

Extrusion die profile plays an important role on material flow, microstructural evolution, speed of production and left out material in the die. The conventional conical dies suffer from two major drawbacks. These are, formation of dead metal zone if die angle is large and large size of die if die angle is small. Some of the prominent developments in this field are described below.

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Samanta [2] proposed an approach for convex shape die profile for axisymmetric extrusion and drawing using upper-bound theorem. Efficiencies of these dies exceeded those of conventional conical dies. Venkata Reddy, Dixit and Lal [3] reported die profile design for hot and cold extrusion using upper bound method and FEM. Joun & Hwang [4] attempted shape optimal design of tube extrusion using sensitivity and rigid visco-plastic finite element approach. Kim, Kang and King [5] optimized die profile of axisymmetric extrusion of metal matrix composites (MMCs) using FEM in order to obtain uniform strain rate profile. Ponalagusamy et al. [6] attempted to design streamlined dies using Bezier curve and upperbound theorem. Lee, Ko and Kim [7] optimized the die profile using Bezier curve to get uniform microstructure in hot extrusion. Neural networks were used in die profile design by Hong Yan & Xia [8] and Bhavin Mehta et al. [9]. Genetic algorithms were also applied for die profile design by Wu & Hsu [10], Chung & Hwang [11], Narayanasamy et al. [12].

Although large amount of literature are available on die profile design, it can be observed that they address specific aspect of manufacturing. It is very rare to find literature which account metallurgical and manufacturing aspects together. To overcome this issue, a holistic approach of die profile design using power law equation is proposed here. The important features of this are the following -

1. Materials modeling using strain dependent rate power law whose coefficients are calculated using GA.
2. Mathematical modeling of the die profile using power law equation.
3. Selection of processing parameters using DMM to produce products of desirable microstructure.
4. Maximization of the speed of production at minimum left out material in the die cavity using GA.

The design problem is formulated as a non-linear constraint programming problem which is solved using genetic algorithms (GA). A rod extrusion problem is successfully designed using the proposed approach. Designed profile is further used for finite element simulation.

Dynamic Materials Modeling (DMM)

DMM is based on relationship between the deformation include visco-plastic heat generation and the energy dissipation associated with the microstructural mechanisms occurring during deformation. DMM uses a non-dimensional iso efficiency index (η) and it is given by Prasad & Sashidhara [13] as:

$$\eta = \frac{m}{1 + m} \tag{1}$$

where m is the strain rate sensitivity of the material. The plot of iso-efficiency (η) 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 (η). The procedure for generation of the map is given in [Prasad & Sashidhara, 13]. In Fig. 1, processing map for γ iron is shown, which is taken from Avadhani [14]. It can be observed that maximum iso-efficiency is 38% corresponding to 1150°C and 0.03 strain rate. The highest efficiency will correspond to dynamic recrystalization which in turn will ensure good workability. DMM has been successfully used for designing of metal forming processes [Srinivasan et al., 15; Venugopal et al., 16].

Material models

The popular material models available in the standard literature [17] and [18] can be described under following heads-

(a) Strain rate independent models

Some of the prominent strain rate independent models are—

Hollomon equation

It gives a power law relationship between stresses and strains.

$$\sigma = K\varepsilon^n \tag{2}$$

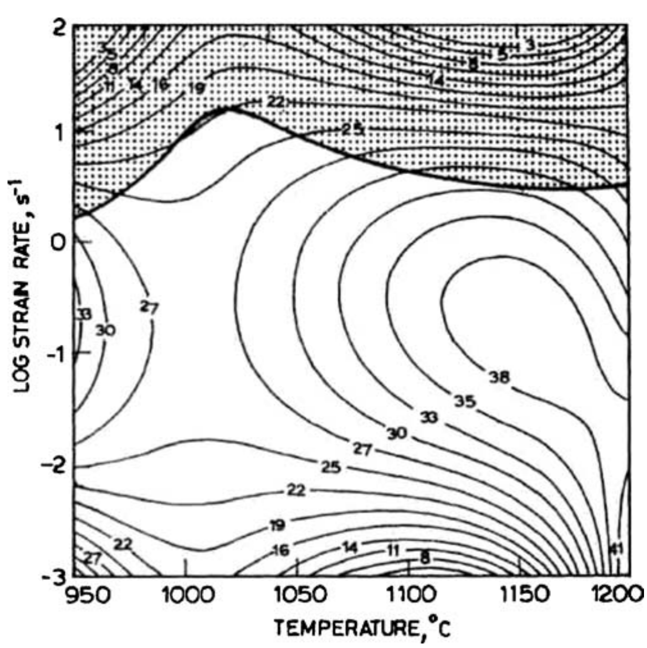

Fig. 1 Processing map of γ-Iron

where K and n are strength coefficient and strain hardening coefficient respectively.

Ludwik equation

This model includes the effect of yield stress σ_0.

$$\sigma = \sigma_0 + K\varepsilon^n \tag{3}$$

Swift equation

This model includes the effect of yield strain ε_0.

$$\sigma = K(\varepsilon_0 + \varepsilon)^n \tag{4}$$

Equations 2, 3 and 4 are valid only in a limited range of stress strain curve. The equations predict infinity slope at zero strain and infinity stress at infinity strain, which are not correct. Experimentally, a saturation of stress occurs at higher strains. These drawbacks are overcome by Voce equation given below.

Voce equation

$$\sigma = A - Ke^{(-C\varepsilon)} \tag{5}$$

(b) Strain independent rate power law

It gives power law relationship between stress and strain rate.

$$\sigma = K\dot{\bar{\varepsilon}}^m \tag{6}$$

(c) Strain dependent rate power law

It includes the effects of both strain ε and strain rate $\dot{\varepsilon}$.

$$\sigma = K\varepsilon^n\dot{\bar{\varepsilon}}^m \tag{7}$$

Materials modeling as an optimization problem

The experimental flow data for the materials modeling are taken from Avadhani [14]. The flow stresses at different strains and strain rates are given in Table 1. The test temperature is 1150°C which corresponds to highest iso-efficiency. These data are to be modeled in a strain rate dependent power law (Eq. 7).

The materials modeling can be framed as a non-linear programming problem. The objective function is the sum total of square root error at 30 sampling points. Coefficients K, m and n are obtained by solving following optimization problem:

$$Min \quad \sqrt{\sum_{i=0}^{30}\left(K\varepsilon_i^n\dot{\bar{\varepsilon}}_i^m - \sigma_i\right)^2} \tag{8}$$

Subject to-

$0 \le m \le 1$

$0 \le n \le 1$

$0 \le K \le 1000$

The solution of this optimization problem is carried out using Genetic Algorithm. The following GA parameters are adopted in the study.

Variable	Real
Population Size	35
Number of generations	100
Reproduction type	Two point crossover
Reproduction Probability	0.85
Mutation Probability	0.005
Population refresh period	10 generations
Selection	Tournament Selection
Elitism	4
Percentage Population Refreshed	10

Optimized values of m, n and K came out to be 0.156, 0.108, and 63.18 respectively. For this, the square root error is 59.08. Using this model, flow stress at 30 sampling points are recalculated and % error is calculated with respect to experimental counterparts (Table 1). It is observed that error is maximum where softening is reported in the experiments. The proposed model compensates the experimental errors and gives best fitting.

Formulation of the die profile design problem

Let D_b and D_e be the diameters of billet and extruded rod respectively and h be the length of the transition zone of the die. Extrusion die profile is modeled by power law equation given below (Fig. 2).

$$y = \frac{(D_b - D_e)}{2}\left(\frac{x}{h}\right)^t \tag{9}$$

t is the power exponent.

Material volume required to fill the die cavity is:

$$V = \pi h\left\{\frac{D_b^2}{4} - \left(\frac{D_b}{2} - \frac{t(D_b - D_e)}{2(2t+1)}\right)\frac{(D_b - D_e)}{(t+1)}\right\} \tag{10}$$

If v is the ram velocity , time to fill this volume will be-

$$T = \frac{4V}{\pi D_b^2 v} \tag{11}$$

Now the mean strain rate can be calculated by—

$$\dot{\bar{\varepsilon}}_t = \frac{\ln R}{T} \tag{12}$$

Table 1 Test & predicted data

S.No.	Strain	Strain Rate (per sec)	Stress (MPa)	Predicted Stress (MPa)	% Error
1	0.1	0.001	15.0	16.09	7.27
2	0.1	0.010	20.8	23.36	12.31
3	0.1	0.100	32.7	33.93	3.76
4	0.1	1.000	56.7	49.27	13.10
5	0.1	10.00	92.7	71.54	22.83
6	0.1	100.0	74.4	103.89	39.64
7	0.2	0.001	14.7	17.34	17.96
8	0.2	0.010	20.5	25.18	22.83
9	0.2	0.100	32.9	36.57	11.15
10	0.2	1.000	60.7	53.10	12.52
11	0.2	10.00	102.3	77.12	24.61
12	0.2	100.0	97.0	111.97	15.43
13	0.3	0.001	14.4	18.12	25.83
14	0.3	0.010	20.4	26.31	28.97
15	0.3	0.100	32.1	38.20	19.00
16	0.3	1.000	55.8	55.48	0.57
17	0.3	10.00	97.4	80.56	17.29
18	0.3	100.0	106.6	116.98	9.74
19	0.4	0.001	14.4	18.69	29.79
20	0.4	0.010	20.9	27.14	29.86
21	0.4	0.100	33.5	39.41	17.64
22	0.4	1.000	54.6	57.23	4.817
23	0.4	10.00	96.7	83.10	14.06
24	0.4	100.0	108.0	120.67	11.73
25	0.5	0.001	14.5	19.14	32.00
26	0.5	0.010	21.7	27.80	28.11
27	0.5	0.100	33.4	40.37	20.87
28	0.5	1.000	54.2	58.62	8.15
29	0.5	10.00	98.1	85.13	13.22
30	0.5	100.0	103.8	123.61	19.08

where R is the extrusion ratio given by-

$$R = \frac{D_b^2}{D_e^2}$$

Selection of mean 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:

$$Max \quad v/V \tag{13}$$

$$\begin{aligned} \text{Subject to}\ &\dot{\bar{\varepsilon}}_t(v,h,m) = c \\ &v_{\min} \le v \le v_{\max} \\ &h_{\min} \le h \le h_{\max} \\ &t_{\min} \le t \le t_{\max} \\ &v,h,t \ge 0 \end{aligned}$$

Here c is the strain rate obtained from the processing map. Min and max are the limits of different parameters.

Numerical example

A γ-iron rod extrusion process is designed using the proposed approach. Billet and extruded rod diameters are 150 mm and 75 mm respectively. In this way, extrusion ratio comes out to be 4. The minimum and maximum limits on velocity (v), transition length (h) and power exponent (t) are 1 & 10 mm/sec, 20 & 50 mm and 1 & 5 respectively. The strain rate of 0.03 is adopted from the processing map of the γ-iron. Using these parameters the optimization of the above mentioned objective function was carried out using GA. The optimized ram velocity, length of the transition zone and power exponent came out to be 7.87 mm/sec, 43.78 mm and 2.93 respectively.

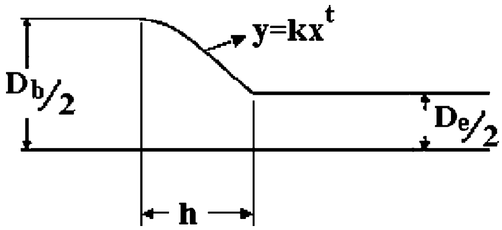

Fig. 2 Die profile

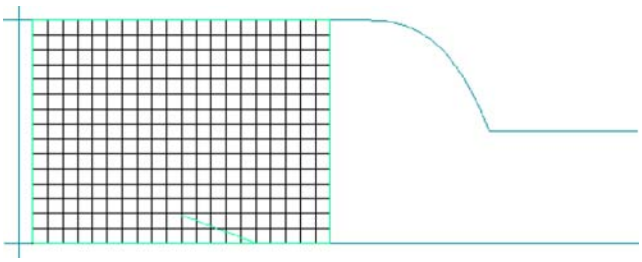

Fig. 3 FE model

Keeping strain rate, ram velocity and extrusion ratio same, die angle of the equivalent conical die can be calculated using following relationship:

$$\dot{\bar{\varepsilon}}_t = \frac{6vD_b^2 \ln\ R\ \tan\ \alpha}{D_b^3 - D_e^3} \tag{14}$$

For this particular case, conical die angle, comes out to be 32 degree. Material volume of proposed power law die can also be calculated and compared with the conical die. If the die thickness is 20 mm, die material volumes in the transition zone of power law and conical dies will be 622452 and 1083263 mm^3 respectively. In this way 42.45% saving of the material can be achieved using the proposed die.

In order to study the deformation behaviour and load requirement, finite element simulation on the optimized die profile is carried out using MSC.Superform software [19]. The axisymmetric modeling was carried out using four noded elements. There are 300 elements and 336 nodes in the model. Overlay quad remeshing criterion has been adopted in the FE simulation. The material model is defined by strain dependent rate power law, (Eq. 7), whose coefficients (K, m & n) were calculated in a previous section. Length of the billet is 200 mm and Coulomb

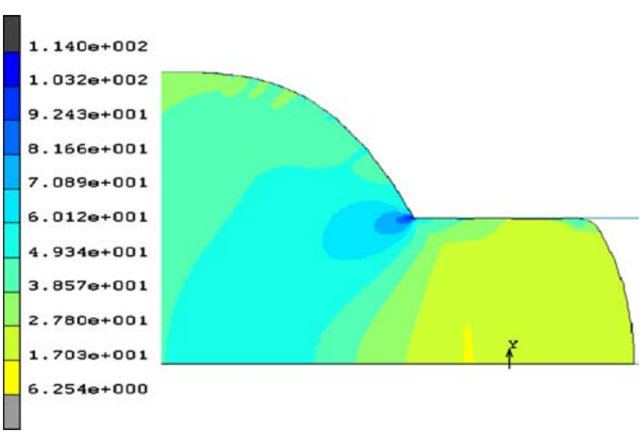

Fig. 4 Effective stress (MPa) contour

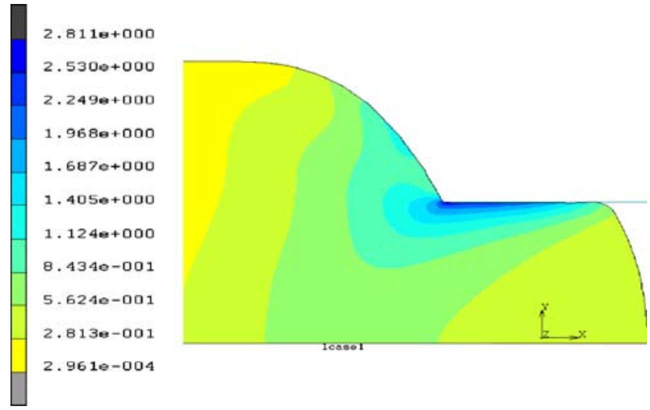

Fig. 5 Plastic strain contour

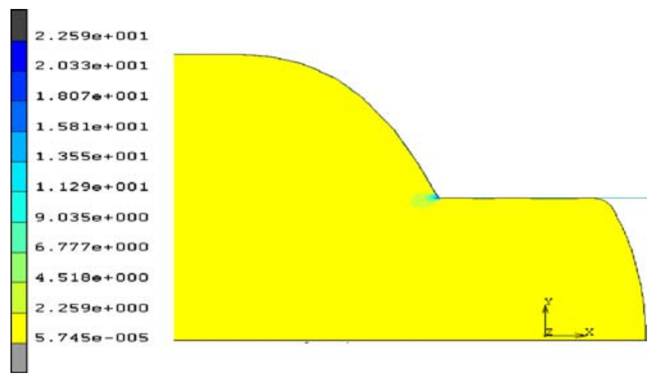

Fig. 6 Strain rate contour

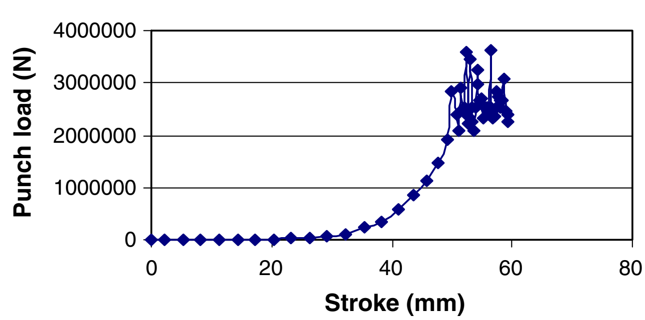

Fig. 7 Load stroke curve

friction is taken as 0.1 based upon the previous extrusion experiences of the authors. Von-mises stress, effective plastic strain and strain rate contours obtained from the FE simulation are shown in Figs. 4, 5 and 6 respectively. It can be observed that maximum stress is 114 MPa. Strain value of 2.81 indicates the occurrence of large deformation. Strain rate distribution in the die is uniform except at the die end. This will assist in uniform evolution of microstructure in the extrudate. The load stroke curve is shown in Fig. 7. The load requirement is 3.62 MN.

Conclusions

In this study extrusion die profile for γ iron is optimized to meet out microstructural criteria at maximum production speed and minimum left out material in the die cavity. Materials modeling is carried out using strain dependent rate power law, whose coefficients are optimized using GA. The die profile design is formulated as a constrained non-linear programming problem, which is solved using GA. Extrusion profile for γ iron is successfully designed based on this approach. Considerable saving in the die material is observed using power law as compared to conventional conical dies. Finite element simulation on the optimized die is also carried out to assess stress and strain distributions and load requirements. It can be observed that proposed approach provides a holistic solution for extrusion process design.

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