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# SIMULATION OF FATIGUE AND WEAR LIFE OF EXTRUSION DIES

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## ABSTRACT
*Replacement of dies and affiliated tooling in hot metal extrusion is costly. Special high-strength and high-hardness tool steels, precision manufacturing methods such as spark erosion, and specific heat treatment and surface hardening requirements contribute to this high cost. One of the major design/manufacturing goals is therefore a longer tool life. Though research in the area is continuing, failure of metal forming dies is a complex issue, and quite difficult to control or prevent. A reasonably accurate prediction of time to failure can form the basis for optimum replacement and stacking strategies, and for performance evaluation of hot working dies. Failure of extrusion dies can be traced to three major modes: fracture, surface wear, and excessive plastic deformation (deflection). Fracture and wear are the more dominant failure categories. In an earlier work, the authors presented a fracture mechanics based fatigue life prediction model. Continuing on the same lines, a model is developed in this paper to forecast die failures under wear and combined fracture-wear modes. Stochastic nature of various fatigue and wear related die parameters is examined. Monte Carlo simulation is used for die life prediction under a set of manufacturing conditions and mechanical properties. Simulated die life values are quite realistic in comparison with actual life data from the industry. Simulated data are also used to fit wear-out type reliability models.*
**Keywords:** Die life/ failure, fracture-wear, extrusion, Monte Carlo simulation

## 1. INTRODUCTION
The two leading failure mechanisms for hot work extrusion dies are fatigue fracture and surface wear [1, 2]. In an earlier paper [3], the authors developed a die life prediction model based on fracture type failures. The current paper extends the previous work to wear and combined fracture-wear failure mechanisms. Geometric features of the billet and tooling, their material properties, and relevant process parameters (extrusion pressure, ram speed, etc) are treated as random quantities. Nature of distributions and related parameters (mean, standard deviation, etc) for the different variables are determined from experimental and manufacturing data. Monte Carlo simulation is used to predict fracture, wear, and combined fracture-wear failures. A case study of actual hot aluminum extrusion from the industry is used for model development and validation.
Actual die failure data have been collected from a commercial aluminum extrusion setup for the two simple hollow dies shown in Fig-1. The tube die predominantly failed by fracture, and only a few times by wear. It has been used to simulate fracture, wear, and combined fracture-wear failure mechanisms. The box die failed almost entirely due to die land wear. It is therefore used only for parameter estimation of wear failures. Die material was heat treated and surface hardened H13 steel, billet material being Al-6063. Average extrusion temperature was around 460°C, and ram speed was 5 mm/s.

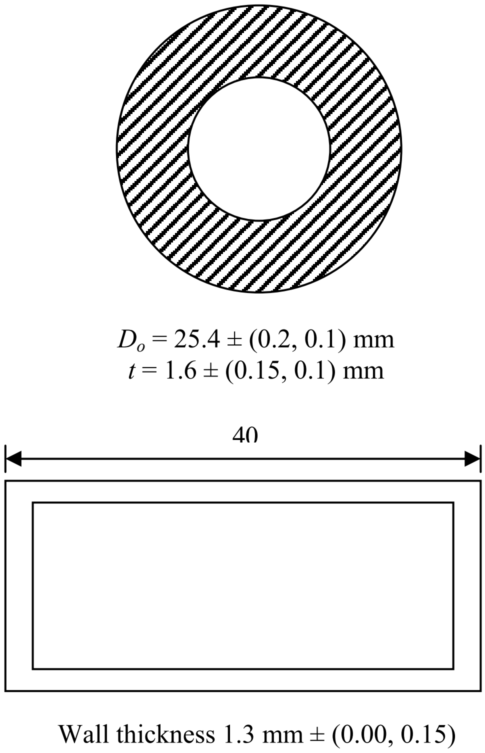


*Figure 1. Profile sections of tube and box dies used in the study*

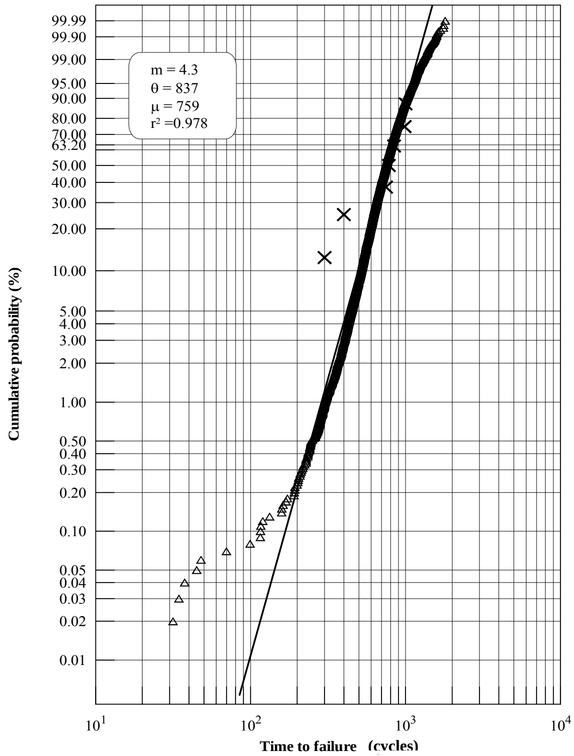


*Figure 2. Weibull model of the simulated fracture-failure data*

## 2. FATIGUE FAILURE

As described in an earlier paper [3], the fatigue life ($N_f$) of a die is expressed in terms of the number of cycles to failure (or billets extruded). Die life is estimated using Monte Carlo simulation, based on the Paris-Erdogan law for crack growth rate (*da/dN*):

$$N_f = \frac{(a_0)^{1-m/2} - (a_c)^{1-m/2}}{C(m/2-1)\alpha^m \pi^{m/2} \sigma_{\max}{}^m}. \tag{1}$$

Here, $a_0$ is the initial or preexisting crack size (0.05-0.1 mm for heat treated, surface hardened H13 steel); $a_c$ is the final (critical) crack size, $C$ and $m$ are the Paris constants; $\alpha$ is the geometry factor (1.12 for an edge crack); and $\sigma_{\max}$ is the maximum stress in the tube die. Information about the distribution type and parameters of all the variables is listed in Table-1.

Curve fitting was performed on the simulated results to obtain standard reliability distributions (normal, lognormal, Weibull, and minimum extreme value). Weibull distribution, shown in Fig-2, gives the best overall *goodness of fit* (correlation coefficient $r^2$ = 97.8%), although lognormal or even normal model cannot be ignored completely. Average die life is linked with the scale parameter and the scatter parameter by the equation

$$MTTF = \theta\, \Gamma\, (1 + 1/m). \tag{2}$$

Based on the simulation results, *MTTF* was found to be 759 billets, whereas the actual *MTTF* due to fracture failures is 722 cycles.

## 3. WEAR FAILURE

Saha [4, 5] studied the effect of ram speed and billet length on wear at the die (cap) and the mandrel for extrusion of a thin walled square tube. Wear depths from these experiments were replotted and it was found that wear progresses almost linearly as more billets are extruded. A simple die wear model would thus be

$$W_f = \alpha t_f. \quad (3)$$

where $W_f$ is the wear-for-failure (limiting amount of wear leading to die failure), $t_f$ is the cycles-to-failure (number of billets extruded before reaching $W_f$), and $\alpha$ is the slope of the straight line representing the progressive wear behavior.

*Table 1. Geometrical and process variables, their distributions and parameters*

| Variable | Distribution | Mean Value | Std Deviation |
|---|---|---|---|
| Billet dia $D_b$ | Normal | 184 mm | 0.5 mm |
| Billet length $L$ | Normal | 660 mm | 4 mm |
| Die outer dia $d_o$ | Normal | 25.4 mm | 0.1 mm |
| Die thickness $t$ | Normal | 1.6 mm | 0.05 mm |
| Paris constant $C$ | Lognormal | 1.6 x $10^{-12}$ ($y_0$ = 1.493 x $10^{-12}$) | 0.192 x $10^{-12}$ ($\omega$ = 0.229) |
| Paris exponent $m$ | Constant | 2.85 | - |
| Fracture toughness $K_{IC}$ | Weibull | 83.6 MP√m $\theta$ = 89.6 MPa√m | 12.54 MPa√m $m$ = 6.67 |
| Ram speed $V$ | Constant | 5 mm/s | - |
| Initial crack size $a_0$ | Normal | 0.01 mm | 0.001 mm |
| Geometry factor $\alpha$ | Constant | 1.12 | - |
| Number of cavities $n_1$ | Constant | 4 | - |

Actual die failure data (due to wear at the die land) has been collected for the box profile shown earlier (Fig-1). The average die life (*MTTF*) for this die was 508 extrusion cycles. Based on the tolerance for minimum wall thickness, it was determined that a failure wear of $W_f$ = 75 µm on the bearing surface of the die or the mandrel would lead to rejection. This means that each time a die failure occurred, wear had reached this limiting value. Slope ($\alpha$) of the wear line was evaluated for each die rejection from the cycles to failure and limiting wear data. Mean and standard deviation values of this parameter ($\alpha$) came out to be 0.169 mm and 0.035.

Monte Carlo simulation based on the wear model (equation 3) was carried out for the same hollow die (simple tube) whose fracture simulation was presented earlier. A limiting wear value of 125 microns was used for this die (tube), determined from tolerances shown in Fig-1. Compared to an actual *MTTF* value of 722 billets, the simulated life (based on wear failures only) came out to be 767 cycles. We know from the actual failure history of this die that wear was not a dominant failure mode. This fact is confirmed by the Weibull fit to the simulated data (Fig-3), yielding a relatively low correlation coefficient of 92.16% (as against $r^2$ = 97.8% for fracture failure).

## 4. COMBINED FRACTURE AND WEAR

Various failure mechanisms operate simultaneously on the die during its operative life. Fracture and wear are thus competing against each other. Final die failure takes place either when a preexisting crack ($a_o$) reaches the critical crack size ($a_c$), or wear on the die land reaches the limiting value ($W_f$):

$$t = \min (t_F, t_W), \quad (4)$$

where $t_F$ is the simulated fracture life, $t_W$ is the wear life, and $t$ is the final predicted life, representing the failure (fracture or wear) that occurs earlier. The *MTTF* of this simulated fracture-wear die life was 717 billets. In comparison with the actual average life of 722 billets, this is a very close prediction. Weibull distribution was once again found to yield the best fit to the simulated die life data, with a coefficient of correlation value of $r^2$ = 98.5%, as shown in Fig-4. This combined fracture-wear model is obviously the best representation of die failure, yielding a shape parameter $m$ = 4.99 and a scale parameter $\theta$ = 786 cycles.

## 5. CONCLUSIONS

Assuming die life and related material and geometrical parameters to be random variables, Monte Carlo simulation has been carried out to predict the life of an extrusion die (hollow tube). Paris law

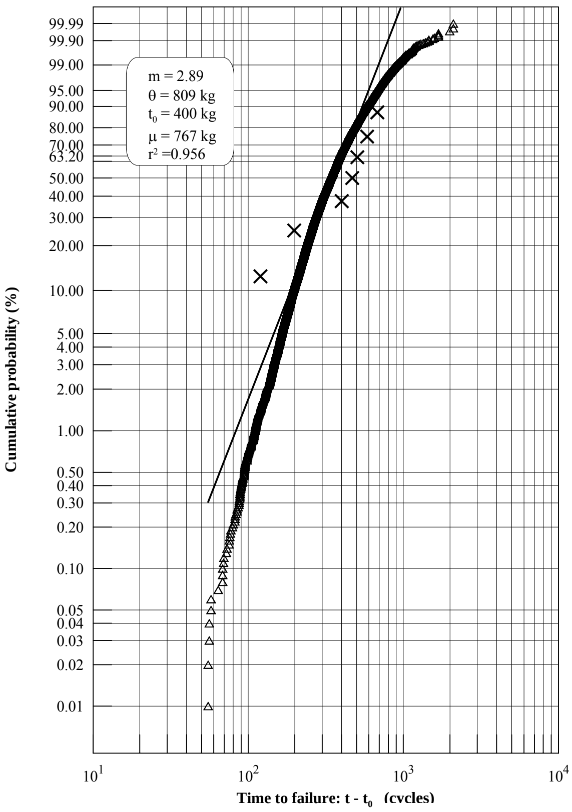


*Figure 3. Simulated wear failure data and 3-parameter Weibull fit*

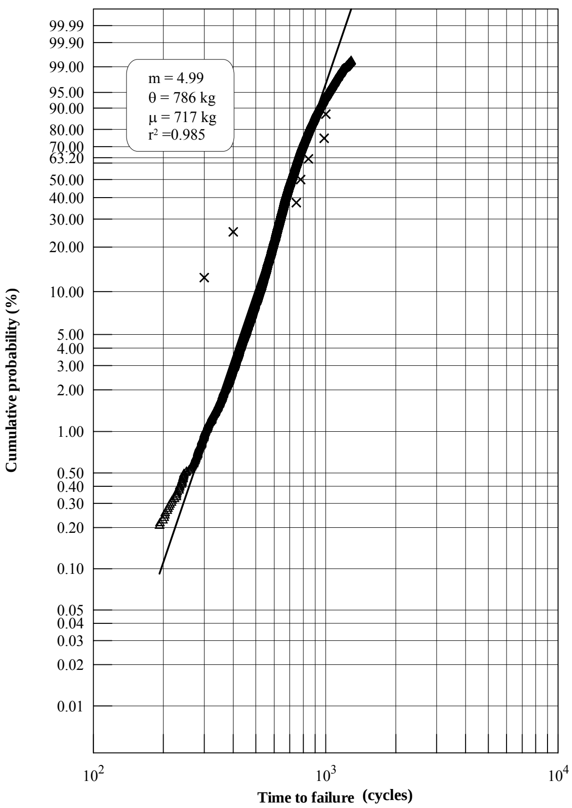


*Figure 4. Weibull plot for simulated competing fracture-wear data*

has been used as the model to estimate fatigue life of the die in terms of number of cycles to failure (billets extruded). As reported in an earlier paper, the resulting (simulated) die life observations are adequately represented by a Weibull probability model, with an average die life of 759 cycles (as against the actual *MTTF* of 722 billets), and a correlation coefficient of $r^2$ = 97.8%. A linear wear failure model has been developed, using actual wear data of a hollow box die. Predicted die life of the tube die (using Monte Carlo simulation) was 767 billets, yielding a Weibull fit with $r^2$ = 85.8%. This lower goodness of fit for wear matches well with failure records; the die rarely failed due to wear in actual practice. The combined fracture-wear failure model yielded the best simulation, with *MTTF* = 717 cycles, and $r^2$ = 98.5%. The strategy outlined here can be easily adapted to forecast life of extrusion dies using tool steels subjected to different tempering routines and used at different operating temperatures.

## 6. ACKNOWLEDGEMENTS
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