CONTENTS
AUTHORS

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FRACTURE PREDICTION OF EXTRUSION DIE MODELED AS PRESSURIZED CYLINDER WITH INTERNAL CRACK

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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. That is why one of the major design-manufacturing goals is 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. The most dominant factor for failure of extrusion dies is fatigue fracture. In an earlier work, the authors presented a fracture mechanics based fatigue life prediction model. Treating the die as a flat plate with edge crack was a major assumption about crack geometry in that work. In order to find a more precise approximation of the die life, the approach used in this paper models the die as a pressurized cylinder with internal crack, a much closer approximation for extrusion using a tube die. Based on this new strategy, a model is developed to forecast fracture failure of extrusion dies. Stochastic nature of various fatigue and wear related die parameters is examined. Monte Carlo simulation is used for die life prediction under a given set of manufacturing conditions and mechanical properties. Simulated die life values thus obtained are quite realistic in comparison with actual life data from the industry.

Keywords: Die life prediction, metal extrusion, fracture mechanics, pressurized cylinder with internal crack, Monte Carlo simulation

1. INTRODUCTION

Prediction of die failure and estimation of die life are critically important, both in extrusion research and in commercial extrusion practice. It has direct bearing on improvement of die design (leading to enhanced plant performance), and formulation of an optimum die replacement strategy (generating reduction in tool warehousing and related costs). Sheikh et al [1] used a reliability approach and Taguchi's loss function to identify important features of extrusion die damage processes, and suggested some measures to minimize the tool damage. Arif et al. [2] investigated the effect of Al-6063 billet quality on the service life of AISI-H13 hot extrusion dies based on microstructural and statistical investigation. Matteis et al. [3] studied the damage caused by repeated cycles of nitriding or nitrocarburizing on dies used for the hot extrusion of aluminum alloys, using techniques such as microscopy, fractography, etc.

Arif et al. [4] found that the most common modes of extrusion die failure are fracture, wear, and plastic deformation, fatigue fracture being the predominant one. A few researchers have tried to investigate the mechanism of fatigue in extrusion dies [5-7], but the studies are generally focused on only a few specific issues and do not give a general treatment of fatigue failure. Feng et al. [8] presented a method for predicting low cycle fatigue life of extrusion dies based on the finite element method (FEM), combining constitutive equations and the relationship between strain amplitude and low cycle fatigue life. Ahn et al. [9] estimated the fatigue life of an axi-symmetric extrusion die, using

FEM to model the crack growth behavior. Sonsoz and Tekkaya [10, 11] determined the effective stress intensity factors for different locations on a typical extrusion die using FEM, and then estimated die life using standard analytical solutions based on crack growth rate.

1.1 Current Work

In an earlier work by the authors [12], a life prediction model based on fracture mechanics was developed for extrusion dies. Though reasonable agreement was found with average die life of actual tube die used in commercial hot-extrusion, the analytical development was based on the rather simplistic geometry of a plate with edge-crack; Fig-1. The current paper models the die as a pressurized cylinder with internal crack (Fig-2), a much more realistic approximation for extrusion through a tube die. Actual fracture failure data for a tube die (simple hollow profile) were collected from a commercial aluminum extrusion setup. Geometry of this die profile is described by an outer diameter (d_o) of 25.4 ± (0.2, 0.1) mm and thickness (t) of 16 ± (0.15, 0.1) mm; Fig-3. Die material was heat treated and surface hardened H13 steel, while billet material was the most common structural aluminum alloy Al-6063. Average extrusion temperature was around 460°C, and ram speed was 5 mm/s. The average die life was 704 extrusion cycles (number of billets extruded).

2. ANALYTICAL MODEL

Paris-Erdogan law for fatigue crack growth can be mathematically written as [13]:

$$\frac{da}{dN} = C(\Delta K)^m \quad , \tag{1}$$

where a is the crack size, N is the fatigue life, and C and m are known as the Paris constants. When we subject a material with pre-existing cracks to cyclic loading, the applied stress intensity range can be expressed as

$$\Delta K = f(a/W)\,\alpha\,\Delta\sigma\sqrt{\pi a}\ , \tag{2}$$

where W is the plate width and α is the geometry factor for the crack type. Neglecting the finite size factor $f(a/W)$ for simplicity, letting $\Delta\sigma = \sigma_{max}$ (as $\sigma_{min} = 0$, each extrusion cycle starting from a minimum load of zero), combining equations (1) and (2), and integrating, we can obtain the fatigue life (number of cycles to failure):

$$N_f = \frac{(a_0)^{1-m/2} - (a_c)^{1-m/2}}{C(m/2-1)\alpha^m \pi^{m/2} \sigma_{\max}{}^m}\ . \tag{3}$$

Values of C and m for ultrahigh-strength steels can be found from standard references such as [14]. Size of preexisting cracks (a_0) in heat treated and surface hardened H13 steel (extrusion die material) is generally in the 0.05-0.1 mm range [15].

Using the standard definition of mode-I stress intensity factor (equation 2), and knowing that the crack becomes unstable ($a = a_c$) when stress intensity equals the plane-strain fracture toughness of the material ($K_I = K_{IC}$), we get

$$a_c = \frac{1}{\pi}\left(\frac{K_{IC}}{\alpha\sigma_{\max}}\right)^2 . \tag{4}$$

Assuming the crack type to be an edge crack, value of the geometry factor (α) is 1.12. However, in the case of a pressurized cylinder with internal crack (Fig 2), stress intensity is given by:

$$K_I = \frac{2pr_0{}^2}{r_0{}^2 - r_i{}^2}\sqrt{\pi a}\ f\left(\frac{a}{t}, \frac{r_i}{t}\right), \tag{5}$$

where,

$$f\left(\frac{a}{t}, \frac{r_i}{t}\right) = 1.1 + A\left[4.951\left(\frac{a}{t}\right)^2 + 1.092\left(\frac{a}{t}\right)^4\right]. \tag{6}$$

The factor A is given by

$$A = \left(0.125 \frac{r_i}{t} - 0.25 \right)^{0.25} \qquad for \;\; 5 \le \frac{r_i}{t} \le 10 \;, \tag{7}$$

$$A = \left(0.2 \frac{r_i}{t} - 1.0 \right)^{0.25} \qquad otherwise \;. \tag{8}$$

As $r_i / t = 6.94$ for the tube die used as a case study, equation (7) should be used to calculate A.

3. LIFE SIMULATION

Information about the distribution type, average values, standard deviations, etc of all the variables is listed in Table-1. Monte Carlo method has been used to simulate the fracture life of the extrusion die. 10,000 sets of independent random numbers are generated and converted into the required statistical distributions through appropriate transformations for each of the independent variables (a_0, D_b, t, L, C, and K_{IC}). The derived variables (a_c, σ_{max}, p, ε, etc) are then calculated for all the 10,000 instances. Cycles to failure (number of billets extruded) due to fatigue fracture are then calculated using equation (3). For every instance of die life, equations (6) and (7) are substituted into equation (5), and calculations are repeatedly done in a loop until the current value of a_c makes the value of K_I the same as K_{IC}. This MATLAB subroutine is used within the larger MATLAB program developed for the Monte Carlo simulation process. Compared to the simulated average die life from the earlier plate-with-edge-crack model (773 cycles), the current approach of pressurized-cylinder-with-internal-crack yielded a die life of 734 cycles, a value much closer to the actual average die life of 704 billets.

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Table 1. Statistical parameters for geometrical, material, and process variables of tube extrusion

Variable	**Distribution**	**Mean Value**	**Standard 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	1.6×10^{-12}	12% of mean
Paris exponent (m)	Constant	2.85	-
Fracture toughness (K_{IC})	Weibull	83.6 MP√m	15% of mean
Ram speed (V)	Constant	5 mm/s	-
Initial crack size (a_0)	Normal	0.01 mm	10% of mean
Geometry factor (α)	Constant	1.12	-
Number of cavities (n)	Constant	4	-

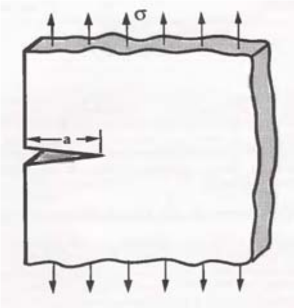

Figure 1. Simplified approach of plate-with-edge-crack

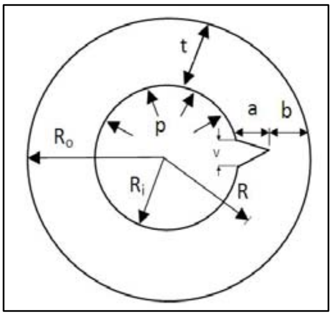

Figure 2. More realistic approach of cylinder-with-internal-crack

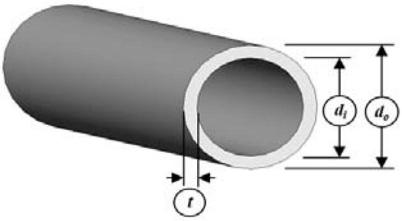

Figure 3. Tube profile identified by inside diameter (d_i), and outside diameter (d_o) or wall thickness (t)