3.3. THE ANALYTICAL APPROACH

3.3.1 Exact Solutions vs. Limit Analysis

Exact analytical solutions are not available for such problems in metal forming as flow through conical converging dies. Approximations and simplifying assumptions are inevitable and many approaches - slug equilibrium, slip line techniques and others - have been partially successful. With recent advances in computer science and technology, numerical approaches are emerging lately.

Limit analysis, as an analytical tool, is a promising approach which is being used with increasing frequency. In this approach, as applied to the study of drawing or extrusion force, two approximate solutions are developed. One, the upper-bound solution, provides a value which is known to be higher than or equal to the actual force; the other, the lower-bound solution, provides a value which is known to be equal to or lower than the actual force; the actual force thus lies between the two solutions. For example, in Fig. <7>, with drawing stress as ordinate and the semi-cone angle of the die as abscissa, upper- and lower-bound solutions are plotted for several reductions together with corresponding measured values of actual stress. Even when experimental results are not available, it is expected that the actual stress and the exact solution, if these were available, would lie between the upper and lower bounds as obtained analytically. Thus, by limit analysis, an approximate solution is given with an estimate of the maximum possible error. The gap between upper- and lower-bound solutions may be narrowed by providing several upper bounds, choosing the lowest upper bound, and by providing several lower bounds, choosing the highest lower bound. Upper- and lower-bound solutions are obtained by following strict rules (including requirement of proper description of friction behavior and material characteristics) which thereby make the solutions upper and lower bounds. In Fig. <7>, the upper bound is from Ref. [4] and the lower bound from Ref. [5]. The experimental data are from Reference [6]. A full illustration of limit analysis is given in Section {9.5}, 'Limit Analysis'.

The rules and procedures for developing an upper-bound solution will be demonstrated in what follows, keeping in mind that several upper-bound solutions may be obtained for any specific process.

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