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Real-Time Process Characterization of Open Die Forging for Adaptive Control

Open die forging is a process in which products are made through repeated, incremental plastic deformations of a workpiece. Typically, the workpiece is held by a manipulator, which can position the workpiece through program control between the dies of a press. The part programs are generated with an empirically derived parameter, called the spread coefficient, whose value is subject to some contention. In this work, we demonstrate how process information can be used in real time to derive the actual spread coefficient for a given workpiece as it is being formed. These measurements and calculations occur in real time, and can be used to regenerate part programs to optimize the forming process, or can be used to adaptively control each incremental deformation of the workpiece. [DOI: 10.1115/1.1396350]

I Introduction

The open die forging process forms workpieces through a series of incremental deformations using dies of relatively simple shapes. It is commonly used to reduce large ingots or billets into square or round bars of smaller dimension, or for forging large high-value parts with limited geometric complexity [1]. In a typical open die forging system the workpiece is held by a forging manipulator that positions it between the dies of the press. Motions of the manipulator and press are coordinated through program control. In contrast to the more common closed die forging process, the dies only deform a limited region of the workpiece surface, so that many programmed forming increments are needed to bring the workpiece to its final shape.

Because material volume is conserved during forming, as the height of the workpiece is decreased, both the length increases (‘‘elongation’’) and the width increases (‘‘spread’’). This behavior complicates the task of creating programs (or forging schedules) to control the forging system. For example, consider the forging of a square bar from a square billet. The billet may be forged to the final thickness in the first pass, is then rotated 90 deg and given a second forging pass. What was the thickness direction is now the width direction, and as forging takes place in the second pass, the width increases due to this spreading behavior. Thus, dimensions set in one forging pass will change in subsequent forging passes. Clearly, the ratio of material going into elongation to that going into spread in each forming step is important since it will affect the number of forging passes required to reach the final dimension. This, in turn, affects the productivity and costs of the process.

This ratio of spread to elongation has been characterized by Tomlinson and Stringer [2] in a quantity called the ‘‘spread coefficient,’’ s. It allows forming behavior to be estimated as a function of process parameters, and is used to generate forming schedules. Starting with a rectangular workpiece of initial height h_0, width w_0 and length l_0, conservation of workpiece volume can be used to show that average width after a single forging pass, w_1, will be:

$$w_1 = w_0\left(\frac{h_0}{h_1}\right)^{S} \tag{1}$$

while the final length, l_1, will be given as:

$$l_1 = l_0\left(\frac{h_0}{h_1}\right)^{1-S} \tag{2}$$

Inhomogeneous deformation in the process leads to bulging of the sides of the workpiece (Fig. 1). Tomlinson and Stringer [2] showed experimentally that these relationships correctly model the volume of material that moves in each respective direction. Forging the bulged workpiece with light ‘‘planishing’’ passes will restore flat sides.

These relationships can be used to predict workpiece dimensions after each forging pass, and have, for instance, been used to derive a theory of forging schedules [3]. As is described in the next section, the spread coefficient itself is estimated both through analytical derivations and empirical models.

Unfortunately, there is limited agreement as to which process parameters affect the spread coefficient, and by how much. For example, Pahnke [4] reported, based on the experience of a forging plant in Sweden, that the steel alloy being forged significantly affects the value of the spread coefficient, while Allen and Cartmell [5] reported that the spread coefficient is largely independent of the alloy being forged, based on experiences of a forging plant in Great Britain. Pahnke [4] also reported that the reduction ratio (the amount of workpiece height reduction in each forging pass) had a negligible effect on spread coefficient, while experiments by Tomlinson and Stringer [2] and Baraya and Johnson [6] found the reduction ratio to be a significant factor.

A consequence of these discrepancies is that forming schedules may not be as efficient or productive as they may be with better spread coefficient estimates, and may limit the ability to automatically produce all but simple prismatic bars. To illustrate the need for accurate spread coefficient values, consider a simplified example of forging a square bar between shoulders (i.e., slightly more complex geometry than forging a prismatic bar). Suppose the bar is initially 100 mm square and a section with final dimensions 75 mm square by 400 mm long will be forged in two passes with a 90 deg rotation between passes (see Fig. 2). From volume conservation it can be shown that the section to be forged will have an initial length of 224.9 mm.

The forging schedule for these two passes is determined with the help of the spread and elongation equations, Eqs. (1) and (2), respectively. Assume a spread coefficient of 0.4 is predicted for this operation before forming starts, while the true value turns out to be 0.3. Using the predicted value of 0.4, the necessary first forging pass reduction can be found to be 38.1 percent over a

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