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ESTIMATION OF DIE WEAR IN HOT FORGING

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ABSTRACT

The goal of precision forging is to produce parts with complex geometries that require little or no finishing. Therefore, die failure and die life are critical issues in maintaining the accuracy and tolerances required by precision forging. This report discusses a computer aided methodology for predicting die wear in forging. Finite element simulation is used to determine process parameters. A post processor is then used to predict wear using the Archard's equation as a model of abrasive and adhesive wear. The ultimate goal is to determine the process parameters affect die life in precision forging.

The particular wear prediction program that was used in this project has already been validated in extrusion with reasonable success. Other researchers have used a similar method to predict wear in upsetting. They also were able to predict reasonably accurate wear profiles based on die temperature, sliding velocity, and interface pressures. Wear prediction was attempted on a upsetting operation as well as a closed die forging operation with a complicated geometry. The predicted results were compared to experimental results.

Keywords: 1. Hot Forging, 2.Die Wear, 3.Process Simulation

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1 Introduction and Background on Die Wear

The objective of hot precision forging processes is to produce parts that require little or no finishing, thereby reducing manufacturing costs. It is also the aim of precision forging to produce parts with more complex shapes than with conventional hot forging processes. In order to achieve both accuracy and complexity in a forged part, the dies must be produced with higher accuracy and tighter tolerances than the part to be forged. As a consequence, the machining time for the dies increases considerably, making the dies more expensive than those needed to produce parts with conventional tolerances.

Complex precision forged parts are almost exclusively produced in closed dies. Therefore the dies have to withstand high contact pressures - well above the flow stress of the billet material at the forging temperature. Also the amount of surface generation and the sliding velocities at which the billet material moves along the die surface are very large. Also, in hot forging operations the die surface is subject to sudden changes in temperature. These changes are mainly due to contact with the hot work piece and the cooling and lubrication practices. The high pressures and sliding velocities, as well as the sudden changes in temperature, may induce die failure due to several mechanisms. When a failure occurs the production must stop to replace or repair the die. Consequently the production costs will be significantly reduced if the die life can be increased.

Several authors (Lange, et al., 1992) have classified die failure mechanisms as follows:

- abrasive wear and adhesive wear (causes geometry changes)
- thermal and mechanical fatigue (causes cracks, and can cause catastrophic failure)
- plastic deformation (causes geometry changes)

Some geometrical features are more prone to a specific type of failure (see Figure 1). However, several failure mechanisms might be working simultaneously on certain geometrical features. This makes it difficult and expensive to characterize the failure mechanisms due to the variety of forging conditions that must be tested.

Therefore, in order to characterize the failure mechanisms the first step is to obtain data that may permit to relate failure mechanisms with material properties and process conditions. The second step is to survey the current industrial die and process design practices that may affect the die life.

To better understand failure mechanisms, it is necessary to perform process simulations for some selected hot forging processes where the die failure mechanism has been clearly identified. These simulations will help in three aspects:

- these will provide information on the conditions necessary for a die failure mechanism to occur.
- these will help to construct a methodology to analyze, design and redesign forging dies.
- a validated FEM model that is able to predict the failure of a die under certain process conditions might be used to predict the life of another die

1.1 Research Objectives

The overall objective is to establish a methodology and tools to identify the relevant die failure mechanisms in hot forging. The specific objectives of this study are to:

- To establish a knowledge base using information available on die materials for hot forging and their performance characteristics. As well as current practices in industry so that a better methodology is developed to select hot forging die materials and surface modification treatments.
- To identify gaps in today's knowledge defining the critical information that needs to be developed in the immediate future.
- To establish a methodology to improve die life by use of: forging simulation, failure mechanism's knowledge, production performance information, and material property's information.

2 Application of Finite Element Computer Simulation to the Prediction of Die Wear

A number of researchers have attempted to use finite element simulation to predict die wear in metal forming and machining operations. The basic concept is to determine process variables (such as temperatures, stress, and sliding distances) using finite element simulation. Then a wear prediction equation or a set of equations is derived in terms of these process parameters. However, all of the equations that exist in terms of meaningful process parameters require some scaling factor that is determined through experiments.

Predicting the exact magnitude of the wear is difficult because the researcher must specify the interaction between the different types of wear that may occur, i.e. abrasion, adhesion, oxidation, etc. In upsetting the dominant wear mechanism is believed to be adhesion, and in closed die forming, it is abrasion.

Another problem associated with wear prediction using finite element simulation is that there is a transient "warm –up" period associated with any process. In forging, it may take several blows to warm the dies up to their operating temperature.

2.1. Wear Prediction Efforts at ERC/NSM

Liou et. al. (1988) used the finite element code, ALPID, to predict the temperature, stress, and sliding velocity distributions with respect to time at the die/work piece interface in high speed hot upsetting of AISI 1043 steel. Both the trend and the magnitude of the predicted wear profiles agree well with experiment. From the magnitude of the wear coefficients, it was determined that adhesive wear is the dominant wear mechanism in high speed hot upsetting.

Vardan et al. (1987) investigated the effect of process variables on die wear. It was found that temperature and sliding velocity (distance for a given stroke rate) had the greatest effect on die wear. The correlation between prediction and experiment was very good for cold, and warm upsetting, but not very good for hot upsetting. Other process parameters seem to have a more significant influence on die wear at hot conditions.

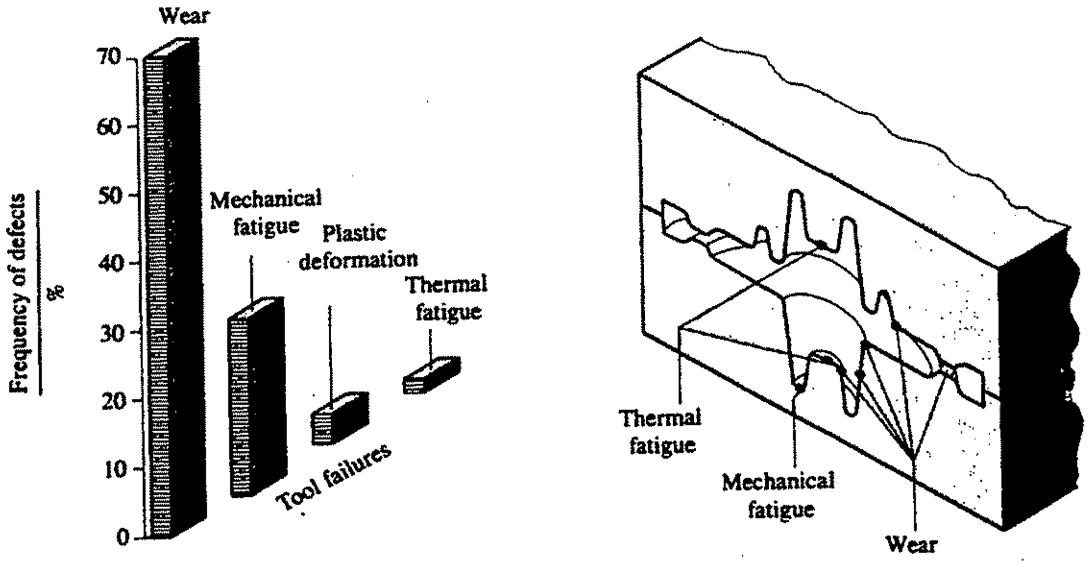


Figure 1: Frequency and typical location of common failure mechanisms (Doege, 1997)

Tulsyan et al. (1993) and Painter, et al. (1995) investigated the use of the finite element code, DEFORM, together with a post-processing code (written by the authors) to predict die wear in extrusion of automotive exhaust valves. Die and workpiece hardness was determined by hardness–temperature polynomials input by the user. The Archard wear equation can be expressed as:

ABRASIVE

$$Z_{ABRASIVE} = K * \frac{p^{a} * V^{b} * t}{H^{c}_{DIE}} \quad (1)$$

ADHESIVE

$$Z_{ADHESIVE} = K * \frac{p^{d} * V^{e} * t}{H^{f}_{WORKPIECE}} \quad (2)$$

where: Z = wear depths

K = experimental coefficients
c,f = hardness coefficients (typically
m =2 for steels)
p = local pressure
V = local sliding velocity
Dt = time interval

H_d = die material hardness (function of die temperature)
H_w = work piece hardness (function of work piece temperature)
a, b,d,e = coefficients determined experimentally

Both abrasive and adhesive wear were investigated in this study. Plastic deformation was acknowledged to be another source of die failure. (See Figure 2). Figure 2 shows a sample predicted wear profile for an extrusion insert.

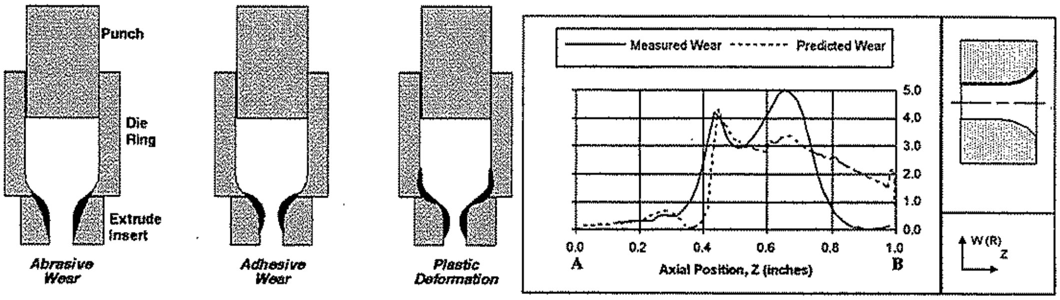


Figure 2: Wear modes commonly affecting the extrusion process (black areas indicate affected regions) and Predicted and measured wear profiles of example insert (Painter, 1995)

2.2. Upsetting, Extrusion, and Closed Die Forming Experiments at IFUM-Hannover

A series of die wear experiments for a variety of process conditions (die material, die coating, die heat treat, die temperature, lubricant type, die geometry, etc.) in upsetting, extrusion, and closed die forming have been performed at the IFUM at the University of Hannover in Germany (Bobke, 1991, Luig, 1993). The conditions used are given in Table 1. :

The die geometry used for the upsetting experiments and the typical wear profiles are shown in Figure 3. The die geometry for the dies used in the closed die forming experiments are given in Figure 4. Die wear was measured at the locations shown in Figure 5. The maximum wear was found to occur at location I.

Press	Billet	Dies (Upsetting)	Dies (Closed Die Forging)
• Mechanical • Rated at 3.09 MN • Stroke: 180 mm • Stroking rate: 2/second • Cycle time: 13 sec	• Material: 1045 steel • Temperature: 1100 degrees C • Billet dimensions were 30 mm in diameter by 40 mm tall for closed die forming and 20 mm in diameter by 30 mm tall for upsetting	• Material: H-10 with various coatings • Die temperatures: 220 and 300 degrees C • Lubricated and dry surfaces were tested	• Material: H-10, H-12, H-13 • Lubricated and dry surfaces were tested • Die temperatures: 140, 220, 300 degrees C • Die material hardness of 1200, 1500, and 1700 N/mm^2 were tested

Table 1: conditions used to run wear experiments at IFUM Hannover

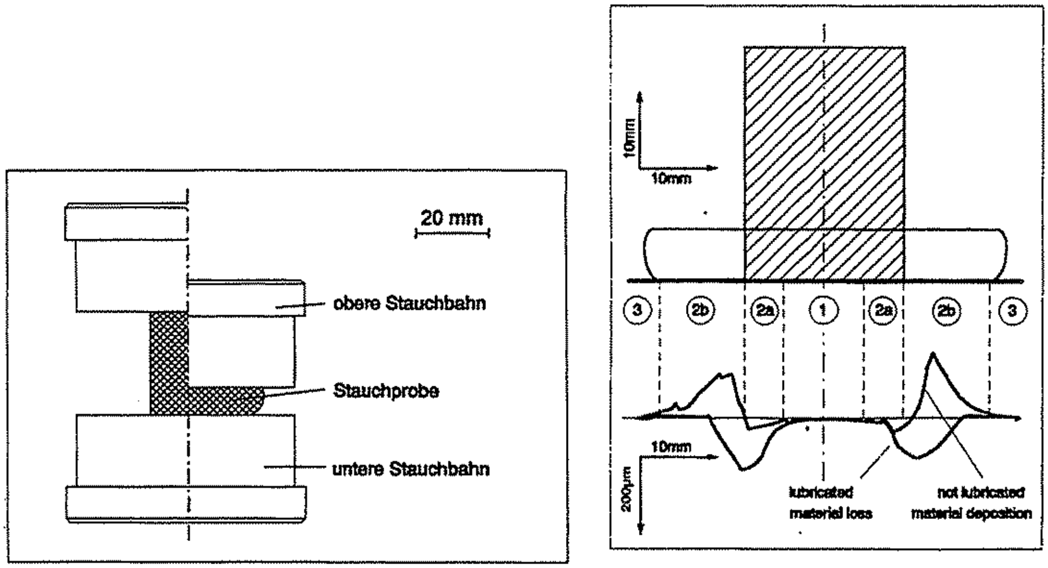
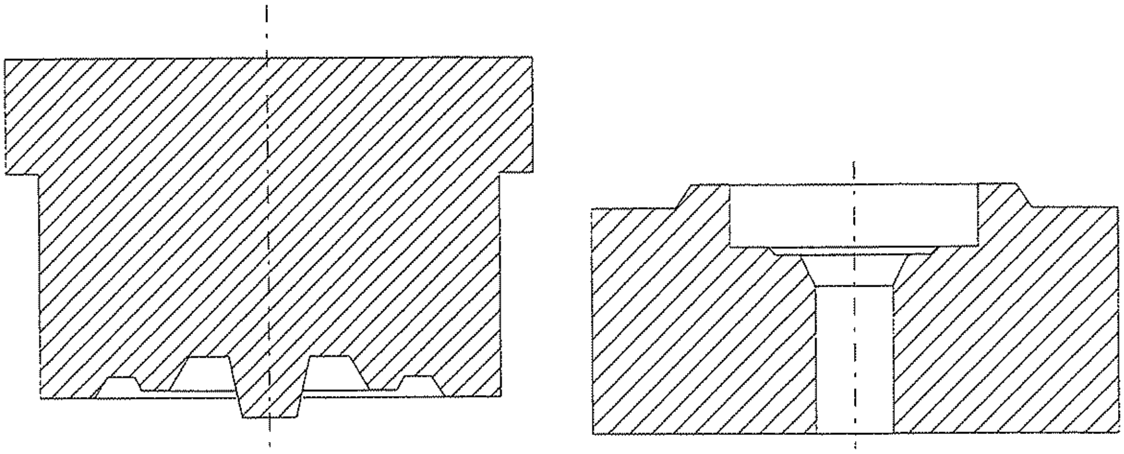


Figure 3: Die geometry in upsetting operation (Luig, 1993), and Die profile after lubricated and dry forging (Doege, et al., 1996)

3 Wear Prediction by FEM Process Simulations

The basics of the wear prediction method is as follows:

- A finite element model of the process is made using DEFORM.
- DEFORM predicts stresses, sliding velocities, and temperatures at the die/work piece interface.
- A UNIX shell program (FWEAR1) is executed by the user. This program provides the interface for the following two programs
    - The user is prompted to input coefficients to modify the wear prediction formulas (Equations 1 and 2), For this experiment, the coefficients on the wear equations were a = 1, b = 1, c = 2, d = 1, e = 1, f = 1, K = 0.02, C = 0.00016.



a) Upper Die

b) Lower Die

Figure 4: Upper and lower dies geometries for closed die forging experiments (Bobke, 1991)

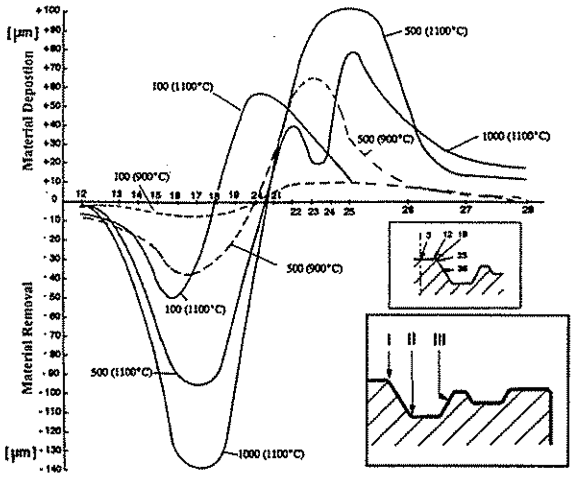


Figure 5: Die wear along the corner radius as measured through experiment for two different billet temperatures at various numbers of forging cycles (Bobke, 1991)

- The program FWEAR1 executes VALVETRANSFER which extracts the stresses, sliding velocities, and temperatures at the die/work piece interface for each saved step in DEFORM.
- The program FWEAR predicts abrasive and adhesive wear at each die/work piece node for each saved step in DEFORM using Equations 1 and 2, respectively. The wear accumulates as FWEAR goes through all the saved simulation steps. Wear profiles for abrasive and adhesive wear are generated. Average die and billet temperature, die and billet hardness, sliding velocity, and interface pressure are also calculated.

3.1. Die Wear in Upsetting Experiments (IFUM –Hannover)

A friction factor of 0.3 was used to simulate lubricated die surfaces. A friction factor of 0.85 was used to simulate non-lubricated die surfaces. In upsetting, both abrasive and adhesive wear take place. Adhesive wear is especially prevalent on non-lubricated surfaces. Temperature, and die material were varied in the literature. However, in this analysis only die temperatures of 200°C and 300°C were used.

3.1 Results for Die Wear Estimations in Upsetting

The predicted adhesive wear on the bottom die is given in Figure 6. The lower friction factor allows more sliding of metal along the die/work piece interface. The higher friction factor causes more bulging of the specimen. Most of the material flow is away from the die surface. Difference in the amount of wear for die preheat temperatures of 200 °C and 300 °C is small. However, as expected, the hotter die becomes softer and wears more quickly.

Figure 6 shows the predicted abrasive wear on the bottom upsetting die. While adhesive wear is thought to be the dominant mechanism in upsetting, abrasive wear also is a factor. It should be noted that both the predicted adhesive and abrasive wear profiles have the same trend as the experiment (see Figure 3). Luig (1993) found that after 1000 forging cycles, without lubrication, and at a die temperature of 200 °C, there was a maximum buildup of 2 μm. While at a die temperature of 300 °C, the die had a maximum buildup of 40 μm. The simulations suggest, lubrication in open die forging will produce more die wear because there is more material sliding. By way of comparison, a lubricated die at 200 degrees C had a maximum buildup of 105 μm. Material buildup corresponds to adhesive wear.

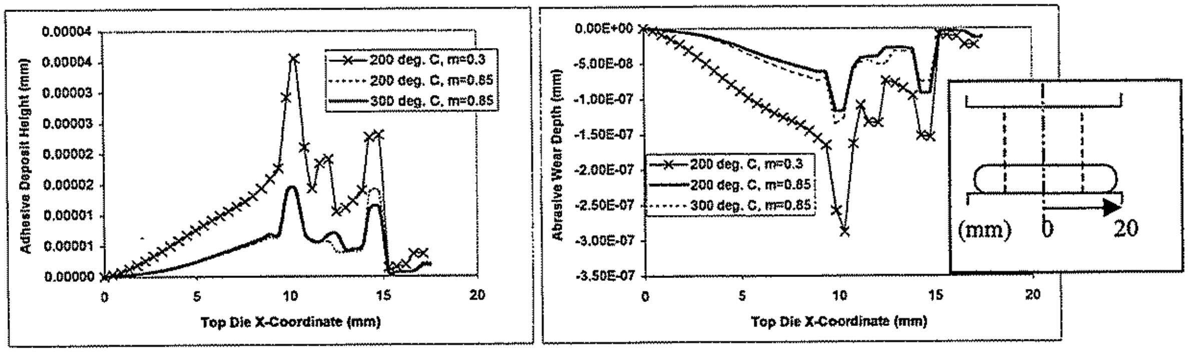


Figure 6: Adhesive and abrasive wear on bottom die in upsetting after 1st forging as predicted through simulation

3.2. Die Wear in Closed Die Forging

After reasonable results were obtained in upsetting, the wear prediction method was extended to closed die forging. A sensitivity analysis was performed on the following parameters: die material, die temperature, friction, die geometry, and press stroke rate. Only abrasive wear was investigated, although plastic deformation was also predicted. Although, press stroke rate was not investigated in the literature, in practice this is very important because it affects the contact time between the die and the workpiece, and how much heat is transferred from the billet to the dies. Thermal softening and heat checking of dies are directly related to temperatures in the die. Figure 7 shows the hardness versus temperature for AISI 1040, H-10, H-12 and H-13.

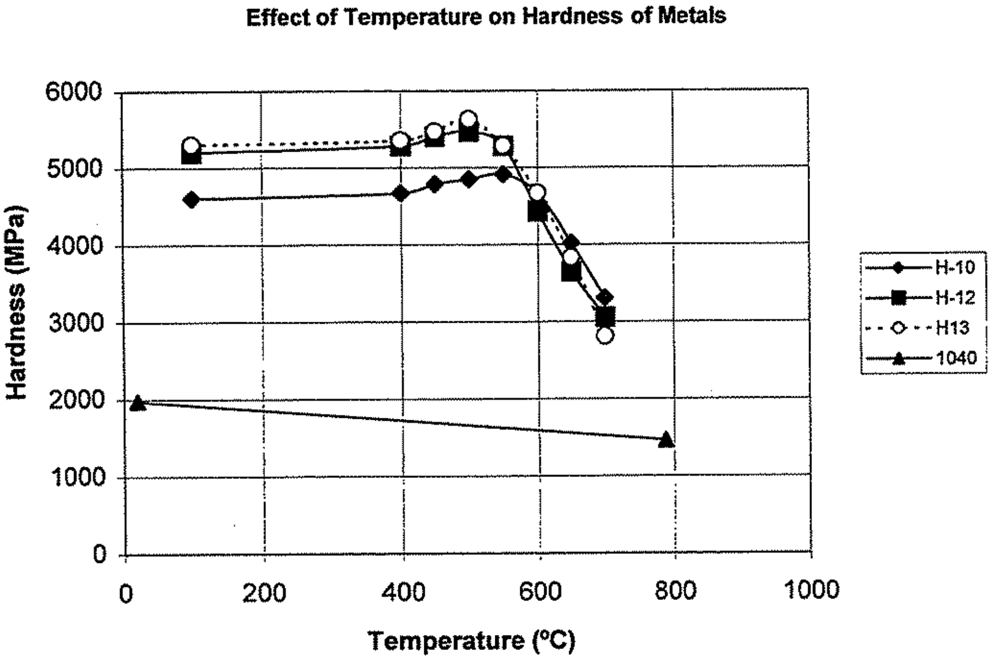


Figure 7: Hardness-Temperature curve fit for hot work tool steels and AISI 1040 (Bobke, 1991)

3.2 Estimation of Die Wear in Closed Die Forging

Figure 8 shows a typical closed die forging simulation. It can be seen in Figure 8a and 8b that there is more material sliding on the top die than on the bottom. Some of this is due to the geometry of the dies and billet and some of this is due to die chilling. The wear prediction for the top die is given in Figure 9.

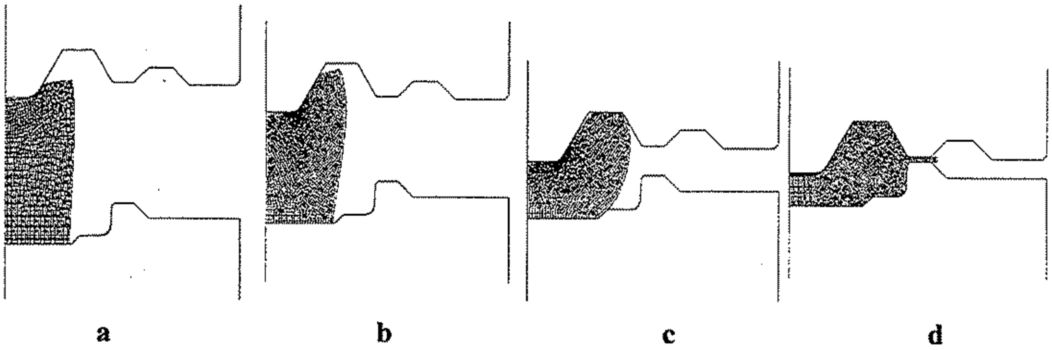


Figure 8: Simulation of closed die forging

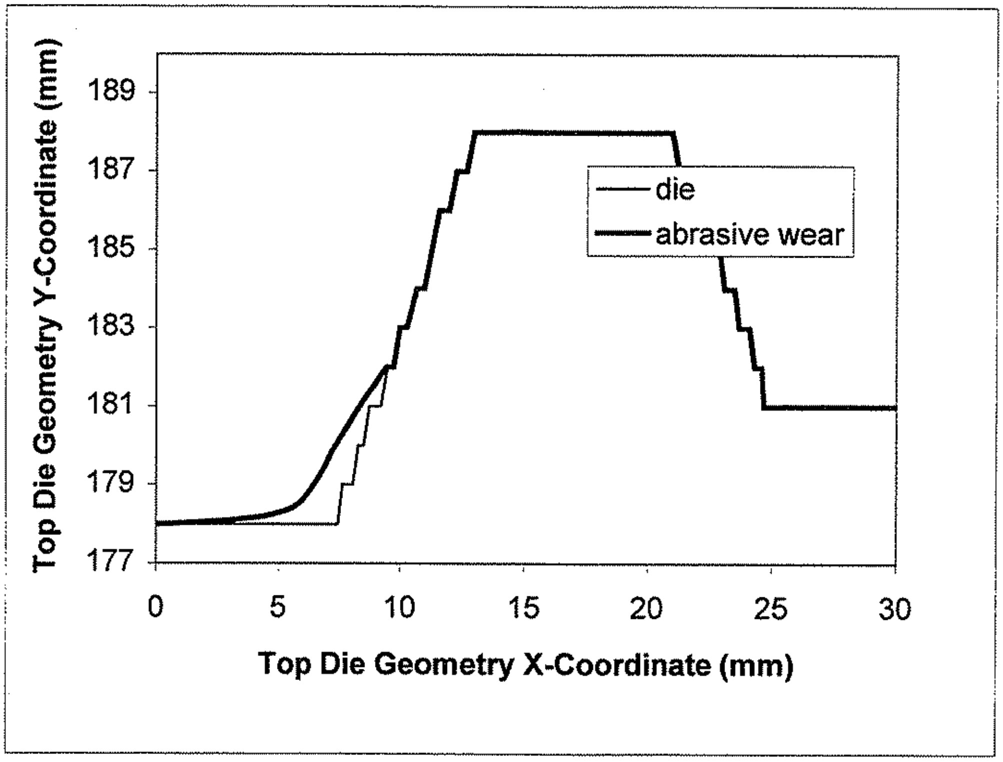


Figure 9: Wear predicted on top die from simulation (1000x)

The effect of various factors was evaluated through simulations to determine which one of these have the largest influence on die wear. The factors evaluated were as follows:

- Die temperature, 140, 220, and 330 °C
- Corner radius

- Friction factor (lubrication)
- Cycle time (stroke rate)
- Die Material Hardness

It was found that corner radius, and material hardness have the most significant effect on die wear. Although cycle time and friction factor, are also important.

Figure 10a shows the effect of corner radius on abrasive wear. As confirmed by the experiments the abrasive wear is more significant when the corner radius is the smallest. Figure 10b shows the effect of tool material on abrasive wear, the hardness of H12 and H13 is higher than the hardness of H10 for a given temperature. Thus, this last material wears more rapidly than the other tool steels.

Figure 11 shows the effect of stroke rate on abrasive wear, notice that the highest magnitude of wear is approximately the same for all stroke rates. However, towards the center of the upper die there is more wear for the largest stroke rate. This is explained because at higher stroke rates the sliding speed is also higher which accelerates wear.

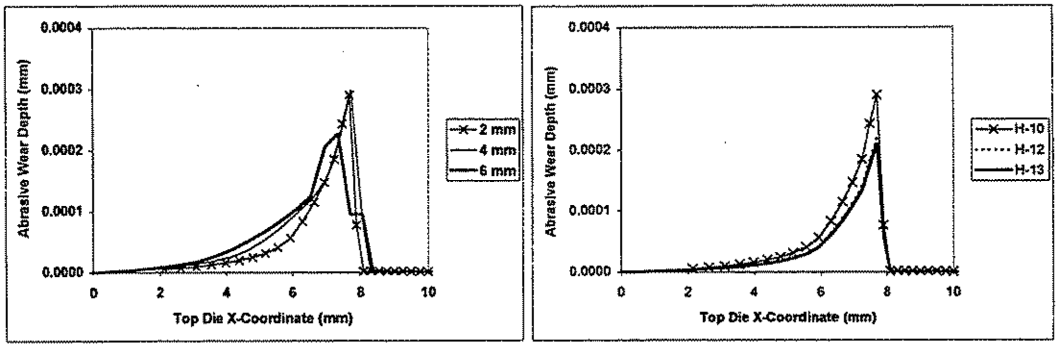


Figure 10: a) Predicted die wear from simulation on top die for 1st forging with three different die corner radii at location I. b) Predicted die wear from simulation on top die for 1st forging with three different die materials

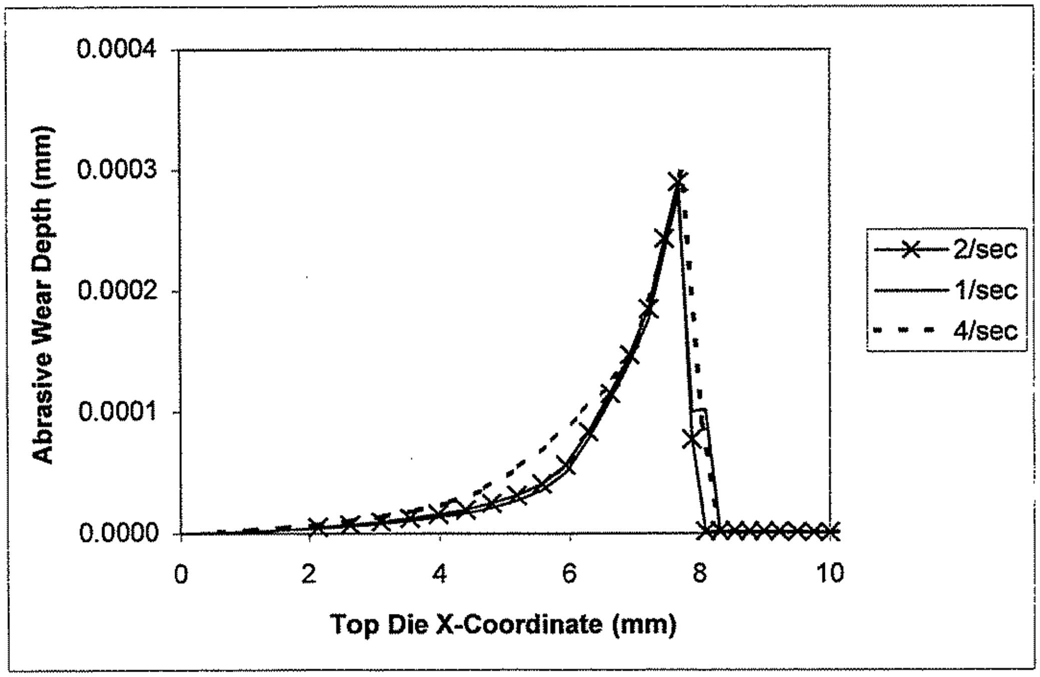


Figure 11: Predicted die wear from simulation on top die for 1st forging with three different press stroking rates

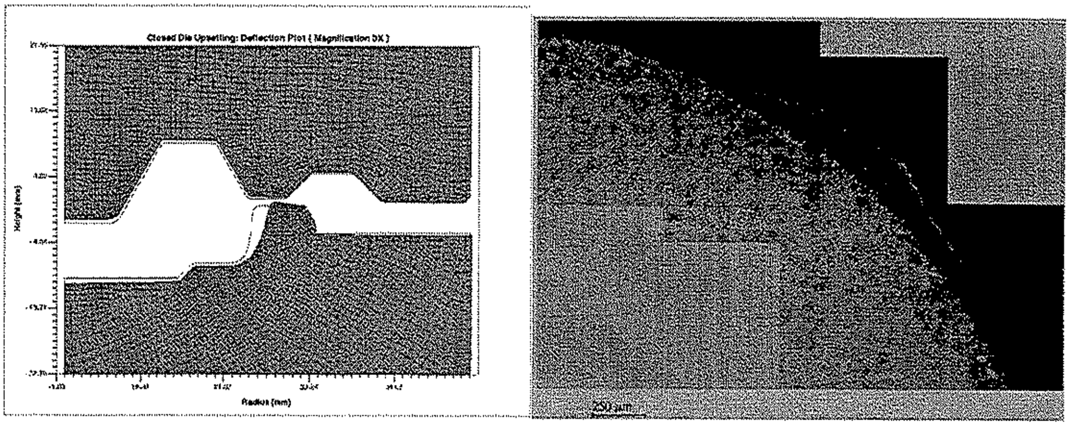
Figure 12a shows the results of a Simulation to determine how much plastic deformation takes place. The simulation shows that there is little plastic deformation on the upper die corner radius after one forging cycle. This suggests that most of the material removal is indeed abrasive wear. Figure 12b shows a micro-graph of the upper die corner radius after 500 forgings. It appears that the corner has "mushroomed." This means that material has deformed or slid down the side of the corner radius. Mushrooming makes it appear that there is more material removal above the radius and more material deposition below the radius.

4 Summary and Conclusions

In summary, the results of the present study indicate that, in general, the predicted die wear trends agree with the measured trends in experiment. In some cases, the interaction of die wear mechanisms or the complicated effects of parameters such as lubricants is not understood well enough for prediction to match experiment.

The future work of this project will include to:

- determine the interaction between various wear mechanisms, especially abrasive wear, adhesive wear, and plastic deformation.
- determine a methodology for incorporating into the wear model the transient warm-up period as the dies reach their steady state temperature.
- determine the coefficients for each process parameter in Equations 1 and 2. These coefficients must be determined through experiment. A full die wear profile is required from the experiments to accurately perform a regression analysis on the profile in order to determine the coefficients for Equations 1 and 2. These coefficients are unique to a given material pair, lubricant, and forming operation (including die geometry).



a) b)

Figure 12: a) Die deflection as predicted by process simulation, b)Micro-graph of the die corner radius at location I after 500 forging cycles. Material is H-10. Die temperature is 220 °C. (Bobke, 1991)

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