JMEPEG (1995) 4:161-165

Computer Modeling of Wear in Extrusion and Forging of Automotive Exhaust Valves

R. Tulsyan and R. Shivpuri

In an automotive engine valve forging process, the billet is cold sheared, induction heated, and fed to a mechanical press for a two-stage forging operation with the first stage being extrusion. The main limiting factor in this operation is the wear of the dies during the first stage, extrusion. In this study. abrasive wear was identified as the primary mode of wear, and computer simulation was used to investigate the effect of process variables, such as press speed, initial billet temperature, and die preheat temperature upon abrasive wear. The result generated by this study should be applicable to other part geometry and not limited just to exhaust valves.

Keywords
abrasive wear, computer modeling, valve forging, extrusion

1. Introduction

WEAR of dies is a complex time-dependent phenomenon that primarily depends on the four components of the system: die, workpiece, interface conditions, and processing conditions. In general, the possible causes of die failure in metal forming include catastrophic fracture, excessive bulk plastic deformation, and wear. Failure due to catastrophic fracture and excessive bulk plastic deformation may be eliminated by implementing an appropriate tool design with adequately selected tool material. However, in most situations, wear does not result from a single mechanism. The interaction of various wear mechanisms at a contacting interface makes the analysis of wear behavior very complicated.

Extensive experimental studies have been done on abrasive wear in hot upsetting. Rooks and coworkers (Ref 1-4) conducted high speed hot upset tests with an initial die and steel billet temperature of 300 and 1000 °C, respectively. They concluded that the most significant process variable influencing die wear was the relative velocity at the workpiece and die interface.

In other studies, Felder and coworkers (Ref 5, 6) developed and verified a computer model estimating the amount of wear in hot forging. According to them, forming pressure, sliding velocity, and the die hardness are the most significant variables influencing die wear.

Vardan et al. (Ref 7) used the FEM (Finite Element Method) code to investigate die wear in upsetting. They found that abrasive die wear is strongly influenced by the temperatures and velocities at the die and material interface.

The main objective of the present research is to study the effect of processing conditions on abrasive wear.

R. Tulsyan, Department of Industrial and Systems Engineering, The Ohio State University, Columbus, OH 43210, USA (presently at Xerox Corporation, 800 Phillips Road, MS. 147-59C, Webster, NY 24580, USA); and **R. Shivpuri,** Department of Industrial and Systems Engineering, The Ohio State University, Columbus, OH 43210, USA.

2. Factors Affecting Die Wear

The important process parameters that affect die wear during extrusion of exhaust valves are as follows.

2.1 *Speed*

To reduce die wear, the valve manufacturers often operate the mechanical press at a reduced speed of 45 to 60 strokes per minute (spm) instead of 80 or 90 spm, which is the usual speed for such a press (Ref 8). The press speed can be further optimized to reduce die wear during extrusion. Low speeds generate excessive die chilling in the forging stage due to large contact time. However, heat generated in the workpiece is greater at higher speed. Temperature gradients are also greater at higher speed. Also the higher the speed, the higher is the relative velocity at the interface and the forging pressure (higher strain rate), which also increases wear. Figure 1 shows the combined effects of deformation speed (contact time) and lubrication on friction and die pressure in hot forging.

2.2 *Temperature*

It is important that the initial temperature of both the die and the billet be optimized. Die temperature should be kept low so as to retain the hardness, but it should be high enough not to

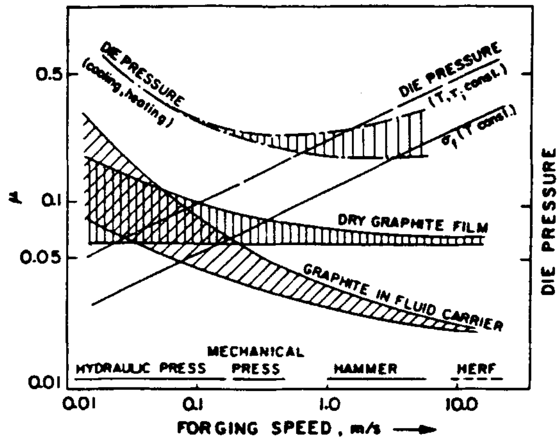


Fig. 1 Effect of press speed and lubrication on friction and die pressure (Ref 19).

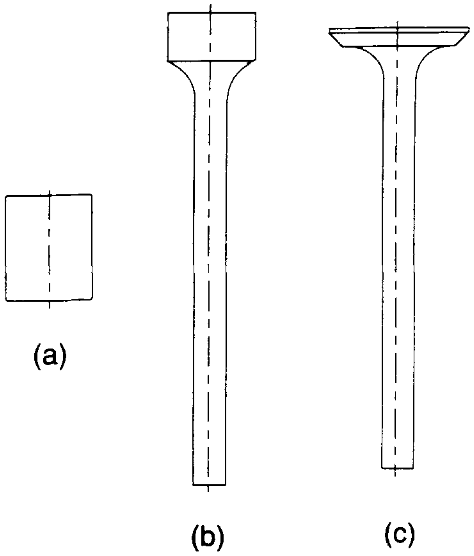


Fig. 2 Different stages in manufacture of exhaust valve. (a) Initial slug. (b) After extrusion. (c) Final forged valve.

cause excessive die chilling due to temperature differential in the workpiece. Die temperature and the time elapsed between lubricant application and contact with the workpiece play decisive roles in the evaporation of the carrier.

2.3 *Lubricant*

Selection of the proper process lubricant based on its properties and method of application can improve die life and workplace conditions. Lubricant generally used is oil-based graphite; however research is being done to use water-based graphite which eliminates flame and smoke. The effect of graphite particle size is still debated. It has been claimed that semicolloidal graphite is more effective than colloidal graphite (Ref 10). Schlomach (Ref 11) found that at high strains and die temperatures a commercial lubricant with finer graphite gave lower friction.

2.4 *Die Design*

A streamlined die shape would reduce die pressures and possibly plastic deformation.

2.5 *Die Material and Coatings*

Proper selection of die material and die coating is important in order to reduce die wear.

3. Abrasive Wear

Abrasion, observed in 70% of all worn dies, is a gradual form of wear. It is defined as "displacement of material from surfaces in relative motion caused by the presence of hard protuberances or hard particles, either between the surfaces or embedded in one of them." Abrasive wear then arises from penetration plowing out of material from a surface by another body in relative motion. Abrasive wear processes are divided, traditionally into two categories: two-body and three-body abrasive wear. Two-body abrasive wear occurs when a rough surface or fixed abrasive particles slide across a surface to remove material. In three-body abrasion, abrasive particles act as interfacial elements between the solid body and the counter body (Ref 12, 13).

The amount of die material removed because of abrasive wear is directly proportional to the interface pressure and the amount of relative sliding and inversely proportional to the hardness of the metal surface. Felder (Ref 5) showed that the wear volume, V, is proportional to the sliding length, L, and normal load, P, and decreases as the surface hardness, H, increases (Eq 1). Most forging dies are typically of rather complex geometry. Therefore, the interface pressure and amount of relative sliding can vary from one area to another. Hence, characterization of abrasive wear in a systematic manner typically makes use of simulative tests of simple geometry.

$$V = K \cdot \frac{P \cdot L}{H_v^m} \qquad \text{(Eq 1)}$$

where m is an exponent, about 2 for the steels; and K is a constant, which depends on the structure of the steel, the surface films (lubricants, scale, etc.).

4. Exhaust Valves

Selection of the materials and heat treatments used for exhaust valves depends upon the operating environment in each specific engine application. The most common materials used for exhaust valve are 21-4N, 21-2N, In 751, and Nimonic 80A (Ref 14). For forging these materials, the die materials are H-13 and H-19. The process of valve manufacture starts with an incoming bar (about 25.4 to 28.57 mm diameter), which is cut into slugs by abrasive saw or warm sheared to precise weight. The slugs are induction heated to around 1150 °C under endothermic (natural gas) atmosphere to prevent scales. The slugs are then fed from the induction heater to the first station on a mechanical press by an automatic feed mechanism. The valve stem is extruded in first die and then either by manual or automatic part transfer brought to the second die where the valve head is upset forged. About 15 to 20 valves are made per minute. Figure 2 shows the different stages in the manufacture of valves.

5. Simulation Approach

Metal flow in forming operations can be simulated using various FEM based computer programs. DEFORM was selected for this study because it is developed specifically for simulation of metal forming processes and has been proven to give good results. DEFORM requires as input the workpiece and the die geometry, material data, press speed, and the interobject boundary condition. Figure 3 shows the different stages

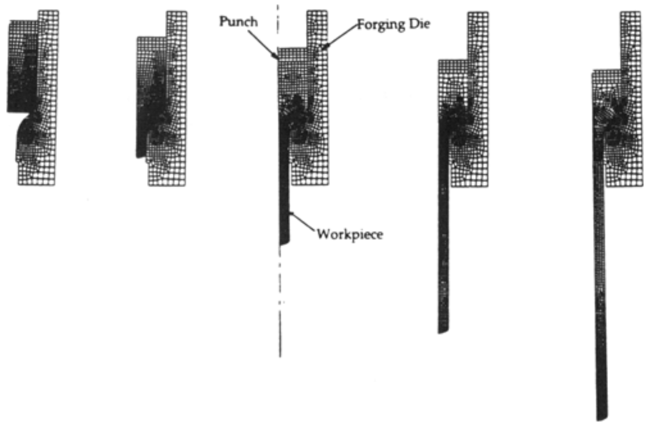


Fig. 3 Computer grid of different stages during extrusion process as obtained by FEM simulation. Due to axisymmetry, only half the geometry was simulated.

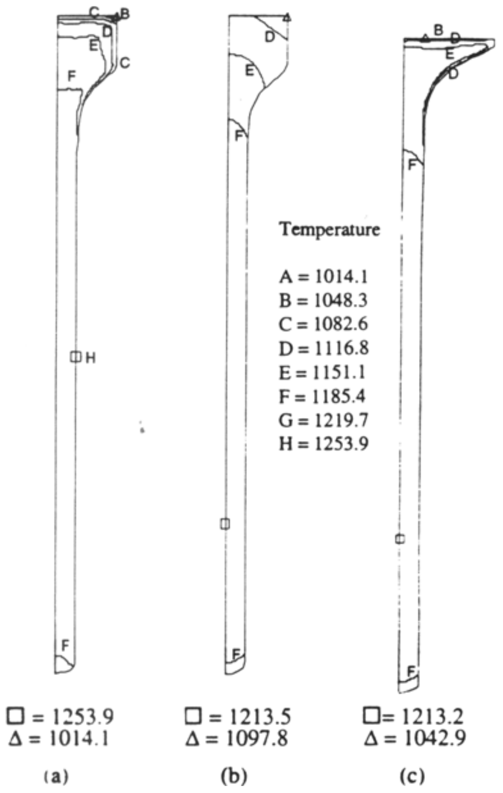


Fig. 4 Temperature distribution in the workpiece (a) after extrusion, (b) before forging (after dwell), and (c) after forging (°C).

during the extrusion process. The important simulation conditions are as follows:

- Workpiece material - IN 751
- Die material - H-13
- Initial billet temperature - 1150 °C
- Initial die temperature - 93 to 204 °C
- Lubricant - oil-based graphite ($m = 0.3$) (Ref 15)

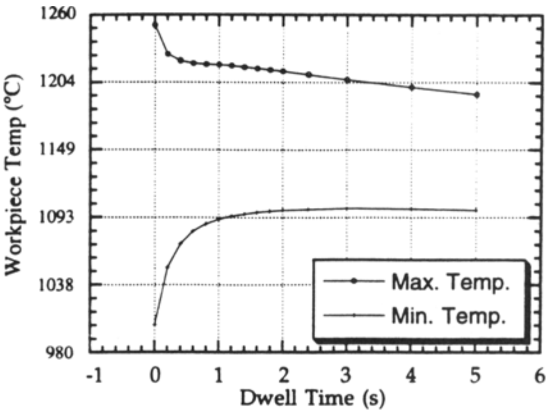


Fig. 5 Effect of dwell time on workpiece temperature.

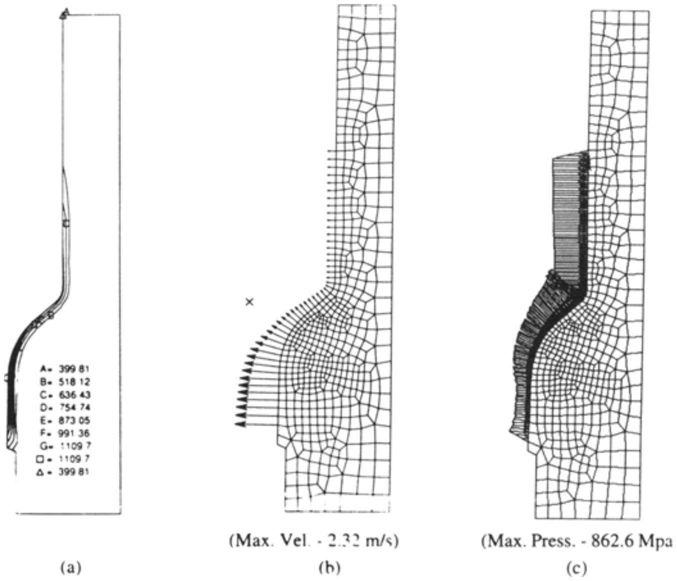


Fig. 6 Extrusion die. (a) Temperature distribution (°C). (b) Velocity distribution (m/s). (c) Interface pressure distribution (MPa).

- Press type - mechanical (stroke = 254 mm)

The output from DEFORM, (Scientific forming technical Corporation (SFTC), Columbus, OH) includes: nodal temperatures of the workpiece; the die, stress, strain, strain rate and velocity distribution in the workpiece; and the deformation load. In order to obtain the nodal pressure and relative velocity on the die at the workpiece interface, a data exchange program TRANSFER (Ref 16) was used. This program transfers the nodal pressures and velocities from the workpiece onto the die.

The thermal properties of the die and billet material and the flow stress of the material were obtained from literature. The initial grid for the workpiece has 646 nodes and 592 elements, and the grid for the die has 545 nodes and 487 elements.

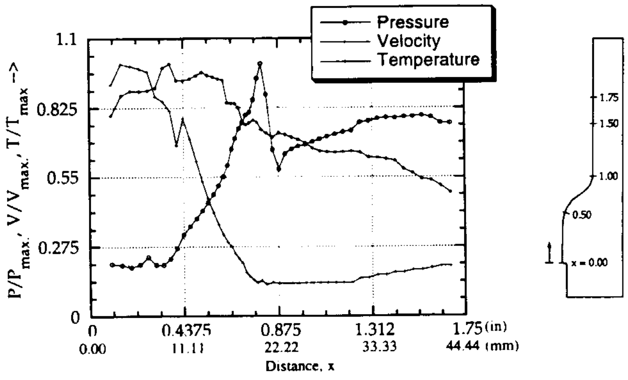


Fig. 7 Variation of pressure, velocity, and temperature with distance along the edge of the die.

6. Discussion of Results

The whole process was simulated using DEFORM. The temperature distribution and the deformation load are very close to that obtained in the industry although more accurate tests are being conducted to verify the finite element model.

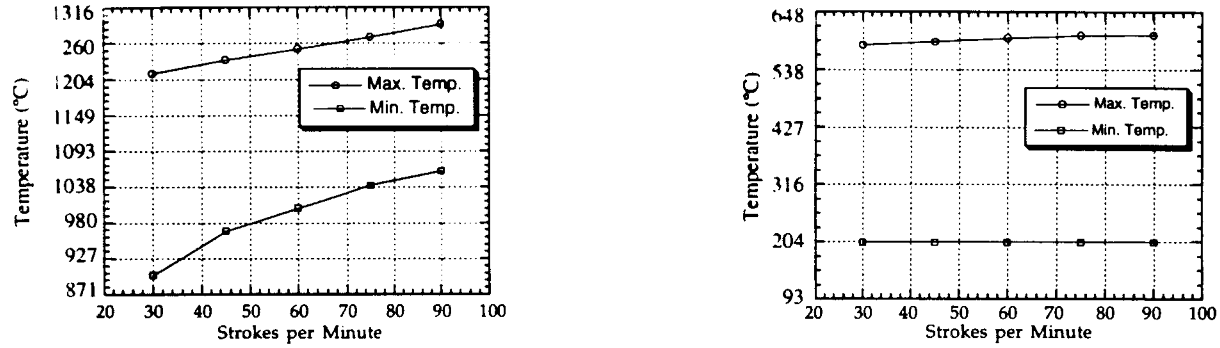
The temperature distribution in the workpiece during different stages of manufacture is shown in Fig. 4. The minimum temperature in the workpiece, which is approximately 1000 °C at the end of the extrusion, goes up before the forging to approximately 1100 °F, even though some heat is lost to the surroundings. This is due to conduction of heat from the inside of the workpiece to the surface during this period. The dwell time was varied from 1 to 5 s, and its influence on the workpiece temperature was studied (Fig. 4). There is a significant change in the workpiece temperature during the first two minutes. After that the minimum temperature is almost steady, and the maximum continues to drop. From Fig. 5, that dwell time should be kept between 1.5 to 2.5 s.

The temperature distribution in the die is shown in Fig. 6(a). The temperature in the die is maximum along the curved surface. This is expected because of frictional heat being generated and high heat transfer in that region. The same region also has very high velocities (Fig. 6b) and medium pressures (Fig. 6c). The arrows in Fig. 6(b) show the magnitude of the velocity; the direction of the velocity is perpendicular to the direction of the arrows. Abrasive wear is most likely to take place in this region and has been observed during actual manufacturing. The same data are represented in a different form in Fig. 7. This plot shows the variation of average pressure, temperature and velocity with distance *x* along the edge of the die. The pressure, temperature, and velocities were normalized by dividing them by their maximum value.

6.1 *Effect of Press Speed and Initial Die Temperature*

The effect of press speed on the workpiece and die temperature was studied by simulating the extrusion process for different speeds. The workpiece temperature increases as the press speed increases because at higher speed, contact time decreases resulting in less heat being lost to the die. Also more heat is generated due to plastic deformation and friction at higher speed. The variation of workpiece temperature at the end of extrusion with press speed is illustrated in Fig. 8(a). In case of extrusion die (Fig. 8b), there is very little change in temperature with press speed. This is because at lower speed, while the heat transfer is more, there is less heat generated by friction at the interface, and less heat is generated in the workpiece due to plastic deformation. Figure 9 shows the variation of the die temperature at the end of extrusion with press speed. The variation of interface pressure with press speed is illustrated in Fig. 10. This figure shows the interface pressure along the edge of the die is fairly constant with press speed. Therefore at lower speed, there would be less abrasive wear because temperature and pressure are almost independent of press speed, but there is a decrease in relative velocity at the die and workpiece interface.

The effect of initial die temperature on final die and workpiece temperature at the end of extrusion was also studied as shown in Fig. 11. This figure shows that decreasing the initial die temperature does not have a significant effect on the workpiece temperature, but there is a decrease in maximum die temperature at the end of extrusion. Hence, it makes sense to keep the initial die temperature low.



(a)

(b)

Fig. 8 Variation of temperature at the end of extrusion with press speed. (a) Workpiece. (b) Die.

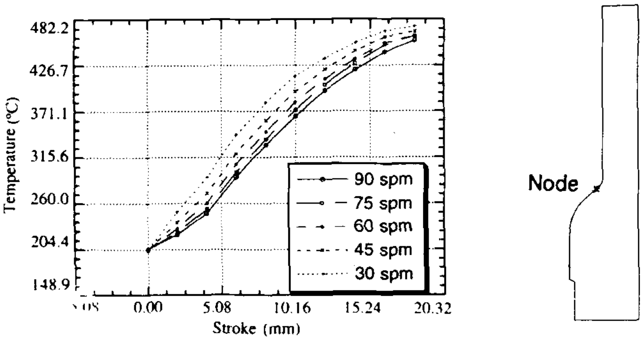


Fig. 9 Variation of temperature for a node on a die with press speed.

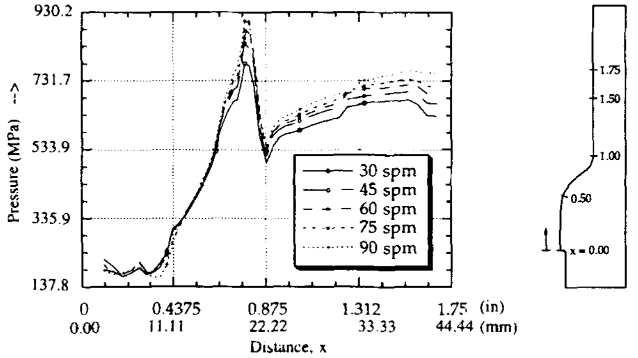


Fig. 10 Effect of press speed on interface pressure along die surface.

7. Conclusion

The primary conclusions are:

- The dominant wear mechanism in extrusion die is abrasive wear, though adhesive wear is also seen in certain regions of the die.
- Die wear is mainly influenced by velocities, temperatures, and pressures at the workpiece and die interface. However the degree of influence of each of these variables varies greatly and will have to be determined by correlating the simulation result with the wear data.
- The press speed had very little influence on interface pressure and die temperature. It did, however, affect the workpiece temperature.

Even though the investigation was conducted for specific case of extrusion and forging of exhaust valve, the results should be applicable to other geometrical shapes. In addition to sliding wear mechanisms, other metallurgical and chemical aspects of wear should be incorporated to obtain a good prediction of die wear profile.

Acknowledgment

This work was conducted with support from Engineering Research Center for Net Shape Manufacturing funded by the National Science Foundation. The support is gratefully acknowledged. The author would also like to thank the members of ERC/NSM, who contributed suggestions and discussions.

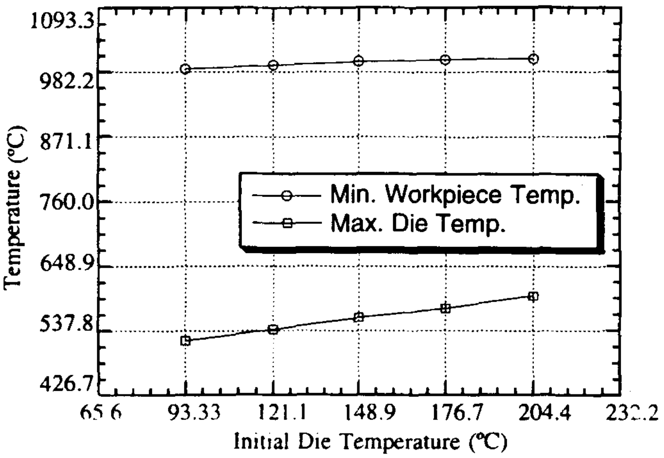


Fig. 11 Effect of initial extrusion die temperature on final die and workpiece temperature.

References

1. S.M. Ali, B.W. Rooks, and S.A. Tobias, The Effect of Dwell Time on Die Wear in High Speed Hot Forging, *Proc. Inst. Mech. Eng.*, Vol 185, 1971, p 1171-1186
2. B.W. Rooks, A.K. Singh, and S.A. Tobias, Temperature Effects in Hot Forging Dies, *Met. Technol.*, 1974, p 449-455
3. B.W. Rooks, The Effect of Die Temperature on Metal Flow and Die Wear During High-Speed Hot Forging, *Proc. of the 15th International MTDR Conference (Birmingham, England)*, 1974, p 487-494
4. A.K. Singh, and B.W. Rooks, and S.A. Tobias, Factors Affecting Die Wear, *Wear*, Vol 25, 1973, p 271-279
5. E. Felder and J.L. Montagut, Friction and Wear During the Hot Forging of Steels, *Tribol. Int.*, 1980, p 61-68
6. J. Renaudin, G. Batit, Y. Thore, and E. Felder, A Way to Build a Computer Program for Forecasting the Abrasive Wear of Hot Forging Dies, *11th International Drop Forging Conference (National Forging Industry Association, Germany)*, Koln, Germany, 1983
7. O.C. Vardan, A. Bagchi, and T. Altan, Investigation of Die Wear in Upsetting Using FEM code ALPID, *Proc. of NAMRC-XV* (Bethlehem, PA), Society of Manufacturing Engineers, 1987
8. Private communication between Mitsubishi Heavy Industries and T. Altan (Battelle Memorial Lab., Columbus, OH 43210), 1976
9. W.E.J. Cross, *Metal Treatment*, Vol 16, 1949, p 141-145
10. E. Schlomach, *Werkstatt und Betrieb (German)*, Vol 107, 1974, p 145-148
11. R. Shivpuri and S.L. Semiatin, Friction of Wear of Dies and Die Materials, *ASM Handbook*, Vol 14, 1992, p 621-648
12. E. Robinowicz, *Friction and Wear of Materials*, John Wiley & Sons, 1965
13. J.M. Larson, L.F. Jenkins, S.L. Narasimhan, and J.E. Belmore, Engine Valves - Design and Materials Evolution, *J. Eng. Gas Turbines Power (Trans. ASME)*, Vol 109, 1987, p 355-361
14. G.D. Lahoti, V. Nagpal., and T. Altan, Selection of Lubricants in Hot forging and Extrusion, IITRI (Chicago, IL), Illinois Institute of Technology Research Institute, 1978
15. M. Knoerr, H. Krueger, C. Rentsh, and T. Altan, "A Technique to Avoid Failure of Forging Dies," Report ERC/NSM-B-D-92-18, Engineering Research Center for Net Shape Manufacturing, The Ohio State University, 1992
16. A. Kannappan, Wear in Forging Dies, *Met. Form.*, Vol 36, 1969, p 335-34