J. Mater. Shaping Technol. (1988) 6:55–71

# Past Developments and Future Trends in the Rotary or Orbital Forging Process

Rajiv Shivpuri

**Abstract.** Rotary forging is a relatively new manufacturing process with potential for cost-effective applications, especially in cold forging of intricate parts to net shape. In this paper orbital forging and axial die rolling processes are included as subsets of rotary forging while radial forging, also known as rotary forging, has been excluded; these decisions are primarily based on die kinematics. Because of its recent origins, the rotary forging process is first described. Then, a historical perspective is provided to trace its recent origins. The machines are classified based on die kinematics. Die kinematics influence the stick–slip or position discrepancy behavior of the different machine types and have deep implications on the die filling and accuracy capabilities of these machines. Rotary forging machines currently in operation in the U.S. and their applications are presented in greater detail. The discussion on future applications and potential research issues is primary based on the author's own perception of future trends in this emerging field.

## INTRODUCTION

Rotary or orbital forging is a metalworking process which incrementally deforms a workpiece using a combination of rotation, rolling, and axial compression techniques. In this paper the generic term rotary forging includes orbital forging and axial rolling processes.

In rotary forging, one die is tilted at a small angle with respect to the axis of the other die as shown in Figure 1(a). This results in the forging force being concentrated on a small, "footprint" area [Fig. 1(b)], of the workpiece in contact with the tilted die. The dies are then moved in such a way as to deform successive small areas of the workpiece until a final shape is formed. Because the force necessary to produce deformation is directly proportional to the contact area and the material flow stress, rotary forging requires a force typically 10% of that required by conventional forging techniques. Forging forces being smaller, machine and die deformation, as well as friction, are inherently smaller, giving rotary forging the potential of becoming a near-net shape metal forming process.

Since the late 1960s, research and development in rotary forging has been concentrated in England, Poland, West Germany, Japan, and China. China, a late entrant, has established a comprehensive program in which four universities, five research institutes, and 30 factories are involved.

In the U.S., the NSF Engineering Research Center for Net Shape Manufacturing at The Ohio State University has begun an investigation into identifying the special "niche" of this technology in the net shape manufacturing environment.

On the other hand, the rotary forging machine market seems to be maturing with both Schmid Corporation of Switzerland and Wagner Dortmund of West Germany having successfully introduced rotary forging machine lines to the automotive market. The major users of this technology are in Europe.

This paper begins with describing the rotary forging process. Then the developments in machine construction are presented chronologically. In this section, production machines introduced by Schmid and Wagner in the U.S. market are described in detail. The applications of this process to part production are discussed next. Issues that need research are presented last. The paper sums up the presentation in the concluding section.

---

The author is with NSF Engineering Research Center for Net Shape Manufacturing, The Ohio State University, Columbus, OH 43210.

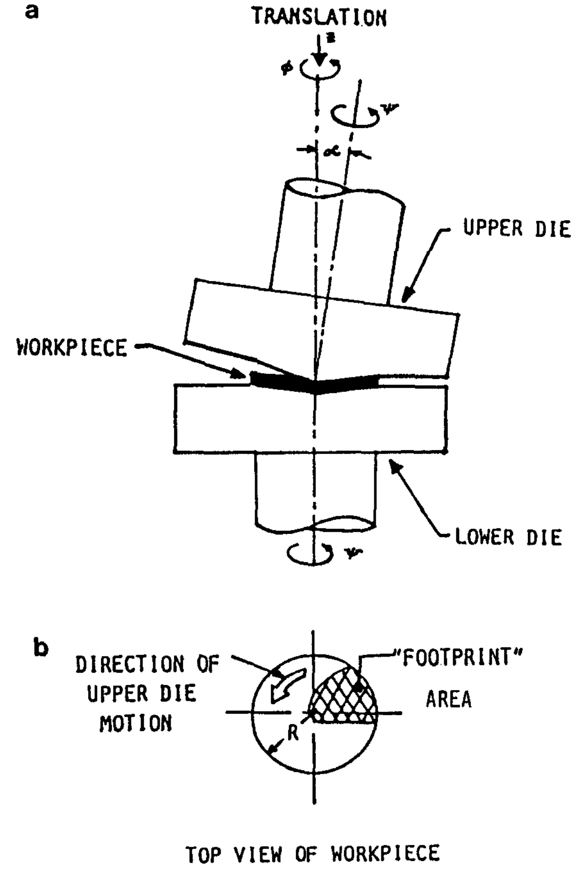

**Fig. 1.** A schematic of the rotary forging process: (a) die arrangements and kinematics, and (b) top view of the workpiece showing the area of die–workpiece contact (footprint area).

## TYPES OF ROTARY FORGING MACHINES AND DIE KINEMATICS

For convenience, let us consider a vertical press assembly and refer to the tilted die as the upper die and the die with vertical axis as the lower die, Figure 1. A horizontal arrangement or inverting the roles of the dies will not affect our present discussion. Let us call the angle between the axes of the dies the forging angle and assign it the symbol $\alpha$. During forging the dies may experience several types of motions. First, the dies may rotate about their own axes. We will use $\Psi$ to represent this rotational angle, or "spin" motion. In addition, the axis of one die may precess about the axis of the other causing the die to appear to rock or wobble. The term "orbiting" has been used to describe this motion. We will use $\phi$ to represent the amount of angular displacement of the precessing axis. Note that in an actual process, it is permissible to have orbiting motion without rotational motion; this is often a point of confusion. Finally, we have translational motion along the vertical direction $z$ which is often called "feed". These definitions are summarized in Table 1.

For machine classification purposes, we will assume that the workpiece experiences the same motion as the lower die. Standring and Appleton [1] classified rotary forging machines into three major types based on the kinematic motions of the dies. Type 1 has both die axes fixed, with each die having rotational motion, but no orbital motion. In Type 2, one die axis is fixed; the other die axis orbits but also has rotational motion. Finally, they define Type 3 to have one die axis fixed with the other having just an orbiting motion; no rotation.

This classification, which is based on orbital motion and rotational motion, seems adequate for general purposes. In studying the relative motion between the upper die and the workpiece, we found that the Type 1 machine can be divided into two subgroups, depending on the independence of each die's rotational motion. If one of the dies is a driver and the other a follower, we shall call the machine a Type 1A. If both the dies are power driven and each can rotate independently, it will be called a Type 1B machine. It will be shown that Type 1A is similar to Type 2 in relative die motion; when both dies are driven with the same rotational velocities, Type 1B is similar to Type 3. Table 2 shows these types of machines with the translation motion also indicated. It gives examples of some existing machines and their types [2–15]. Schematic arrangements of each type, including die motions, are shown in Figure 2.

Standring and Appleton [1] have studied the kinematics of a simple conical upper die on a flat or conical surfaced workpiece for the three types of rotary forging processes. The most interesting phenomenon is the slip between upper die and workpiece that may occur under various conditions. This slip is best

**TABLE 1.** Definitions of Die Motions in Rotary Forging [2]

| Type of Motion | Other Names Used | Symbol | Definition |
|---|---|---|---|
| Rotational | Spin | $\Psi$ | Angular motion of rigid body about an axis |
| Orbiting | Rocking, wobbling | $\phi$ | Precession of a line in a body about an axis (without rotation of the body about axis) |
| Translational | Feed | $z$ | Motion in a linear direction |

**TABLE 2.** Classification of Rotary Forging Machines

| | | Motion of Upper Die | | | Motion of Lower Die and Workpiece | |
|---|---|---|---|---|---|---|
| Type | Examples | Translational | Rocking or Orbiting | Rotational | Translational | Rotational |
| 1A | • Dyna East, RF-50 [2]<br>• University of London [3]<br>• Wagner Disk Rolling [4, 5] AGW-125, AGW-400 | Yes (Drive) | No | Yes | No | Yes (Drive) |
| 1B | • Slick Mill [6]<br>• USSR Bevel Gear Machine [7, 8]<br>• University of London [3] | Yes (Drive) | No | Yes (Drive) | No | Yes (Drive) |
| 2 | • Slick Rocking Die [9]<br>• VSI Spinnomatic [10] | Yes (Drive) | Yes (Drive) | Yes | No | No |
| 3 | • Marciniak Rocking Die PXW100 [12]<br>• VSI OFP-100 [12]<br>• Massey ROTAFORM [13, 14]<br>• Schmid, T-200 [32]<br>• Schmid, T-630 [32] | No | Yes (Drive) | No | Yes (Drive) | No |

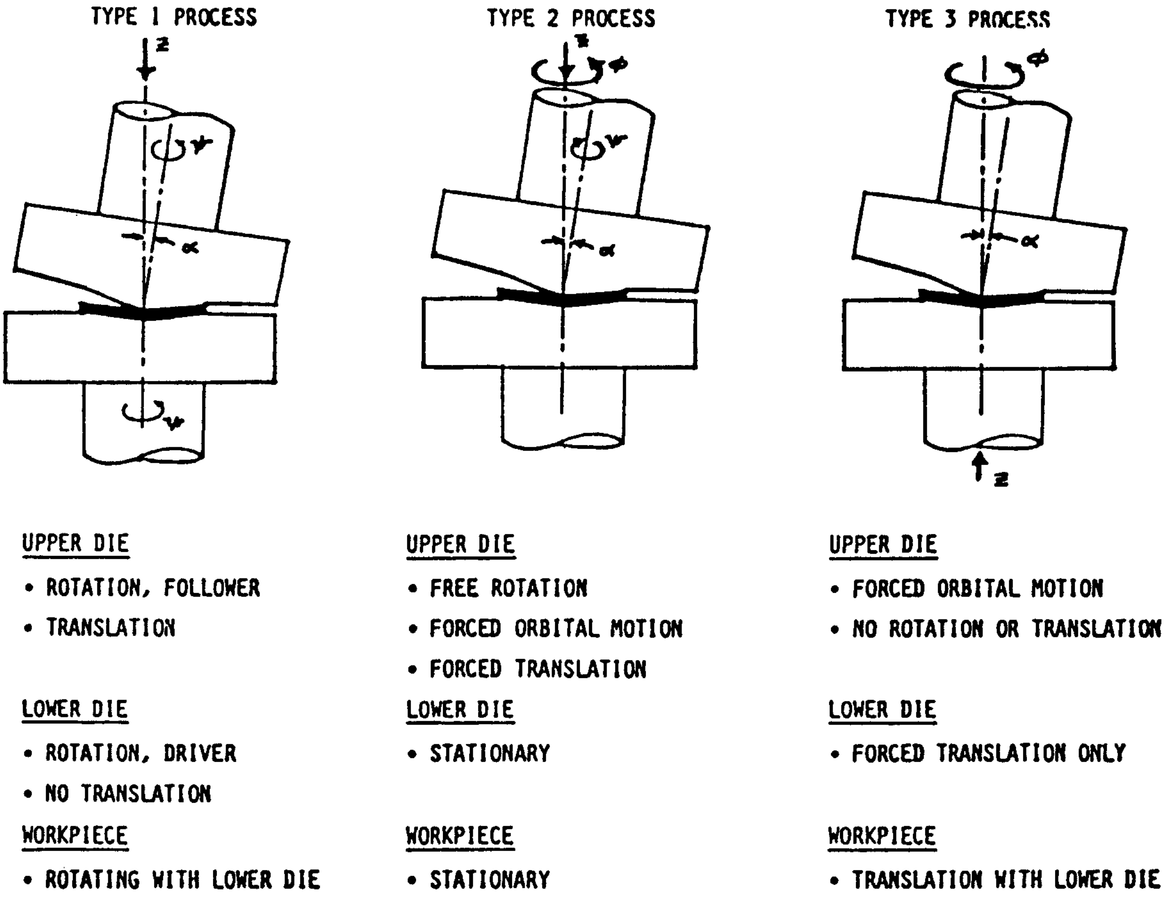

**Fig. 2.** Classification of rotary forging machines into three types based on die motions [2].

understood by investigating the die kinematics of various types of rotary forging machines.

## ROTARY FORGING MACHINE DEVELOPMENTS

The first modern rotary forging machine was developed in the U.S. in 1918 by Edwin E. Slick [6,9], vice-president of Midvale Steel and Ordinance Co. The "Slick Mill" was capable of producing large wheel-type forgings directly from heated ingots. Until recently, Bethelem Steel Corporation was using a modified, fully-automated "Slick Mill" to forge steel components at the rate of about one per minute using an orbit angle of 10.7 deg [10].

Since the development of the Slick Mill, rotary forging machine development has progressed steadily worldwide. The following presentation chronologically traces the important developments and categorizes them according to their country of origin.

### United Kingdom

In 1929, H.F. Massey, founder of B & S Massey, Ltd., designed and patented a vertically operated rotary forging press [13]. Although Massey's early design was never built, he predicted some of the problems associated with rotary forging and anticipated the types of parts this press could forge.

In 1964, B & S Massey produced a simple experimental model machine that led to the design and manufacture in 1966 of the prototype "Rotaform" rotary forging press [14]. After six years of experimental tests, the first "Rotaform" press was built for production and installed at Stockton Precision Forge, Ltd. This machine was the first fully automated rotary forge to be produced and featured a hydraulic billet tipping device, vibratory feed unit, induction furnace, and automatic feeding and ejection facilities. The upper die was inclined at an angle of 4 deg and was operated at 1000 cycles/min. The "Rotaform" press was capable of producing up to 600 forgings per hour. The original design was for the cold or hot forging of metal, but after conducting tests on die wear and formability at temperatures of up to 1200° C, B & S Massey established an optimum working temperature range of 600–800° C. This was a Type 3 machine. B & S Massey stopped production of this machine in the late 1970s.

At about the same time, in 1967, a research group under Drs. Johnson and Slater [16] built an experimental Type 3 rotary forging machine at the University of Manchester Institute of Science and Technology (UMIST). This machine had an electric motor driven upper die and a mechanical lever driven lower die. It was capable of working on lead workpieces. The effects of machine parameters on workpiece deformation were studied on this machine [17]. A larger machine was constructed here in 1972. Dr. Slater joined the University of Salford in 1969 and Appleton [18] continued using the UMIST machine for their experiments on workpiece deformation.

Appleton later moved to the University of Nottingham, where with Standring he built a 30 ton Type 3 rotary forging machine. This machine was further developed by Standring in 1980. It is a very versatile machine capable of simulating all the three types of motions [19]. Numerical control has been implemented to control the feed and rotational rates.

At the University of London in 1979, work started on a Type 1 machine. Slater with Penny and Jebb [3,20] built a 10 ton prototype for upsetting small automotive parts. Details about this machine have not been published.

### Poland

Meanwhile in Poland, Marciniak at the Politechnika Warsaw started rotary forging work in 1967. He designed and patented the "Rocking-Die," Type 3, machine [11] in 1970. Based on his design, Ponar Plasomat, Poland, is marketing worldwide PXW100 A, a 160 ton machine. This machine was initially used for part manufacture in most of the industrialized countries and since has been extensively copied.

### Soviet Union

A type 1 machine was first built in 1970 in the Soviet Union. Silichev [7,21] patented a design for a hot rolling machine for the production of spiral-bevel gear crown wheels. Very similar to the "Slick Mill," this press has an upper spindle head, inclined at an angle of 30 deg to the vertical, which rotates around a lower rotary table via bevel gears on both upper and lower dies. The workpiece is heated to approximately 1100° C by an induction heating head. This machine incorporates a fully automatic feed. Part loading and unloading is carried out by a hydraulic robot unit.

### Japan

In 1972, at the Government Industrial Research Institute, Nagoya, an experimental Type 3 rotary forging press was developed with an orbit angle of between 0–10 deg. In 1973, another press of similar type was built and showed considerable improvement over the earlier machine. This press operated with an upper die angle between 0–5 deg and an ejector unit which was hydraulically raised [22]. Since then, Naito-Tekko-Sho Co., Ltd., received a license on the Polish PXW100 press; they completely rebuilt and sold the Polish machines. Nito-Kaiko have built their own experimental press and are currently working on an improved design [10]. Development of the Type 3 machine is continuing in Japan [23] and it is finding increasing applications in the powder metallurgy area.

### People's Republic of China

Rotary forging was introduced in China in 1973. A few Polish machines (PXW100) were installed and research started on the mechanics of deformation. Several rotary forging machines were built, based on the Polish design, with capacities varying from 3.6 to 400 tons [24]. There are eight vertical models and three horizontal models of rotary forging machines currently in operation. Extensive use of the rotary riveters is also being made.

Though the Chinese have made impressive strides in machine building, they have remained with the basic Type 3 design and have not investigated the merits of other design alternatives.

### United States

Though the United States was the first to build a rotary forging machine, the "Slick Mill," no further development took place until 1973 when VSI, Inc. of Troy, Michigan, began to import Polish machines, the PXW100. They later modified its electrical and hydraulic units [12,25]. A few machines sold by them are still in operation [26]. VSI, Inc. merged with Fairchild Industries in 1983 and pulled out of the rotary forging area.

In 1983, Dyna East Corporation of Philadelphia, under the sponsorship of the National Science Foundation, built a 50 ton machine (Type 1) for high precision cold forming of shallow conical parts [27,28,29]. They, under the sponsorship of the Ben Franklin Trust of Pennsylvania, upgraded this machine to 150 tons and implemented computer numerical control [30]. This machine is currently producing high precision ordinance parts for the defense industry. Dyna East is planning to further enhance their rotary forging capability by building a 500 ton prototype [31].

### Switzerland

Heinrich Schmid of Rapperswil modified the Polish Type 3 machine by increasing its capacity to 224 tons, increasing workpiece accessibility and substantially improving the hydraulic unit. They started marketing this machine, T-200, in the U.S. in 1983 [32]. They have recently introduced a higher capacity 708 ton, T-630, model to the U.S. [33]. Also, an intermediate capacity press, 440 tons, has been developed and will be marketed in 1987.

### West Germany

Wagner Dortmund of Dortmund, a subsidiary of Thyssen Maschinenbau, have been marketing the SW 400 (AGW 400) Disc Rolling Mill, a 400 ton, Type 1 machine since 1983 [15]. This machine has automatic loading and unloading devices. An automatic production line for weld neck flanges has been in operation in Sao Paolo, Brazil since the early '80s. Wagner [34] is setting up a production line in U.S. for the manufacture of automotive ring gears using AGW 125, a 125 ton machine. This line will probably become operational by 1987/88.

### Current Status

Rotary forging machine research is being actively pursued in a large number of countries. Most of the machines developed are for internal research or production and are not being marketed. The first large scale marketing of rotary forging presses was by Poland: Orbital Forging Press PXW100A. This 160 ton, Type 3 press has been widely copied and significantly improved. One of its successful production versions is Schmid T-200, which is being marketed in the U.S. Schmid is also marketing two larger capacity machinies, T-630 and T-440. These presses are primarily for cold working, while Wagner Dortmund of Germany is marketing Type 1 machines of 125 ton and 400 ton capacity, AGW 125 and AGW 400, for hot working.

## RESEARCH IN WORKPIECE DEFORMATION

The review below presents production research according to its country of origin. The research is divided into three main topics: effect of machine parameters on part information, workpiece metal flow during the process, and final workpiece material properties.

### United Kingdom

In 1969, Slater et al. [16] published one of the earliest articles on rotary forging. Using the small experimental press at the University of Manchester Institute of Science and Technology (UMIST), the British investigators used lead at room temperature as an intial workpiece material to simulate the forging of steel having a temperature of between 700–1400° C. Their findings showed that rotary forging is feasible for upsetting cylindrical workpieces and that the optimum axial force required to forge specimens with initial height by diameter (H/D) ratios of less than unity is a small fraction of the force required by conventional forging methods.

Slater shortly followed up his work on the rotary forge concept [17], this time using cylindrical laminated plasticine specimens to study the mode of deformation during rotary forging. Pure lead was used as a model material to simulate rotary forging of hot steels. The effect of axial force on mode of deformation was studied by forging cylindrical lead specimens to fixed heights using different magnitudes of axial force. It was found that "mushrooming," larger radial flow at the upper die compared to the lower die, occurs at a relatively low axial force and central cracking occurs at relatively high axial forces. Experimental plots of fractional reduction in height and number of revolutions of upper die (tilted die) were made for different values of axial force and rotation rate for pure lead specimens. On these plots, regions of acceptable deformation (regions where mushrooming or tensile instability, preferential thinning at workpiece center, does not occur) where shown. These plots provide a convenient method to estimate the rotary forging machine parameters, such as forging force and rotation rate, that would avoid workpiece defects.

Again, using laminated plasticine and pure lead as model materials, Appleton and Slater [18] in 1972 conducted an experiment to determine the effect of the upper die geometry on the performance of their rotary forging press in terms of forging load, number of revolutions of upper die, total deformation energy, fractional reduction in height, etc. An experimental plot between mean die pressure and penetration of the upper die during indentation and rotary phases of the process was obtained. Analytical relations for calculating the areas of contact between conical upper die and cylindrical workpiece were presented. The theoretical values compare favorably with experiments at low depths of indentations.

In 1977, B. Hawkyard, et al. [35,36] conducted an experiment to measure the pressure distribution on the workpiece using a pressure-sensing lower die. Peak die pressures were found to be about two to three times the workpiece material yield stress while the pressures at the workpiece center were less than the material yield stress. They suggested a deformation mechanism involving plastic hinges. This was used to explain observed central tensile failures and other related phenomena when orbital forging flat discs. Using plastic hinges, predictions of forging force were made. They compared reasonably well with experimental measurements.

In 1980, Standring, Moon, and Appleton [37] at the University of Nottingham experimentally studied the formation of plastic deformation zones during indentation of cylindrical aluminum workpieces by metallurgical methods. Hardness distribution along a vertical section of the deformed workpiece was given. Photographs of annealed grain structure of workpieces indented to various depths were shown, and from these the deformation zones were identified. A qualitative insight into the mushrooming phenomenon was provided.

Standring and Appleton [22] reviewed the significant contribution Japanese researchers have made to orbital forging knowledge. The research areas covered in this paper were machine performance, deformation characteristics, workpiece accuracy, frictional conditions, powder compaction, and sinter forging.

Leheup, Moon, and Standring [38] in 1982 reported a study of metal flow during rotary forging of powdered metals (PM) using a configured upper die. They formed bevel gears from sintered annular preforms. The effect of rotary compaction on part densification was studied by metallurgical techniques. Improved die filling and densification was reported.

Hawkyard and Moussa [39] applied upperbound techniques to economize on force and power during forging of circular parts with rectangular flanges. They included the power consumed in the formation of plastic hinges in their analysis.

At the 3rd International Conference on Rotary Metalworking Process held in Tokyo in 1984, no contribution came from the U.K. signaling a decline in rotary forging research there.

### India

Appleton, Sinha, and Prasad [40], using upperbound techniques, estimated mean die pressures generated during the indentation phase of rotary forging. Indentation loads and energies were also calculated. Sinha and Prasad [41] further extended the work to the rotary phase. Theoretical estimations were verified by experimental results.

### Japan

A look at the many contributions of Kubo, Hirai, and Kobayashi in the past decade [42,43,44,45,46,47] reflects the commitment the Japanese have made in utilizing and understanding the rotary forging process. Many investigations have been carried out in both governmental and private research laboratories.

The following areas are under serious current study:

1. Machine performance
2. Deformation characteristics
3. Workpiece accuracy
4. Frictional conditions
5. Powder compaction and sinter forging

Most of the Japanese work is experimental. Comparisons have been made between rotary forging and conventional forging (called single-axis compression in Japan). Japanese researchers have derived empirical formulas to characterize the effect of machine and die parameters on the workpiece deformation. For further details on each of these, the reader is referred to the excellent synopsis given by Standring et al. [22] of the Japanese rotary forging work up to 1980.

Two recent papers by a group of researchers under the direction of M. Kobayashi, at the Technological University of Nagaoka, report on the deformation behavior of three different materials, commercially pure aluminum, oxygen free copper, and 0.35% carbon steel, during upsetting and extrusion by rotary forging. They reported results on simultaneous forward extrusion–upsetting in 1979 [43]; simultaneous backward extrusion–upsetting in 1982 [44]; and simultaneous forward–backward extrusion–upsetting in 1984 [45]. Upset profiles of flanges, flange diameters, and extrusion lengths were measured for different specimen initial dimensions (height/diameter ratios), lubrication, and height reductions to quantify material flow. A semi-empirical approach utilizing upsetting or extrusion ratios, to determine initial blank size for a given final part geometry, is suggested. A few examples are given to demonstrate its applicability.

Kubo et al. [46] warm rotary forged thin discs of 0.55% carbon steel. Billets were heated to 500–900° C and dies to 150° C. Compared with cold rotary forging, the warm process provided a greater reduction in height and a smoother surface finish without fracture. Working time required were about one quarter of that in cold forging. At large strains, part properties deteriorated because of die chilling effects.

Ayano and Kumakura [23] described the development of a 2.5 MN (250 ton) machine. Clutch hubs and gear blanks were successfully warm and hot rotary forged on this machine. Low die life continues to be a major concern with warm and hot forging.

Kiyoto and Takemura [47] compared compaction of PM valve seat preforms achieved by conventional forging and rotary forging. They found that higher densification and better mechanical properties were achieved by cold rotary forging or presintered preforms.

A strong research effort in the industrial applications of rotary forging is continuing in Japan.

## Poland

Since A. Marciniak's early work [11,48] in developing the "Rocking-Die" forging press and the subsequent testing of the process, much of the recent rotary forging research in Poland has centered on cold forming of powder and sintered materials using rotary forging machines. The densification of these materials by rotary forging compares very favorably to conventional forging.

Marciniak [49] theoretically analyzed the warm rotary upsetting of flanges with rigid circular hubs. Assuming radial flow in the flange, the strains and strain rate were determined. Effects of intermittent contact of the upper die with warm material on temperature distribution and heat transfer were studied.

Grzeskowiak [50] tried to predict the future application of rotary forging by tabulating the varieties of parts that can be produced by this process. Principles of group technology were applied to ascertain the forgeability of a given family of parts.

Research in Poland is concentrating on finding new industrial applications for the rotary forging process.

## People's Republic of China

Serious attention to the production uses of the rotary forging process has recently been given by researchers at the Harbin Institute of Technology in the People's Republic of China. Pie et al. [51,52] have done studies analyzing the deformation process, forging load, and pressures associated with rotary forging and comparison of their results with conventional forging performance. Measurements of strain distribution in the footprint area of the workpiece were taken by Moire technique and verifications sought for Johnson's theory of plastic hinges [52]. Also, measures for avoiding central tensile failures have been suggested.

Lu et al. [53] of Qinghua University proposed a semi-empirical criterion to predict the workpiece height at which center thinning instability would begin during rotary forging. This criterion provides an upper bound to the forging loads and is an extension of the earlier work of Appleton and Slater [17].

At the 3rd International Conference on Rotary Metalworking Processes, 1984, there were numerous papers from China. Some of them are reviewed below.

Wei et al. [24] gave an overview of the extensive research on rotary forging being done in China. A Commission on rotary forging has been established to coordinate four universities, five research or design institutes, and more than 30 factories working in this field. An extensive data base on machine characteristics and mechanics of workpiece deformation has been built up. Full-scale production of automotive components has begun, resulting in substantial savings in cost.

Liu [54] rotary forged thrust bearing races for automotive steering axles using PM preforms. He found that greater compaction, better utilization of material, higher productivity, lower energy consumption, and lower fatigue wear of parts were achieved by the rotary forging process in comparison to conventional forging.

Zhang [55], using upperbound techniques, calculated force and energy requirements in the rotary forging of flat plates. He treated the out-of-plane buckling of thin plates during rotary forging by considering velocity discontinuities produced in the deformation zone and the formation of plastic hinges in the plate.

Geng [56] analyzed the deformations in the upper-die shaft using the finite element method. Results for 25 ton and 500 ton rotary forging machines are shown. Fillets are added to the root area to decrease stress concentration.

### United States

Little and Beyer [57], at the University of Michigan-Dearborn, experimentally plotted the true axial stress–strain curve of workpiece material during rotary forging and compared it to the true uniaxial stress–strain curve of the material (steel). The agreement was adequate enough to predict approximate rotary upsetting loads.

In 1982, a group of researchers at the Dyna East Corporation, under a National Science Foundation grant, studied the possibility of increasing the precision of the rotary forging process. They proposed minimizing deterministic part errors by optimum machine design and implementing numerical control. While Carleone et al. [27] introduced a process model to characterize part precision, Chou and Shivpuri [28,29] applied this model in the design of a rotary forging machine for precision work. A 50 ton rotary forging machine was built in 1983 and was used to produce high precision disc shaped parts. Tolerances of 0.004 in. were achieved on a 4.5 in. diameter cold forged part. Oxygen-free copper was used as preform material. This machine was upgraded in 1987 to 150 tons to work with tantalum and steel preforms [31].

### Current Status

While research in the U.S. and England is primarily concentrating on the mechanics of metal flow during simple upsetting, the Chinese and Japanese are concentrating on the industrial use of this process. They are empirically studying upsetting, backward and forward extrusion of cylindrical workpieces, and compaction of PM preforms. PM applications are also being studied in Poland.

## ROTARY FORGING MACHINES IN THE U.S.

There are four models of rotary forging machines currently operational in the U.S.: Schmid T-200, Schmid T-630, Dyna East RF-50, and Wagner AGW125. These will be described in this section.

(The Polish PXW100A press was developed in early 1970. It is a Type 3 machine. It is marketed worldwide by Metal Export, Warsaw. It has been exported to many countries and widely copied. Serious limitations in its hydraulic drive system which resulted in frequent breakdowns caused it to be phased out in most production shops. This machine will not be described in this paper.)

### Schmid T-200

Heinrich Schmid acquired Polish PXW100A press in the late 70s. Their T-200 has a design similar to PXW100A but has vastly improved hydraulic and control systems, and it also incorporates automatic loading unloading devices. Figure 3 shows the press cross section; the main components of the press are labeled in the figure. A cross section of the inclined die is shown in Figure 4 and the die motions possible in Figure 5.

Unique features of this machine are:

- the travel of the forging (main) and the ejection cylinder are limited by means of mechanical stops which are adjustable.
- All danger zones are protected with covers. The die area is surrounded by a light curtain which prevents unintentional entry. Forging forces and the speed of rotation are adjusted via potentiometers.

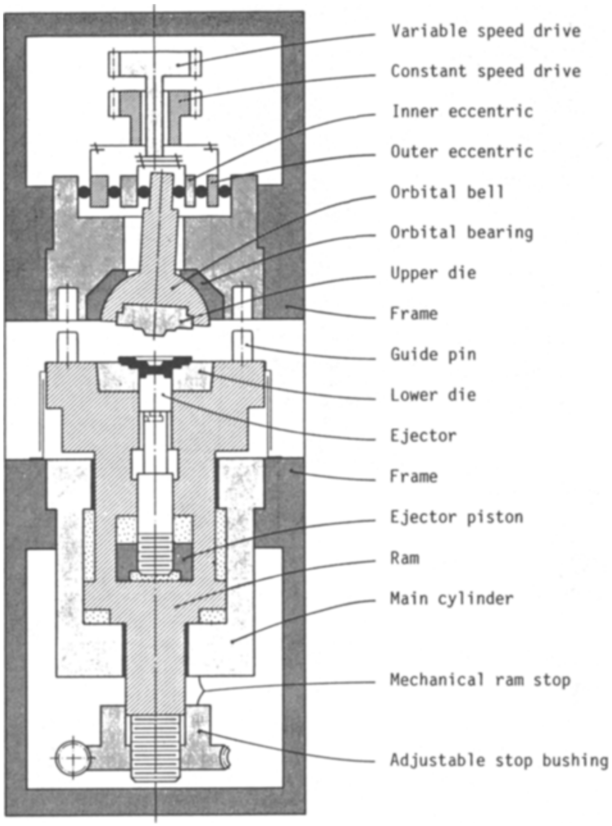

**Fig. 3.** Cross-sectional view of a T-200 (Type 3) machine. The main components are labeled [32].

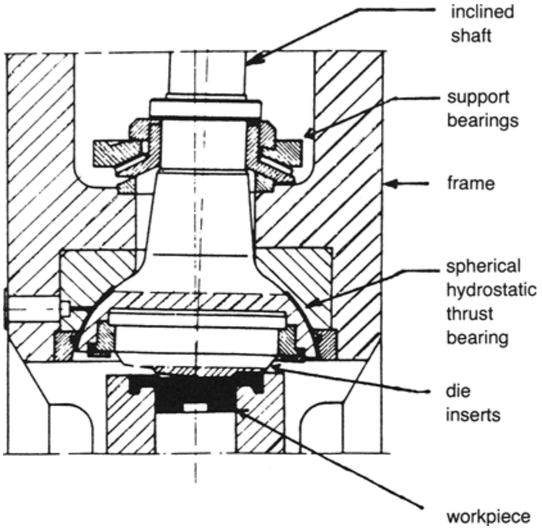

**Fig. 4.** Cross-sectional view of the inclined dies of PXW100A [12].

- Various programs can be selected by pushbuttons and selector switches.
- Guide pins on the lower die holder mate with guide holes in the upper die holder to prevent relative displacement of the dies due to eccentric loads generated during the operation.

Its production rates, 4–12 parts per minute, are higher than that of the Polish press PXW100. Schmid has successfully marketed this machine to the European and U.S. cold forging manufacturers in large numbers [33]. Some parts cold formed on this machine are shown in Figure 6.

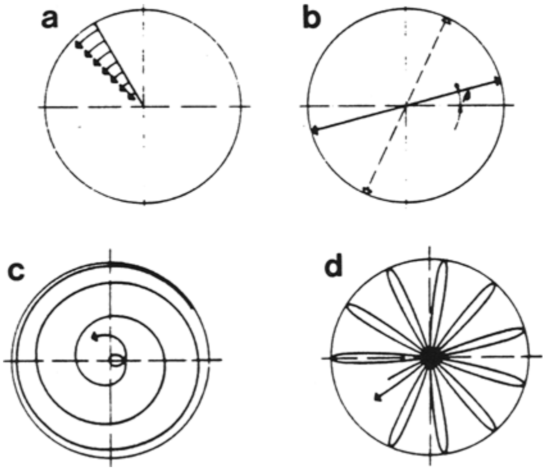

**Fig. 5.** Four types of upper die motions generated by adjusting the eccentric sleeve rotation rate and direction of rotation of die: (a) circular or orbital; (b) straight line or rocking; (c) spiral; and (d) planetary or daisy [12].

### Schmid T-630

Schmid T-630 (708 ton capacity) is the largest rotary forging press in the world. Its design is similar to T-200. Though Chinese reports suggest the existence of larger presses in China, no information is available on them; they will not be considered here. The press has a push-down hydraulic drive with a four-column structure. Steel parts of up to 9.8 in. diameter can be cold forged on this press. It can produce up to 600 parts per hour.

### Dyna East RF-50

This machine (prototype) was built under a grant from the National Science Foundation under the Small Business Innovative Research Program (SBIR). A schematic of the machine is shown in Figure 7. The main cylinder mounted on the top of the frame is of 50 ton capacity while the ejection cylinder is of 3 ton capacity. It is a Type 1 machine with both the upper and lower dies rotating around their respective axes. The frame is of a four-column construction with I-beams oriented to afford maximum rigidity to resist eccentric loads. The upper ram is guided via linear bearings mounted on the flanges of the I-beam columns. Two important issues regarding this design are [2]:

- The machine is a research prototype. Bolted construction is used for its ease of assembly and modifications.
- The machine is built in a university environment. A necessary requirement was that the individual components be easy to handle: small size and weight.

The machine capacity has been recently upgraded to 150 tons, the frame has been reinforced, and the control system being is enhanced for Computer Numerical Control interfacing.

The machine is primarily being used for the manufacturers of high precision disc shaped parts for ordinance applications.

### Wagner AGW125

AGW125 is a 125 ton gap frame machine with tie rod construction. The main components of the machine are:

- Upper and lower rotary unit
- Machine frame: gap type with tie rods
- Hydraulic drive for feed and rotary drive
- Ejection system
- Cooling and lubricating system
- Tool and dies

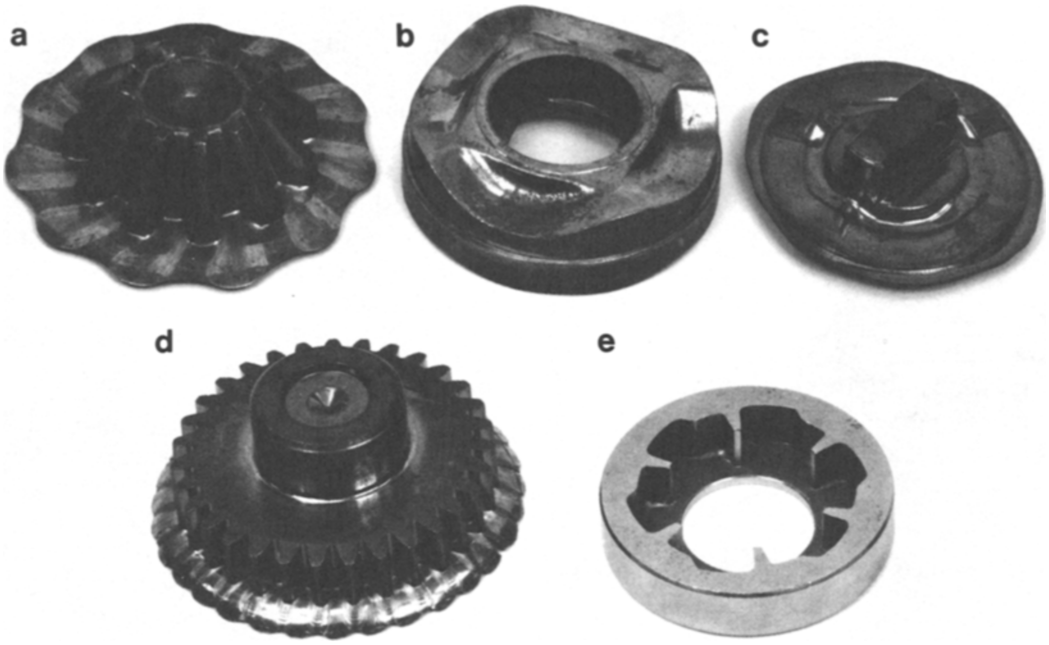

**Fig. 6.** Sample parts made by cold orbital forging: (a) Bevel gear, (b) cam disc, (c) central cam, (d) reverse idler and (e) cam race [32].

The lower rotary unit is rigidly connected with the upright and the base frame. The upper rotary unit is guided at the upright and is moved vertically downwards for pressing stroke. The upper die axis is inclined to the vertical between 3 to 12 deg. The angle is fixed for a particular machine depending on the part diameter and the product mix. Support bearings of the rotary unit are either the standard antifriction type or hydrostatic type based on pressing loads.

Forging forces in rotary forging are directly proportional to the footprint area ratio (footprint area/total area), therefore, for smaller forces smaller ratios are desired. Figure 8 shows plots of outer diameter of workpiece versus footprint area ratio for different feed rates and internal diameters for forging of discs (top) and rings (bottom). The inclination angle is held constant at 7 deg. Smaller footprint area ratios are realized at larger workpiece outer diameters and smaller feed rates.

The gap frame of the machine is stiffened by tie rods. The upper rotary guidance slide is attached to the back of the frame. Gap design permits good accessibility to the working area from three sides.

The hydraulic system consists of pressing and rotary subsystems. The pressing (feed) drive is effected via two or four cylinders. The rotary drive to the upper and lower units is effected via one or several hydromotors. The ejection system is installed in the lower die. Parts without draft angle can be safely ejected.

Eccentric loads during forging can cause eccentricity in the parts. To reduce eccentricity, dies, upper and lower, are guided against each other. In ring type (punched out center) parts, the upper die is guided at the center stud of the lower die. In parts with other profiles, the upper die is guided at the O.D. or I.D. of the lower tool. Some parts made on this machine are shown in Figure 9.

A possible automated line for workshops with and without an existing blank manufacturing facility using

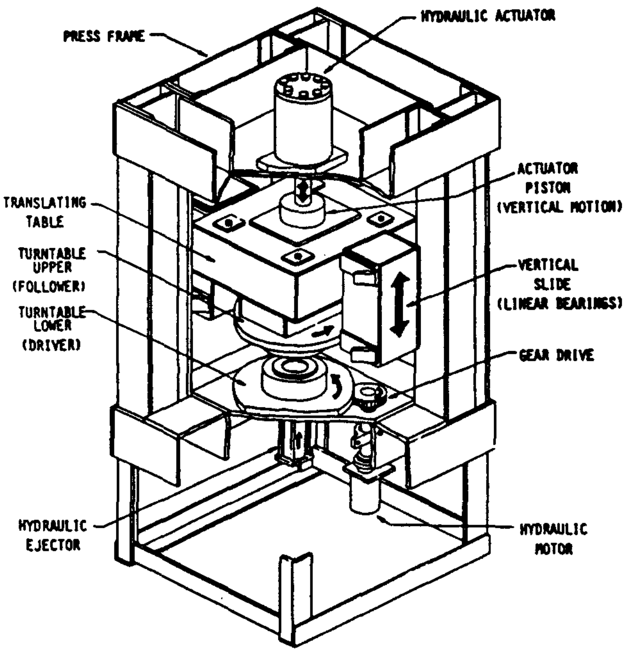

**Fig. 7.** A schematic of Dyna East RF-50 [2].

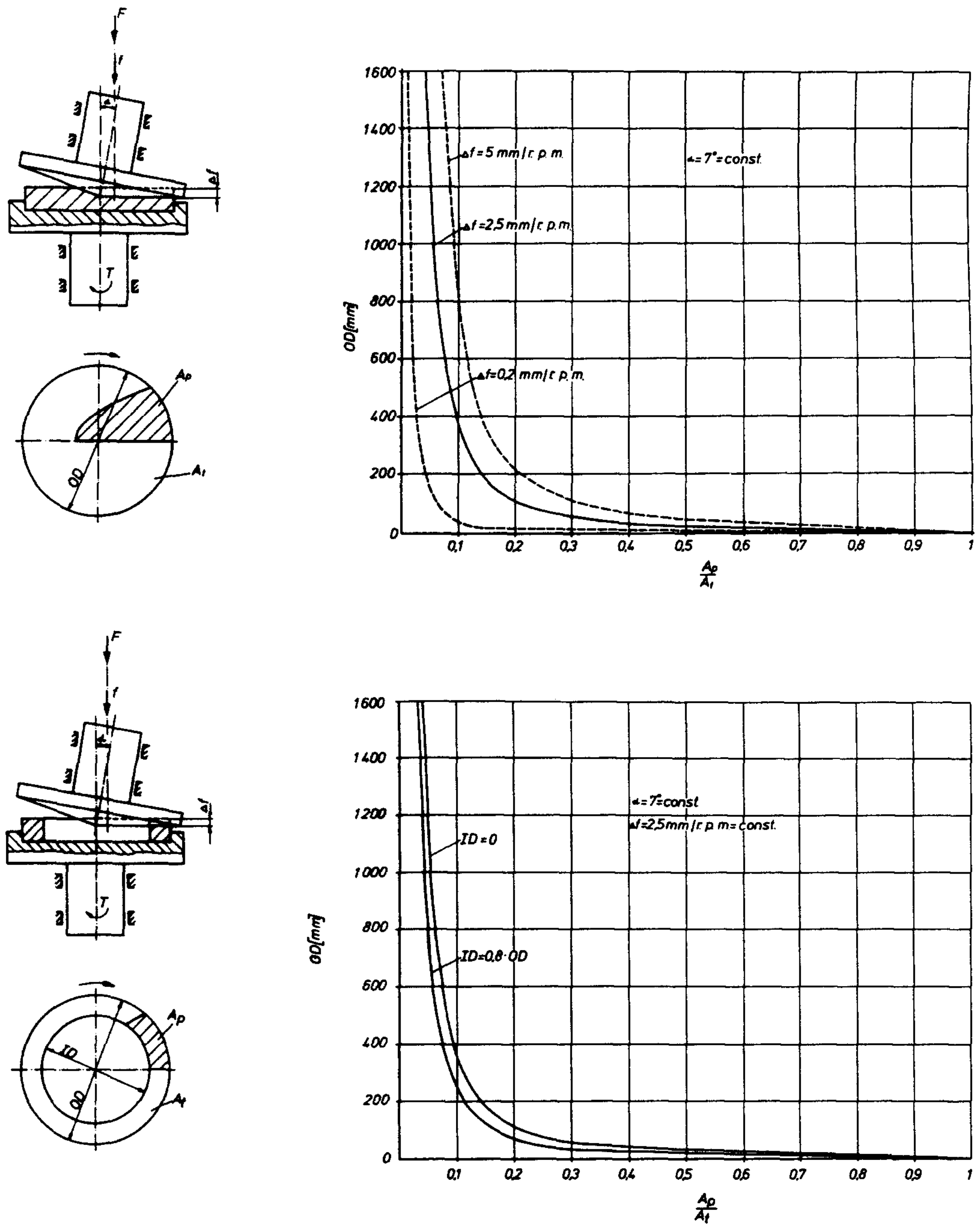

**Fig. 8.** Plots of outer diameter (O.D.) vs. footprint area ratio ($Ap/At$) for different feed rates ($\Delta$f) and internal diameters (I.D.), at constant inclination angle of 7 deg: top disc forging and bottom ring forging [15].

AGW125 is shown in Figure 10. The AGW125 machine is provided with automatic cooling and lubricating system. Parts with internal bores are prerolled on a ring-rolling machine; other parts are fed directly to the AGW125. The lines part in front of preceding machines A or B depending on whether a high speed forging/blanking press is available at the shop or not. Block A contains an unloader, a shear, a feeding and orienting device, an inductive furnace, and a chute. Block B contains a bar rack, an inductive furnace, a shear, a forging press, and a transporting system. According to Wagner [34] similar production lines will be operational in the U.S. by 1987/88 for the production of automotive ring gears.

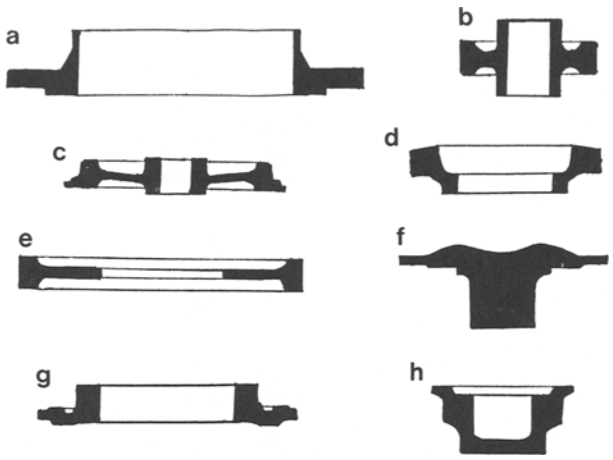

**Fig. 9.** Axisymmetric parts hot rotary forged on AGW125 and AGW400 machines [5, 15] (a) Weld neck flange, (b) Crane wheel preform, (c) Railroad wheel, (d) Bevel gear preform, (e) Ring gear preform, (f) Clutch disc, (g) Hub, and (h) Bearing ring.

## APPLICATIONS OF ROTARY FORGING

In this section, we list some of the recent applications of the process and also future possibilities. We discuss cold and hot applications separately. In each we subdivide based on the shape of the part: axisymmetric or nonaxisymmetric. Nonaxisymmetric parts have been produced only by the cold forming process.

### Cold Forging of Axisymmetric Parts

Axisymmetric applications can be further classified based on the predominant deformation mode: upsetting, radial flow, and axial flow (forward or backward extrusion).

In upsetting deformation the metal flow is primarily radial. Disc shaped or flanged parts are produced from cylindrical preforms. Because the rolling action of the dies generates low interface friction, rotary forging is especially suited for inducing radial flow. Examples of these geometries are thin discs, hubs, and flanges; these parts are difficult to form by conventional forging techniques.

Axisymmetric parts with geometric details, for example, gears and clutch plates, requires a mixture of upsetting (radial) and extrusion (axial) deformation. These parts have been cold forged to near-net shape by the rotary/orbital forging. Daisy motion of the dies is especially suited to gear manufacture. Some gear applications are shown in Figure 6.

Some unique applications of this process are in axisymmetric part production. Rolling of bearing rings or rings with internal profiles of monolithic or PM material is an important area of application where ro-

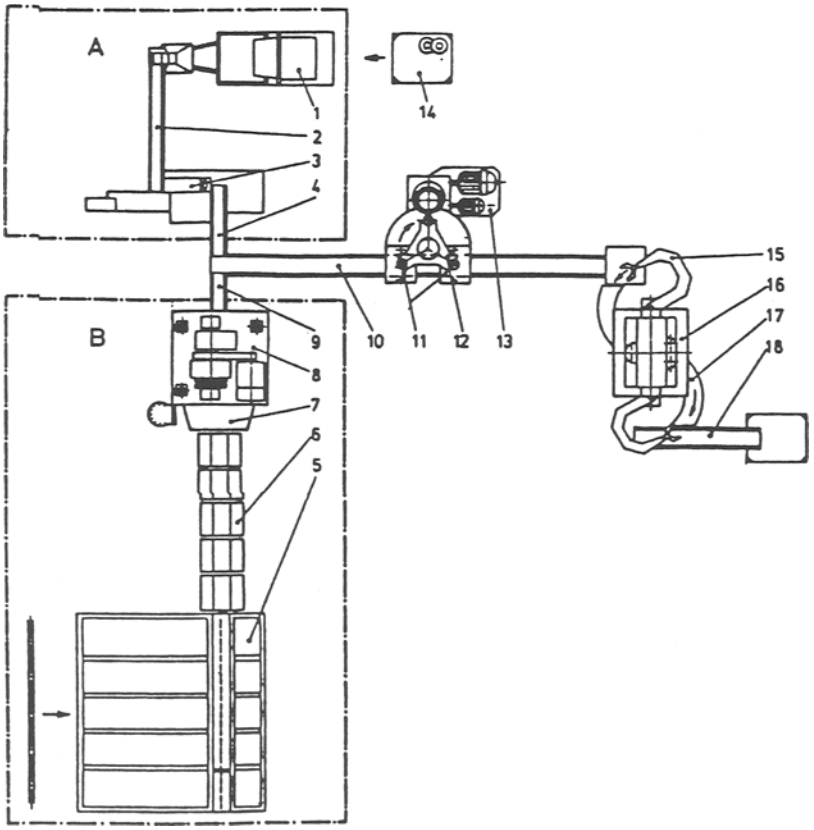

**Fig. 10.** A layout drawing of an automated manufacturing line with AGW125 for the production of ring shaped axially symmetrical automobile parts with and without inner bore on an axial closed-die rolling mill [5, 15]. (1) Unloading of container, (2) Feed to orienting device, (3) Induction heating unit, (4) Chute, (5) Bar rack, (6) Induction heating unit, (7) Hot shear, (8) Die forging press, (9) Transporting system, (10) Conveyor belt, (11) Lifting tables, (12) Mandrel turret of prerolling mill, (13) Prerolling mill, (14) Container with forged blank from rapid forging press, (15) Loading manipulator, (16) Axial closed die rolling mill, (17) Unloading manipulator, and (18) Conveyor belt.

tary forging can compete with ring rolling. A synchronous ring for truck transmission is a very good example of cost-effective application. Needle bearing busing is an application where rotary forging competes with backward extrusion. Because of the rolling action on the wall, no "ironing" operation will be needed. Rotary forging has also been used in the production of automobile axles, coupling shafts, valves, differential gears, and bearing races.

### Cold Forging of Nonaxisymmetric Parts

Nonaxisymmetric applications of rotary forging have been few. Most have been produced on PXW100 and T-200 using the rocking or straight line motion of the tilted die. Rotary forging is very cost effective in these applications because it is an incremental forging process and can force metal around corners incrementally.

A unique application of rotary forging (Type 3 machines) is in the cold forging of variable pitch racks for front wheel driven cars, Figure 11. These parts are very difficult to make by other cold forming processes. It is in applications like these that rotary forging will establish a niche.

### Warm Forging

Forging in the warm temperature ranges avoids shrinkage and scale problems associated with hot forging while the beneficial effect of lower yield stress is realized. In rotary forging this temperature range has the additional benefit of reduced die wear. Rotaform, developed by Massey of U.K., was the first machine to work in the warm region. On this machine, steel parts were produced in the 1100° F to 1500° F temperature range. Sample parts were friction plate [Fig. 12(a)], tail shaft flange [Fig. 12(d)], auto gear change hub [Fig. 12(b)], and gear wheel [Fig. 12(c)]. Aisin Seiki Co., Japan, rotary forged automobile clutch hubs at 1000° C and coupling shaft and gear blanks at the 800° C to 950° C temperature range. Workpiece material was low carbon steel.

### Hot Forging

Large wheel and ring type forgings are being produced in the hot temperature range. Rotary forging machines designed for the hot temperature range are Wagner's AGW125 and AGW400. Both these machines are of the Type 1 (both the axes of rotation fixed) and have upper die tilt angles of 7 deg from vertical providing for a large radial flow and force advantage. AGW400 produces axisymmetric parts up to 42 in. diameter while AGW125 produces parts up to 10 in. diameter. Sample parts produced on these machines are weldneck flanges [Fig. 9(a)], crane wheel [Fig. 9(b)], railroad wheels [Fig. 9(c)], bevel gear preforms [Fig. 9(d)], ring gears [Fig. 9(e)], clutch discs [Fig. 9(f)], hubs [Fig., 9(g)], bearing rings [Fig. 9(h)], and thin-walled discs. Most of these applications produce preforms for subsequent processing and do not contain difficult-to-fill geometric details. Wagner [15] reports satisfactory die lives though Massey encountered severe die wear in hot rotary forging. This is because Wagner primarily used hot rotary forging for rolling ring type parts which do not touch the die center where greater die wear occurs.

### Future Applications

Grzeskowiak [58] analyzed the applicability of the rotary forging technique to forging manufacture using group technology concepts. He concluded that 50% of all forging shapes can be produced by this process. Based on the past applications and the machine capability, the following future trends in rotary forging applications can be foreseen:

- Application of rotary forging will continue in the cold forming of axisymmetric parts, with external details and large thin flanges, such as clutch discs, ring, spur, and bevel gears, and belville springs. Application of cold rotary forging to difficult-to-make nonaxisymmetric parts will grow. Type 3 machines are ideally suited to this niche in the forging market.
- A market will emerge in the cold forming of spur, helical, and spiral bevel gears. The last two will require split dies or special ejection mechanisms. These gears could possibly be made to net shape by rotary forging technique.
- In the warm forming regime, rotary forging could be effectively applied to parts requiring side extrusion, such as splines, sprockets, and spiders. Planetary (daisy) and rocking (straight) motion of dies could be utilized to push material in radial cavities. In the hot forming regime, rotary forging will continue to challenge ring rolling in the production of large ring or disc shaped parts with flanges.
- An area of application in the compaction of PM pre-

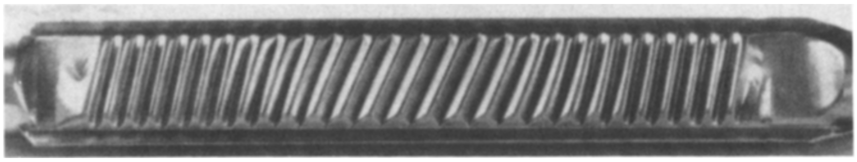

**Fig. 11.** Variable pitch gear rack, 25 mm × 570 mm, for rack and pinion steering of a front wheel drive car made on an orbital forging machine, finish machined and induction hardened.

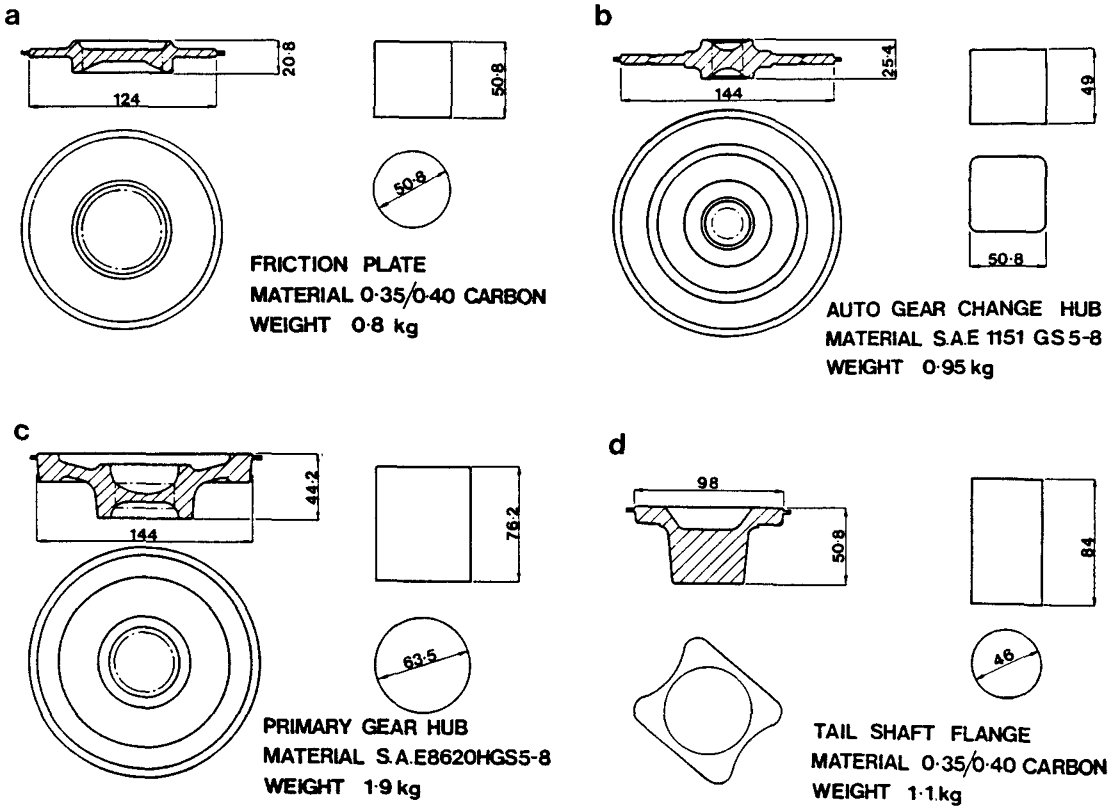

**Fig. 12.** (a,b,c,d) Automotive parts warm rotary forged on Massey Rotaform. All dimensions in millimeters [14].

sintered performs of small gears and bearing races to net shape will emerge. Small parts with fine details will be the obvious candidates.

## POTENTIAL RESEARCH ISSUES

In this section we divided rotary forging research into two sub-areas: machine design and workpiece deformation. First we discuss the key issues confronting the machine designer and suggest possible solutions. The key research issues in workpiece deformatiton mechanics are discussed next. Lastly we present die design considerations.

### Machine Design Considerations

In rotary forging, one of the dies is tilted with respect to the other generating a large eccentric force vector during forging. As the dies are moved in complex kinematical motions, (orbital, daisy, planetary, etc.) the direction and point of application of the forging force vector moves. This results in the following problems:

- Large deflections of the dies and support structure in the direction of low frame or die rigidity. Large inaccuracies in part dimensions can result especially in open die forging due to relative angular and linear displacements of the dies.
- Excessive wear of the bearings and guideways causes loss of part precision with usage.

The machine design research issues connected with the above problems are:

- Determination of the forces and moments generated during rotary forging with various die kinematics.
- Innovative design of the drive mechanism to minimize the eccentric forging force vector.
- Optimum design of the die support and guidance structure to minimize die deflection.
- Design and location of bearings and guideways to minimize their wear. Though hydrostatic spherical bearings are widely used in rotary forging machines, they are expensive to build and have maintenance problems especially at warm or hot temperatures.

### Workpiece Deformation Mechanics

In conventional forging (upsetting) the workpiece deformation is axisymmetric. In rotary forging the deformation is nonaxisymmetric. Also, symmetry of workpiece deformation around the workpiece midthickness does not exist. In other words, the workpiece deformation is truly three-dimensional. The flow of the workpiece material in the axial or radial direction not only depends on the axial feed as in the case of conventional forging, but also on the tilt angle of the upper die and the rotation rate of the dies.

Studies have been made in the past to understand the workpiece deformation mechanics using either the experimental approach or the upper bound technique. These studies have been reviewed in an earlier section of this paper. Though the upper bound technique is easy to apply, it depends on a prior knowledge of the deformation mechanics. An unknown deformation field in complex processes like rotary forging makes this difficult. With the current developments in the finite element method, a detailed analysis of the metal flow in rotary forging becomes possible. Two different approaches can be adopted. In the first, workpiece deformation can be modeled by a set of two-dimensional simulations, one simulation of the axial flow and the other of the radial flow [59]. The second approach could use three-dimensional simulation. One limitation of the latter is that there are very few three-dimensional finite element codes available for metal forming applications. In addition, three-dimensional simulations can be very expensive.

Some of the key processing problems needing research are:

- *Center thinning and fracture*: Center thinning occurs when a high axial feed rate (axial feed per revolution) is used during forging. Large tensile radial stresses result in fracture at the center of the workpiece. In workpieces with extra material provided at the center (rods with flanges), central fracture does not occur, though dimensional inaccuracy may result.
- *Mushrooming*: Mushrooming occurs when the axial feed rate is small. Radial flow is higher adjacent to the tilted upper die compared to the vertical lower die, producing a mushroomlike shape. This defect causes dimensional inaccuracy in the axial direction; the plastic strain distribution is nonuniform across the thickness.
- *Interface friction*: Die–workpiece interface friction is lower in rotary forging than conventional forging. In addition, the frictional constraint is different at the two die–workpiece interfaces. The effect of the frictional constraints on material flow and die filling needs investigation.
- *Workability limits*: Lots of researchers have experimentally determined that higher workability limits can be achieved by rotary forging in comparison with conventional forging. Some have even suggested that hard-to-cold-forge metals, such as high carbon steels, can be cold forged by rotary forging. These claims need investigation by thorough experimental and analytical studies.
- *PM compaction*: Japanese researchers suggest that higher compaction (densification) is realized by rotary forging of sintered preforms than that possible by conventional forging. In-depth research in compaction mechanics is needed to verify the advantages of rotary forging in PM part compaction.

### Die Design Considerations

Most die design considerations in rotary forging are similar to conventional forging. A few additional considerations are:

- Lower die pressures are generated in rotary forging; pressure peaks are significantly reduced (50–70%) during open die forging. It will be interesting to find out how this affects the die filling of intricate parts. Will the heat transfer coefficients be lower? How does the tilt angle affect the die pressures?
- Lower die pressures permit the selection of cheaper die materials. On the other hand, die design and manufacture is complicated by the die tilt angle. What are the die cost benefits realized in rotary forging?
- Due to the tilt of one of the dies and the consequent eccentric load, there is a tendency for the workpiece to slip at the initial die–workpiece contact. In addition, the nonsymmetric bucking mode is induced by the initial bite. How should dies be designed to provide support to the workpiece during deformation?
- In hot rotary forging die wear is significantly high; especially near the apex of the conical (tilted) die. This phenomenon can be explained as follows. Based on the die–workpiece contact time, the surface area of the tilted die can be divided into three regions: the central region which is always in contact with the workpiece; the intermediate region which is in contact 50–70% of the time; and the outer region which is in contact 20–30% of the time. These regions have differing wear. Because the central region is always in contact with the workpiece, it is subjected to maximum heating and abrasive frictional forces. In addition, being an apex of a cone, it is weak mechanically. Therefore, there is significant wear of the die in this region. Using similar reasoning, we can state that the intermediate region has less wear and the outer region the least wear. The research issue then becomes: prediction and minimization of die wear by die design, die material selection, die coating application, and adequate lubrication.

## ACKNOWLEDGMENTS

This article was prepared from information available in research publications and company brochures. Information provided by Mr. K.H. Beseler of Girard Associates, Mr. Heinz Roth of Schmid Corporation, and Dr. P.C. Chou of Dyna East Corporation were instrumental in enabling the author to present a more balanced picture of the developments in Western Europe and the U.S. The author acknowledges the support of the NSF Engineering Research Center for Net Shape Manufacturing at The Ohio State University in the preparation, and Ms. Darline Wine for the typing of this manuscript.

## REFERENCES

1. Standring, P.M. and Appleton, E., The Kinematic Relationship Between Angled Die and Workpiece in Rotary Forging, 1st Intl. Conf. on Rotary Metalworking Processes, London, U.K., Nov. 20–22, 1979, pp. 275–288.
2. Chou, P.C. and Shivpuri, R., Numerically Controlled Orbital Forging Process, NSF Proj. No. MEA-8115012A02, Final Rep., Dyna East Tech. Rep. No. DE-TR-84-06, Dec. 1984.
3. Jebb, A., Penny, W.A., and Slater, R.A.C., U.S. Patent No. 4313332 (1982).
4. Bregen, E., U.S. Patent No. 2739726 (1956).
5. Beseler, K.H., Shape Rolling of Seamless Rings, *Near Net Shapes—I Conference*, Sept. 27–39, 1982, Pittsburgh, PA, Society of Manufacturing Engineers, Technical Paper No. MF82-334.
6. Slick, E.E., The Slick Wheel Mill, *The Iron Age*, 1918, Vol. 102, No. 9, pp. 491–498.
7. Skhlyarov, I.N., Hot Rolled Bevel Gears, *Russian Engineering Journal*, 1964, Vol. 44, No. 8, pp. 43–45.
8. Yakimanskii, V.V., and Basov, M.I., New Profile-Rolling Methods of Producing Bevel Gears, *Russian Engineering Journal*, 1967, Vol. 47, Nov. 10, pp. 62–65.
9. Slick, E.E., U.S. Patent No. 1359625 (1920).
10. Huthwaite, B., VSI Spinnomatic Machine, private communication.
11. Marciniak, Z., A Rocking-Die Technique for Cold-Forming Operations, *Machinery and Production Engineering*, Nov. 1970, pp. 792–797.
12. Maicki, J.R., Orbital Forging, *Metallurgia and Metal Forming*, June 1977, pp. 265–269.
13. Massey, H.F., British Patent Specification No. 319065 (1929).
14. Spiers, R.M., "The Massey Rotaform Die Forging Process and Machine," *Forming Equipment Suppliers Symposium*, June 1973, Chicago, pp. 26–28.
15. Grone, S., Axial Closed-Die Rolling-Hotforming Process for the Manufacture of Axially Symmetrical Forgings for the Automobile Industry, *Thyssen Technische Berichte*, Duisberg, Germany, 1986, Vol. 2, pp. 353–60.
16. Slater, R.A.C., Barooah, N.K., Appleton, E., and Johnson, W., The Rotary Forging Concept and Initial Work with an Experimental Machine, *Proc. of the Inst. of Mech Engrs.*, (UK), 1969–70, Vol. 18, Pt. 1, pp. 557–592.
17. Slater, R.A.C. and Appleton, E., Some Experiments with Model Materials to Simulate the Rotary Forging of Hot Steels, *Proc. 11th Intl. Machine Tool Design Research Conf.*, Birmingham, U.K., Sept. 1970, pp. 1117–1136.
18. Appleton, E., and Slater, R.A.C., Effects of Upper Platen Configuration in the Rotary Forging Process and Rotary Forging into a Contoured Lower Platen *Proc. of 13th Intl. M.T.D.R. Conf.*, Birmingham, U.K., Sept. 1972, pp. 43–62.
19. Dr. Standring, University of Nottingham, U.K., private communication.
20. Dr. Penny, University of London, U.K., private communication.
21. Silichev, A.N., U.S. Patent No. 3494161, January 1968.
22. Standring, P.M. and Appleton, E., Rotary Forging Developments in Japan, Parts 1 and 2, *J. of Mech. Work. Tech.*, Jan. 1980, Vol. 3, pp. 253–273 and April 1980, Vol. 4, pp. 7–29.
23. Ayano, M. and Kumakura, I., The Development of a Rotary Forging Machine and its Practical Applications, *Proc. 3rd Intl. Conf. on Rot. Metalworking Processes,* Kyoto, Japan, 1984, pp. 71–80.
24. Wei, J., Lu, Q.R., Wang, Z.R., and Pei, X.H., New Developments on Rotary Forging in China, *Proc. 3rd Intl. Conf. on Rot. Metalworking Processes,* Kyoto, Japan, 1984, pp. 61–70.
25. Boehm, S., Noiseless Orbital Forging Today, *Tooling and Production,* June 1978, pp. 72–75.
26. Mr. Werner Meese, Fine Blanking Co., Los Angeles, CA, private communication.
27. Carleone, J. and Shivpuri, R., Precision Rotary Forging, *Proc. of the U.S.-Sweden Conf. on CAD/CAM for Tooling and Forging Technology,* Cornell University, Nov. 1982, pp. 331–362.
28. Chou, P.C. and Shivpuri, R., A High Precision Rotary Forging Machine *Proc. 11th Conf. on Prod. Res. and Tech.*, Carnegie-Mellon University, Pittsburgh, PA, 1984, pp. 113–124.
29. Chou, P.C. and Shivpuri, R., The Design and Construction of a Precision Rotary Forging Machine, *Proc. 3rd Intl. Conf. on Rot. Metalworking Processes,* Kyoto, Japan, 1984, pp. 43–60.
30. Project Progress Report, Advanced Technology Center, Benjamin Franklin Trust, December 1986.
31. Labriola, Michael and Clark, William J., Dyna East Corporation, Philadelphia, PA, private communication.
32. Schmid Corporation of America; Goodrich, Michigan; Orbital Forging Press Brochures, 1984, 1985, and 1986.
33. Roth, Heinz, President, Schmid Corp. of America, private communication.
34. Beseler, K.H., Girard Associates, private communication.
35. Hawkyard, J.B., Gurnani, C.K.S., and Johnson, W., Pressure Distribution Measurements in Rotary Forging, *J. Mech. Eng. Sci.*, 1977, Vol. 19. No. 4, pp. 135–142.
36. Hawkyard, J.B., Yunus, N.M., and Gurnani, C.K.S., Prediction of Force in Rotary Forging of Short Circular Cylinders, *1st Intl. Conf. on Rotary Metalworking*

*Processes,* London, U.K., Nov. 20–22, 1979, pp. 111–124.

37. Standring, P.M., Moon, R.R., and Appleton, E., Plastic Deformation Produced During Indentation Phase of Rotary Forging, *Metals Technology,* April 1980, Vol. 7, Pt. 4, pp. 159–166.
38. Lehueup, E.R., Moon, J.R., and Standring, P.M., The Rotary Forging of Powder Metallurgy Preforms Using a Configurated Upper Die Technique, *Proc. 2nd Intl. Conf. on Rot. Metalworking Processes,* Stratford-Upon-Avon, U.K., 1982, pp. 113–124.
39. Hawkyard, J.B. and Moussa, G., Rotary Forging of a Component Job with a Non-Circular Flange—Control of Forging Force and Energy Dissipation, *Proc. 2nd Intl. Conf. on Rot. Metalworking Processes,* Stratford-Upon-Avon, U.K., 1982, pp. 73–80.
40. Appleton, E., Sinha, K.P., and Prasad, S.C., Analysis of Metal Flow During Indentation Phase of Rotary Forging, *Proc. of the Indo-British Conf. of Prod. Engr.,* New Delhi, 1976, pp. C-68–C-83.
41. Sinha, K.P. and Prasad, S.C., Analysis of Metal Flow During Rotary Forging, *Intl. Conf. on Prod. Eng.,* 27th C.I.R.P. General Assembly, New Delhi, India, 1977.
42. Kubo, K. and Hirai, Y., Deformation Characteristics of Cylindrical Billet in Upsetting by a Rotary Forging Machine, *Proc. 1st Intl. Conf. on Rot. Metalworking Processes,* London, U.K., Nov. 1979, pp. 99–110.
43. Kobayashi, M., Nakane, T., Kamada, A., and Nakamura, K., Deformation Behavior in Simultaneous Extrusion–Upsetting by Rotary Forging, *Proc. 1st Intl. Conf. on Rot. Metalworking Processes,* London, U.K., Nov. 1979, pp. 251–264.
44. Nakane, T., Kobayashi, M., and Nakamura, K., Deformation Behavior in Simultaneous Backward Extrusion–Upsetting by Rotary Forging, *Proc. 2nd Intl. Conf. on Rot. Metalworking Processes,* Stratford-Upon-Avon, U.K., October 1982, pp. 59–72.
45. Nakamura, K., Nakane, T., and Kobayashi, M, Deformation Behavior in Simultaneous Forward–Backward Extrusion–Upsetting by Rotary Forging, *Proc. 3rd Intl. Conf. on Rot. Metalworking Processes,* Kyoto, Japan, 1984, pp. 13–22.
46. Kubo, K., Kirai, Y., and Nakamura, M., Warm Rotary Forging of Thin Disk, *Proc. 3rd Intl. Conf. on Rot. Metalworking Processes,* Kyoto, Japan, 1984, pp. 31–42.
47. Kiyota, K. and Takemure, K., Densification of P/M Valve Seat by Cold Rotary Forging, *Proc. 3rd Intl. Conf. on Rot. Metalworking Processes,* Kyoto, Japan, 1984, pp. 101–108.
48. Marciniak, Z., Cold Forming of Wedge-Shaped Workpieces, *Proc. 1st Intl. Conf. on Rot. Metalworking Processes,* London, U.K., Nov. 1979, pp. 137–146.
49. Marciniak, Z., Rotary Upsetting of Flanges in Warm Forging Temperature Range, *Proc. 3rd Intl. Conf. on Rot. Metalworking Processes,* Kyoto, Japan, 1984, pp. 23–30.
50. Grzeskowiak, J., Whether in the Coming Years the Rocking Die Forming Can be Widely Applied in Forging Manufacture?, *Proc. 3rd Intl. Conf. on Rot. Metalworking Processes,* Kyoto, Japan, 1984, pp. 109–114.
51. Pie, X.H., Zhou, D.C., and Wang, Z.R., Some Basic Problems of Rotary Forging and its Practical Applications, *Proc. 2nd Intl. Conf. on Rot. Metalworking Processes,* Stratford-Upon-Avon, U.K., Oct. 1982, pp. 81–90.
52. Pie, X.H., Zhou, D.C., and Wang, Z.R., Some Basic Problems of Rotary Forging and its Practical Applications, *Proc. 2nd Intl. Conf. on Rot. Metalworking Processes,* Stratford-Upon-Avon, U.K., Oct. 1982, pp. 91–100.
53. Lu, Z., Lu, Z., and Wei, J., Criterion of Centre Thinning in Rotary Forging of Circular Plate, *Proc. 2nd Intl. Conf. on Rot. Metalworking Processes,* Stratford-Upon-Avon, U.K., Oct. 1982, pp. 137–148.
54. Liu, G.Q., Application of Rotary Forging Process in Processing Thrust Bearing of Steering Axle, *Proc. 3rd Intl. Conf. on Rot. Metalworking Processes,* Kyoto, Japan, 1984, pp. 93–100.
55. Zang, M., Calculating Force and Energy During Rotary Forging, *Proc. 3rd Intl. Conf. on Rot. Metalworking Processes,* Kyoto, Japan, 1984, pp. 115–124.
56. Geng, S.H., The Theoretical Research on the Rocking Shaft of the Spherical Hydrostatic Bearing of the Rotary Forging Machine, *Proc. 3rd Intl. Conf. on Rot. Metalworking Processes,* Kyoto, Japan, 1984, pp. 1–12.
57. Little, R.E., and Beyer, R., Load-Deformation Relationships During Upsetting by Rotary Forging, *Proc. 1st Intl. Conf. on Rot. Metalworking Processes,* London, U.K., Nov. 1979, pp. 125–136.
58. Grzeskowiak, J., Whether in the Coming Years the Rocking Die Forming can be Widely Applied in the Forging Manufacture, *Proc. 3rd Intl. Conf. on Rot. Metalworking Processes,* Kyoto, Japan, Sept. 1984, pp. 109–114.
59. Chou, P.C., Shivpuri, R., and Wu, L., Recent Developments in the Rotary Forging Process, *Advanced Systems for Manufacturing,* Conf. Proc., Society of Manufacturing Engineers, 1985, pp. 257–66.