

State of Cold forging Technology in Global Competition

Prof. Dr. Taylan Altan, Dr. Gracious Ngaile and Mr. Manas Shirgaokar

ERC for Net Shape Manufacturing, the Ohio State University,
339 Baker Systems, 1971 Neil Ave, Columbus OH 43210 USA

www.ercnsm.org

Abstract

Global competition in the cold forging industry raises the significance of managing innovation and technological change. Strategies for development and application of new technology are extremely important for maintaining a competitive position and protecting sales. This paper reviews some of the advances in cold forging technology with an emphasis on the application of virtual process simulation, press and tool design for complex forging operations and the need for continuous training.

1 Introduction

Global competition raises the significance of managing innovation and technological change and places a premium on strategic technology development [1]. The process of technological change within the global economy is becoming more complex and challenging as the cold forging companies face increasing global competition.

Automotive companies, which account for a very large portion of cold forged parts, are rapidly expanding global operations in an effort to produce cost effective vehicles. This has vast implications on local automotive suppliers. A global economy allows any supplier, that can satisfy part design requirements, to bid and obtain a contract irrespective of the geographic boundaries. For example, a North American car manufacturer announced recently that it plans to import parts worth about \$10 billion from China during the next five years. This implies that the current automotive suppliers will have to change their production strategies to remain competitive in the global marketplace.

Due to globalization, cold forging technologies are diffusing across firms and across boundaries at increasing rates through channels such as overseas patenting, licensing, exchange of technology-intensive goods, international investments and alliances. As a result of inexpensive labor, production costs for simple parts are much less expensive in developing nations. Therefore, it is expected that cold forging suppliers will gradually shift to developing nations for production of low-tech components.

In order to succeed in the global marketplace, cold forging suppliers from developed nations must focus on production of high value-added forgings, finished parts and sub-assemblies with the aid of new developments such as a) advances in the use of computer modeling in cold forging process development, b) advances in press design, c) use of innovative tool design for complex forging operations, d) appropriate training in advanced cold forging technologies, and e) information management in forge shops.

2 Computer Aided Engineering (CAE) in Cold Forging

Global competition requires that cold forging industry utilize practical and proven computer aided design (CAD), computer aided manufacturing (CAM) and computer aided engineering (CAE) technologies for rapid and cost effective process design and die

manufacture. Recently, finite element (FE) simulation software has become an integral part of forging process design to analyze and optimize the metal flow and conduct die stress analysis before conducting forging trials.

The main goal of simulation in manufacturing process design is to reduce part development time and cost while increasing quality and productivity. For instance, in cold forging, process simulation can be used to develop the die design and establish process parameters by a) predicting metal flow and final dimensions of the part, b) preventing flow induced defects such as laps and c) predicting temperatures (warm forging operations) so that part properties, friction conditions, and die life can be controlled. Furthermore, process simulation can be very beneficial in predicting and improving grain flow and microstructure, reducing scrap, optimizing product design and increasing die life. Two-dimensional FE simulation has been state-of-the-art in cold forging process design for more than a decade. With asymmetrical complicated parts, the use of three-dimensional FE simulations is a must. During recent years, 3-D simulation has also gained widespread acceptance in industry. Improvement in computer algorithm efficiency and user interface development have resulted in simulation becoming both robust and practical in a wide range of applications /2/. Figure 1 illustrates the role of FEM in forging process design by means of a block diagram /3/.

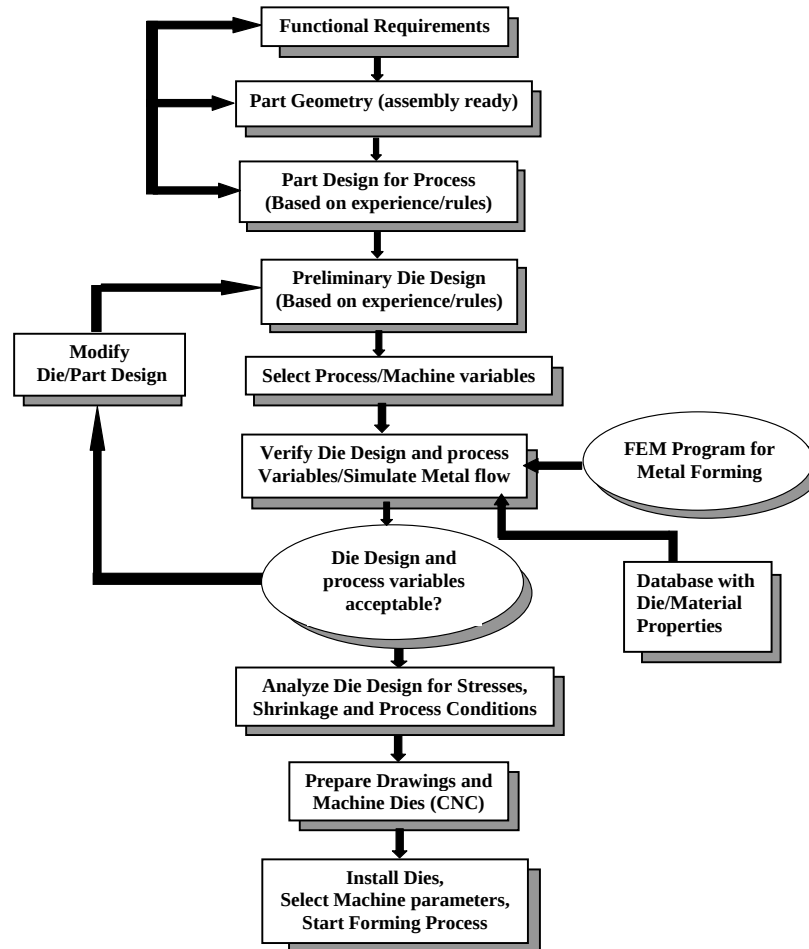


Figure 1: A flow chart illustrating forging process design /3/.

2.1 Input variables in the FEM models

The accuracy of FE process simulation depends heavily on the accuracy of the input data, namely, a) flow stress as a function of temperature, strain, strain rate and microstructure, b) friction characteristics at the interface.

2.1.1 Workpiece and tool material properties

The stress-strain relation of materials, commonly referred to as the flow stress curve, is usually obtained by the cylinder compression test. To be applicable without errors or corrections, the cylindrical sample must be upset without any barreling (Figure 2a) i.e., a state of uniform stress must be maintained in the sample at all times during the test. Use of adequate lubrication prevents barreling to some extent. However, in practice, barreling is inevitable and procedures for correcting flow stress errors due to barreling may be necessary.

Figure 2a shows a sample that was upset to 62 % reduction (true strain of 0.96). This sample shows significant barreling implying that the lubricant applied was ineffective at this high level of strain. The failure of the lubricant is evident by the two different regions (shiny and non-shiny areas) depicted on the surface of the sample (Figure 2a). In general, for process modeling of precision forging, the experimental flow stress curves were found to be reliable only up to a strain level of 0.5 /4/.

One way of correcting the flow stress, or determining approximately the error magnitude at high strain levels caused by inadequate lubrication (barreling), is to simulate the compression process by FEM using various friction factors (Figure 2c) /4/. By measuring the amount of barreling (Figure 2a) and comparing the experimental data with FEM predictions it is possible to obtain more reliable flow stress data at higher strain levels. This method, called inverse analysis technique, has been used to determine simultaneously friction and stress/strain data using a ring test /5/.

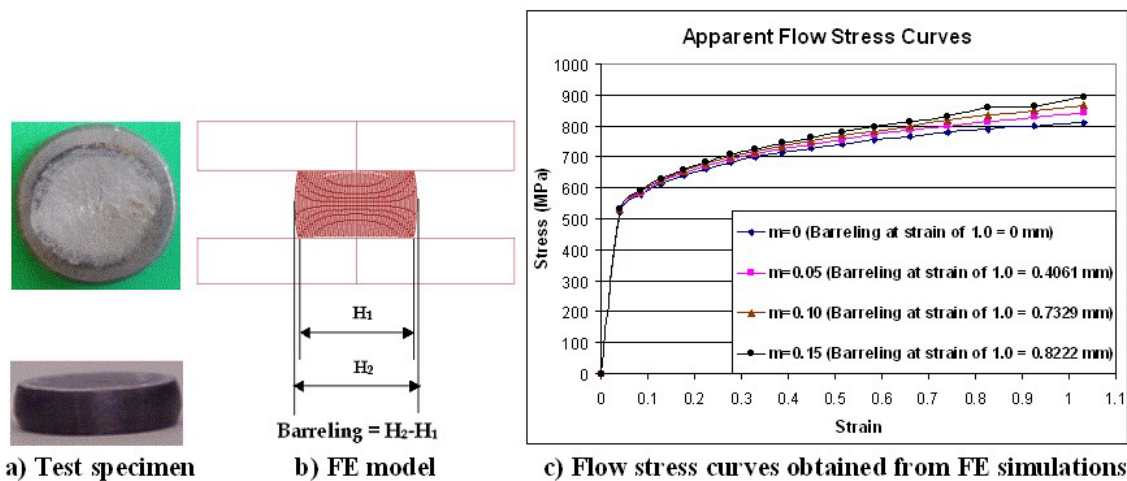


Figure 2: Correction of flow stress data obtained from a compression test /4/.

Attention should also be given to other sources of flow stress error determined through compression tests such as: a) variation in coil material properties, b) specimen preparation, c) surface defects, d) parallelism of platens, and e) specimen size.

Though in most FE simulations the tools are considered rigid, this assumption may not hold good for complicated forgings with tight tolerances, particularly in microforming applications. Hence, depending on the part complexity, elastic-plastic properties of the tools/dies become an important component in the simulations.

2.1.2 Interface conditions

Friction coefficient is another important input to the FE model. Prior to process modeling, it is necessary to know what lubrication system will be used in production. In cold forging of steel, zinc phosphate coating based lubrication systems are commonly used with the exception of simple forging processes such as upsetting, where oil lubricants can be used. Because of environmental concerns, efforts are being made by lubricant companies to develop new lubricants that could replace the zinc phosphate coatings. Examples are the new lubricants developed by a) MEC International – Japan, b) Daido – Japan and c) Metal Coating International – USA /6/. These lubricants, however, need to be evaluated using reliable tests to obtain an accurate friction coefficient for process modeling. Figure 3 shows the performance evaluation of four lubricants tested at the ERC/NSM using the double cup extrusion test.

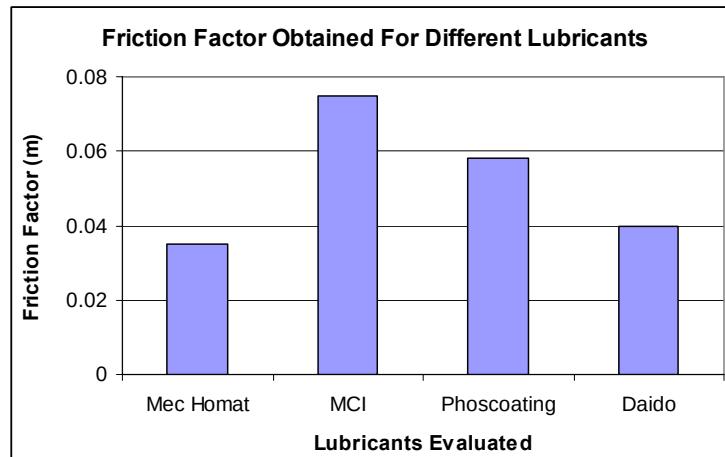


Figure 3: Ranking of lubricants based on the friction factors obtained in a recent study /6/.

2.2 Application of CAE in Manufacturing

2.2.1 Microforming

The trend in miniaturization allows the production of cold forged parts with dimensions less than 1 mm range for electronics and biomedical applications. These parts are currently produced by 3D etching and other metal removal processes. Microforming is a potential process for mass production of net shape/near net shape micro components. However, for microforming to be cost effective and competitive a comprehensive knowledge pertaining to the following factors is needed: a) scale effects/microplasticity b) effect of microstructure on the process, c) relative stiffness of the tooling and d) process control and capability.

With the aid of FEM, the inter-relationships between these variables can be studied so as to provide guidelines for developing microforming processes. In cooperation with industry the ERC/NSM has developed a microforming process for making surgical

blades. Figure 4 shows an example of 3D FE simulations for a surgical blade with initial blank thickness of 0.1mm and final edge thickness of 0.01mm /7/.



Figure 4: Microforming of surgical blades (Blank thickness = 0.1 mm; Final blade thickness = 0.01 mm) /7/.

Due to high surface to volume ratio in microforming process, friction becomes even more important than in conventional forging. Effects of miniaturization on friction have been investigated by using the double cup backward extrusion test with oil as a lubricant (Figure 5)/8/. Comparisons between experiment and simulation show that friction effects increases with a decrease in size of the specimen. The friction observed for a 1mm diameter billet was 4 times that for a 4 mm diameter billet.

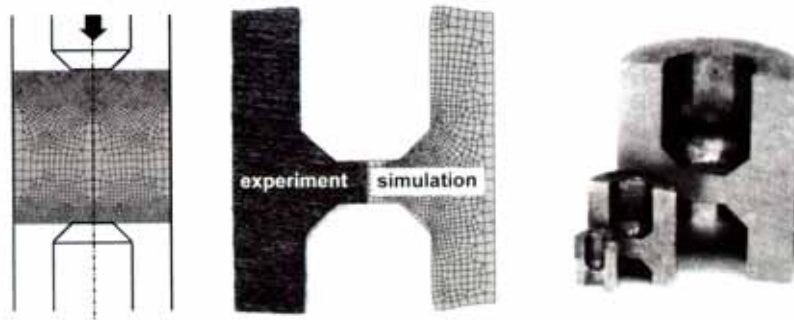


Figure 5: Double cup extrusion test for determination of friction conditions in microforming /8/.

2.2.2 Design of Power Steering Pinions and Inner Races

Net shape forging of power steering pinions with helical teeth, helical gears and inner races present a great challenge. However, the use of commercial 3D finite element software in process development has drastically reduced the production costs by eliminating multiple trials and at the same time has improved part quality, tool life and geometric complexity of forgings. Figure 6 shows the application of FE simulations in the design and development of the helical extrusion process for manufacturing the pinion shown. The advantages of using FEM to simulate and hence design the optimum process were /9/:

- Obtain a better drive feeling.
- Generate the tooth profile freely.
- Establish an iterative technique for die and process design as well as heat treatment.

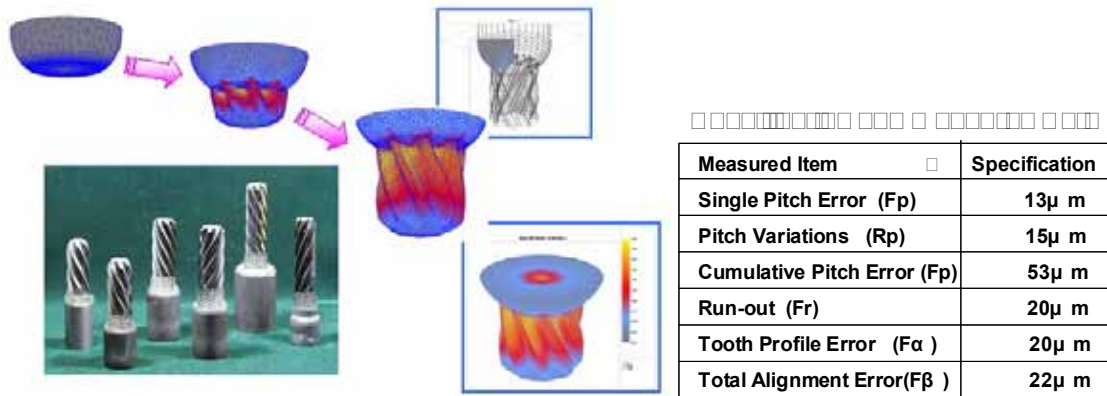


Figure 6: Development of steering pinion with the aid of FE simulation /9/.

Figure 7 shows the simulation of cold forging of the inner race, which is a part of the constant velocity joint assembly. The raw material is a round bar, which is forged in an enclosed die set. Thus, accurate control of the billet volume is essential. This can be checked via FE simulations in addition to the metal flow and die stress analysis. The advantages of simulating this process were /9/:

- Obtained net-shape on the grooves, thus eliminating the costly grinding process used in the finishing stages.
- Establish an iterative technique for die and process design as well as heat treatment.
- Secure forging accuracy without using a special press.

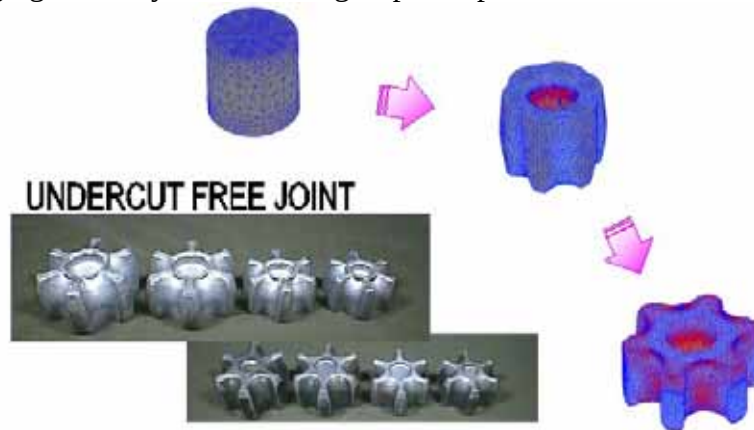


Figure 7: Cold forging of the inner race of a CVJ /9/.

2.2.3 Prediction of Chevron Cracks in Forward Extrusion

In the automotive industry, many shaft and shaft-like components, including fasteners, are produced by forward extrusion. Some of these components are critical for vehicle safety and must be free of defects. These defects could be visible external ones, such as laps or cracks, or non-visible internal defects, such as chevrons cracking (Figure 8) /10/.

Ductile fracture can be defined as a fracture that occurs after a component experiences a significant amount of plastic deformation and is influenced by numerous parameters including the deformation history of the workpiece material and the process conditions (i.e. rate of deformation, lubrication, and friction).

Other factors that influence fracture include chemical composition, microstructure, surface conditions, and homogeneity. At the ERC/NSM a methodology for predicting ductile fracture via FE simulations was developed using the modified Cockroft and Latham criterion /10/. Figure 8 shows that FEM can successfully predict the formation of chevron cracks in forward extrusion using this methodology. The commercial FE code DEFORM® was used for this study.

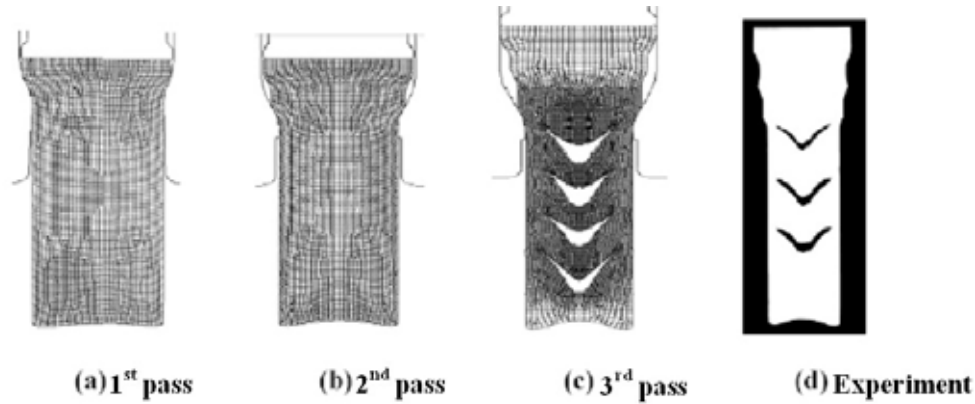


Figure 8: Simulation of chevron cracks and experimental validation /10/.

2.2.4 Integrated Heat Treatment Analysis

Design of heat treatment sequences is a complex task and has generally been performed based on experience or trial and error. Advanced FE process simulation tools like DEFORM-3D® are now capable of studying the residual stresses after heat treatment. This includes modeling of microstructural effects, thermo-mechanical influences and modeling of the quenching process for cracking and distortion /2/. An example of a heat treatment simulation is shown in Figure 9. Dark regions show the volume fraction of martensite transformation and light regions indicate a mixture of bainite and pearlite /2/.

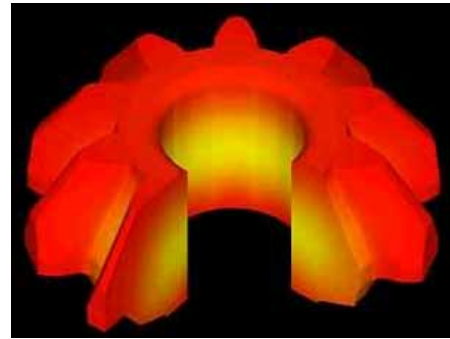


Figure 9: Heat treatment simulation of a bevel gear /2/.

2.2.5 Orbital Forging

Orbital forging is a very unique process with a complicated die movement that can be used to reduce axial load requirements for axisymmetric or near-axisymmetric forging operations. At the ERC/NSM, orbital forging simulations using DEFORM-3D® were conducted to study and develop a robust assembly process of an automotive spindle and an outer ring. Figure 10 shows the simulation progression, which considers elastic and plastic deformation, residual stresses, and quality of assembly. This application illustrates the current capabilities of FEM in simulating complex and incremental cold forging operations to optimize process conditions and product design.

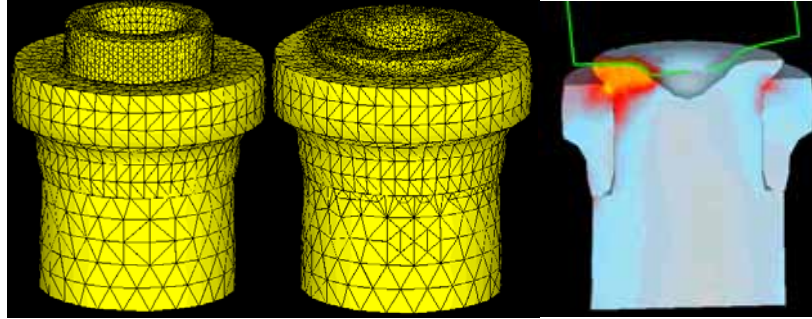


Figure 10: FE simulation of orbital forming (FE model and stress distribution).

2.2.6 Prediction of tool stresses and tool life

2.2.6.1 Tool life improvement in cold forging of a bevel gear

Numerical process simulation and a subsequent set of stress analyses were used to predict the pressure distribution at the material-die interface and thus improve the design and service life of a punch in cold forging of bevel gears (Figures 11a and 11b). The geometry of the highly stressed punch is seen in Figures 11c and 12 /11/. The original geometry of the punch, which resulted in very high stresses, is compared with the modified geometry. Using the interface pressures calculated by DEFORM® as input, the ABAQUS code was used for the elastic-plastic analysis of the punch stresses. Very high pressures were obtained at the lower punch corner and in the upper fillet radius. By varying the punch geometry, after a few iterations, it was possible to reduce the peak stresses and distribute the punch load more evenly (Figure 13) /11/. As a result of these geometric changes, the punch life was increased by a factor of 6 to 8.

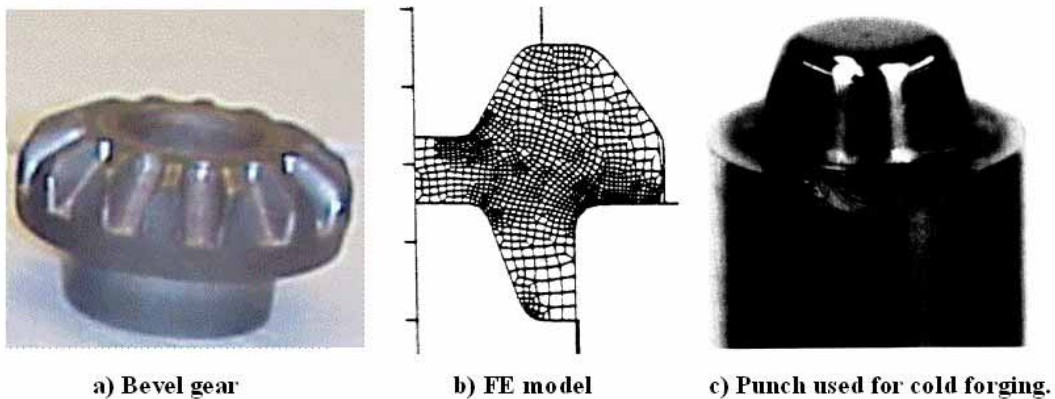


Figure 11: Bevel gear and its FE model along with the punch used to forge it /10/.

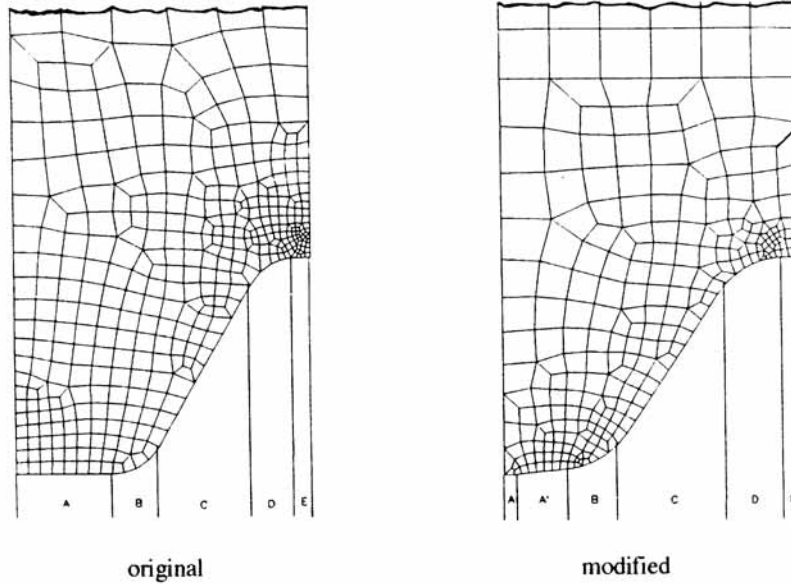


Figure 12: FE models of upper punch tips used for stress analysis (A – face; B – corner radius; C – cone angle; D – fillet radius; E – edge) /11/.

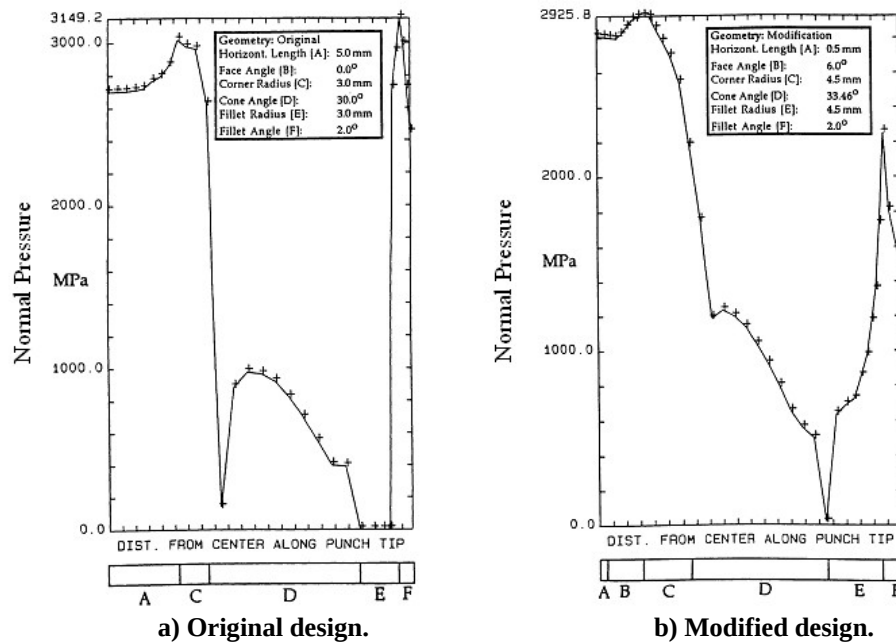


Figure 13: Normal stress distribution along the punch tip from the center outwards for the original and modified punch design /11/.

2.2.6.2 Tool life in upsetting

FEM was used to study the failure mechanism of the die insert used for an upsetting process (Figure 14). The pressure distribution along the die surface showed that the normal peak pressure was exhibited between points B and C, and also on the inner side of point D (Figure 15). This pressure gradient seemed to have caused the die insert to fail /12/. The stress level was reduced successfully by altering the shrink fit and the outer diameter of the die insert.

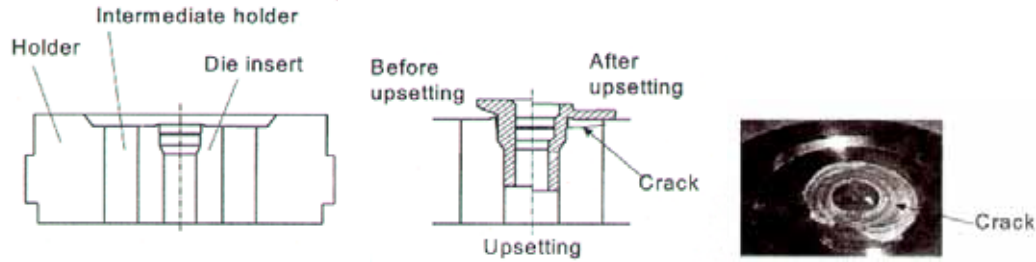


Figure 14: Die used in upsetting process /12/.

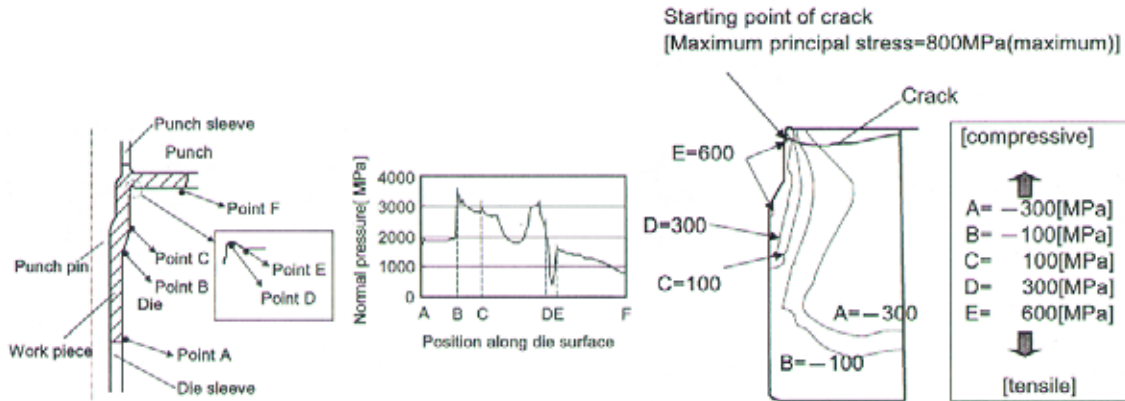


Figure 15: Pressure distribution along the die surface along with the distribution of maximum principal stress /12/.

2.3 Advances in Press Design

Net-shape forging of complex parts such as helical gears, helical-tooth pinions, etc. requires new concepts in press and tooling design with consideration of a multitude of interacting variables such as those shown in Figure 16. In order to increase the accuracy of the product and to extend the service life of the tools, press builders have developed multi-slide and multi-action hydraulic presses /13/14/.

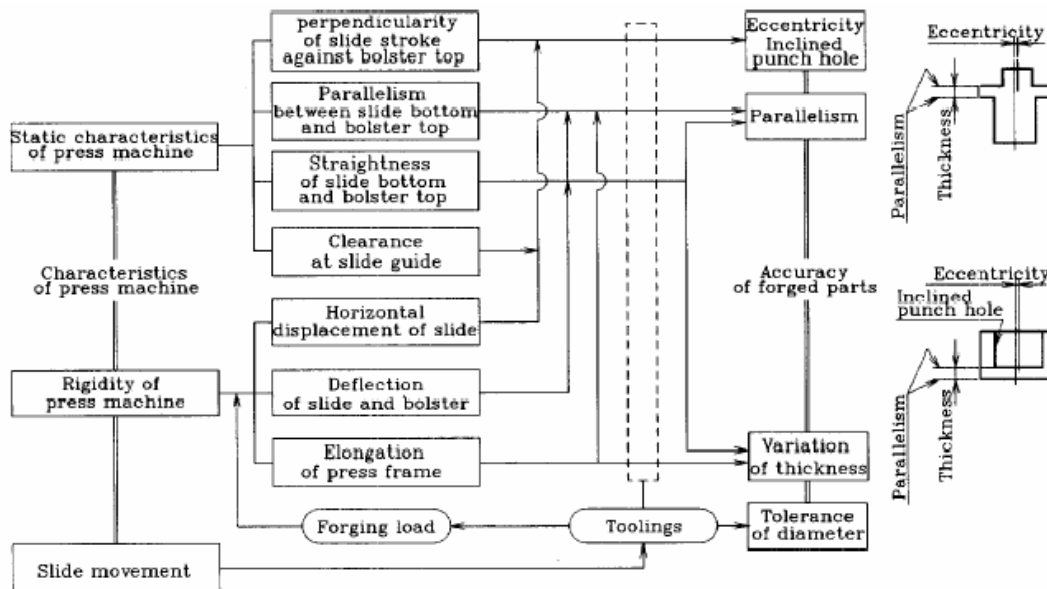
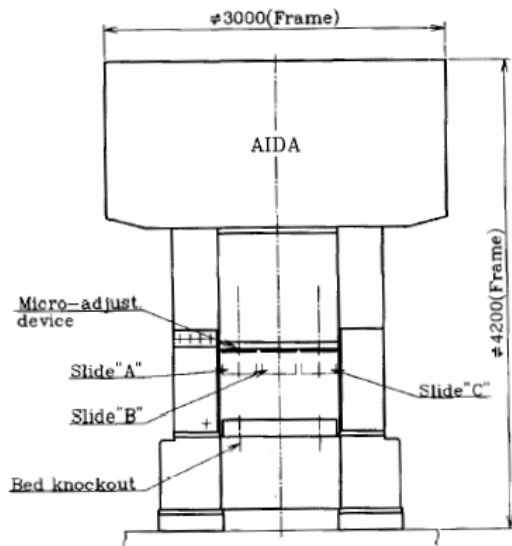


Figure 16: Characteristics of press and accuracy of formed products /13/14/.

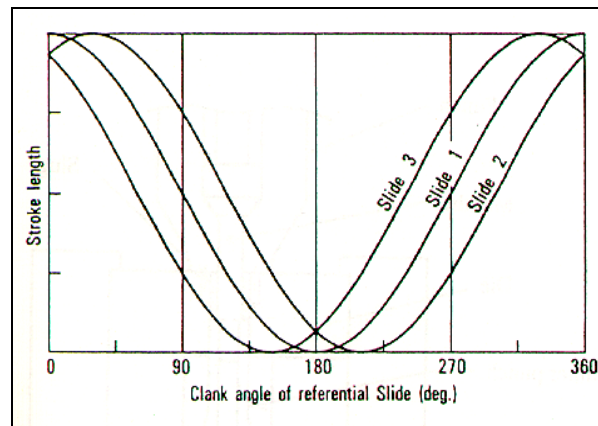
2.3.1 Multi-slide Forging Press

Aida Engineering Co. has developed a multi-slide forging press for the purpose of minimizing the effect of off-center loading during multi-process transfer forming. In their model MF-7500, three independent slides operate with a phase difference of 30 degrees, and a capacity per slide of 2500 kN. The total capacity is 7500 kN with different working timing. A schematic of the press with the slide and die area is shown in Figure 17a, whereas Figure 17b shows the slide motion. Figure 18 shows a part formed using the MF-7500 press /13/. As a result of these features it was possible to:

- Downsize the press and reduce facility cost due to reduction of total load and torque of the press.
- Reduce slide tilting and thus improve the accuracy of the formed parts since the slides perform independently without any mutual interference.
- Reduce the vibration and noise during working.



a) Schematic of the press.



b) Slide motion diagram.

Figure 17: Multi-slide forging press MF-7500 /13/.

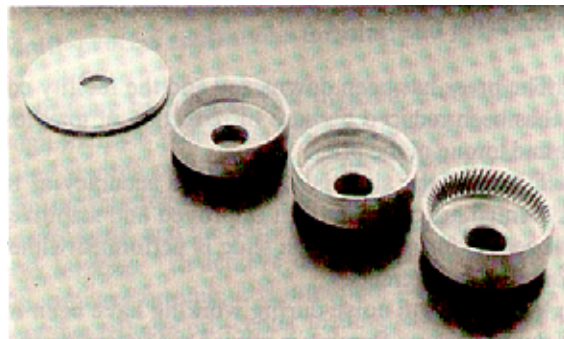


Figure 18: Helical gear cup formed using the MF-7500 /13/.

2.3.2 Multi-action Forming Press

Multi-action forming is an effective means of net-shape forming of parts with complex features. Several press and die manufacturers have recently focused on the development of new concepts in this field. In multi-action forming, there is more than one pressure source to operate the dies and the slide. Also the dies make several relative motions during one stroke. A multi-action press for forming helical gears is shown in Figure 19a. This hydraulically operated press has 5 cylinders; one for driving the slide, two cylinders in the slide and two in the bed. Figures 19b shows the construction of a die for forming the helical gear in Figure 19c /13/.

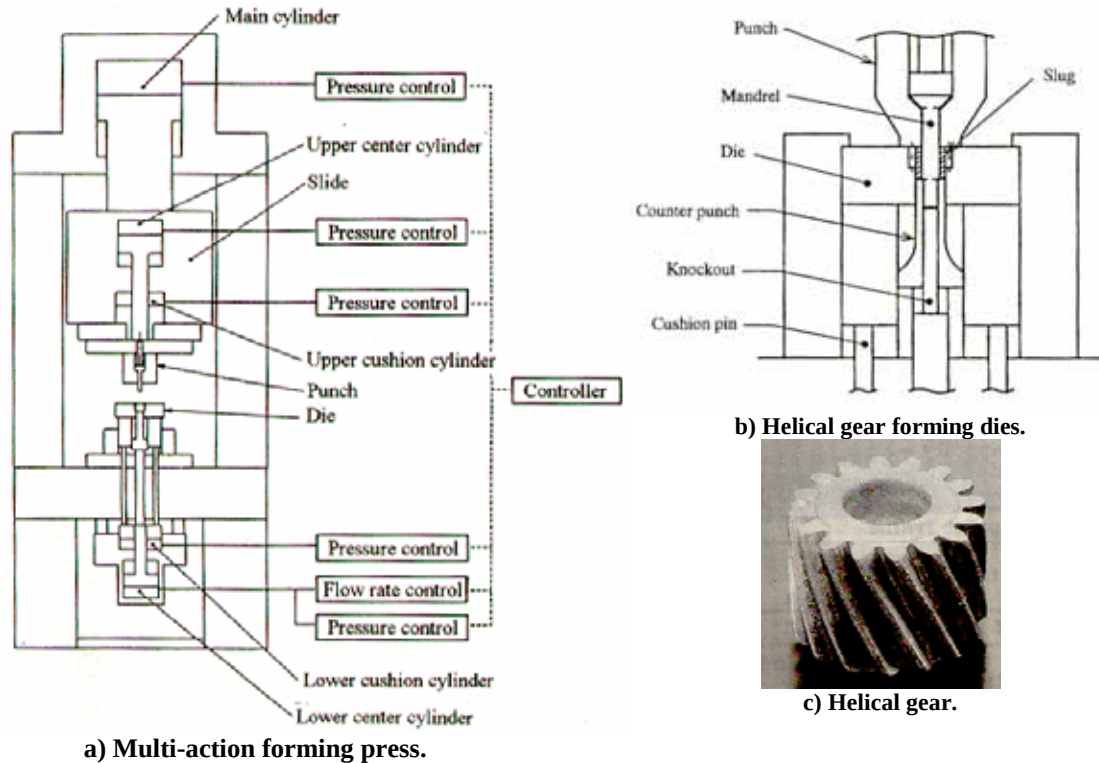


Figure 19: Multi-action forming press with the dies and the forged gear /13/.

2.3.3 Servo Motor Press

Figure 20 shows a servomotor press that combines a newly developed large size, high torque servo motor drive with a crank mechanism /15/. The press uses CNC controls for high functionality. It is thus possible to program the forming motion and speed in order to set the optimum parameters required to form the part. This can be used advantageously to increase die life and produce hard-to-form materials.

The servomotor is protected from overheating by forced air-cooling, and from current and voltage surges with the help of interlocks. The press achieves reduced power usage by using a capacitor to store energy (Figure 20). Table 1 shows a comparison between conventional presses and the servomotor press. The torque of a servomotor press compares with that of a mechanical drive. A conventional press is incapable of doing forming work until it reaches a set speed, whereas the servomotor press can start forming

immediately. Also, since there is no changing or adjusting of v-belts this press is easy to maintain /15/.

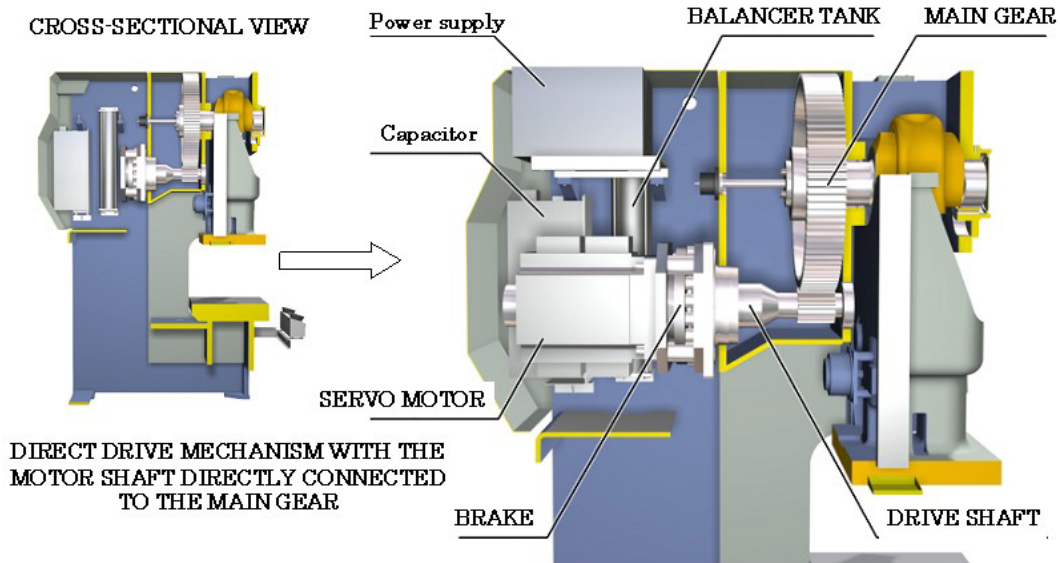
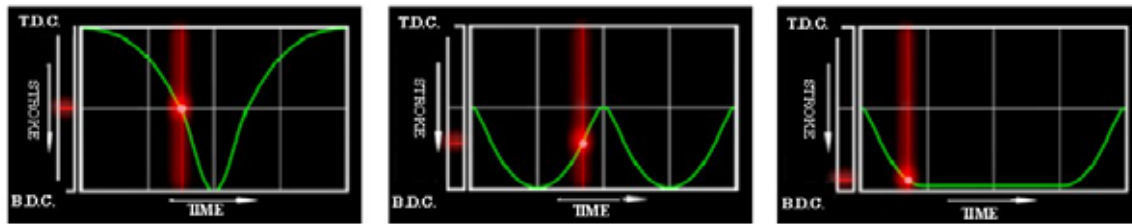


Figure 20: Sectional view of the drive mechanism of the Aida Digital Servo Former /15/.



a) Slow contact, quick return.

b) Continuous motion.

c) Blanking motion.

Figure 21: Some example settings of forming motions and speeds /15/.

Table 1: Comparison of the servomotor press with conventional press designs /15/.

ITEM	CONVENTIONAL MECHANICAL PRESS	CONVENTIONAL HYDRAULIC PRESS	AIDA DIGITAL SERVO FORMER
MAX. FORMING FORCE(kN)	1 ~ 100,000	1 ~ 100,000	1 ~ 20,000
ENERGY RELEASE SOURCE	FLYWHEEL	DIRECT OR ACCUMULATOR	AC SERVO MOTOR
SLIDE MOTION CONTROL	NONE (SPM CHANGE ONLY)	POSSIBLE	POSSIBLE BY CNC
HIGH ACCURACY CAPABILITY	ACCEPTABLE (1)	MARGINAL (1)	BEST (2)
MAINTENANCE	ORDINARY	DIFFICULT	EASY
LOW NOISE & VIBRATION	DIFFICULT	DIFFICULT	POSSIBLE
NOISE LEVEL	MEDIUM	HIGH	LOW
VARIABLE FORMING PATTERNS	NONE	NONE	POSSIBLE BY CNC
RUNNING SPEED SPM(3)	~100	~20	~100

(1) – Position accuracy at BDC can be increased by using stopping blocks.

(2) – Position accuracy is available at any stroke position.

(3) – When slide stroke is 200mm.

2.4 Tool Design for Complex Forging Operations

While press builders have been developing multi-action presses for net-shape forging operations, tool and die makers have put more effort in developing new tooling concepts that will not require specialized presses (Figures 22 and 24).

A Japanese tool supplier has recently developed a special die set for forging radially extruded parts and a family of bevel gears (Figure 23) /9/. The advantages obtained from this die set were a) high productivity, b) fits in almost all presses, c) easy installation, d) requires only compressed air and e) low initial cost.

A similar concept in die design was developed earlier by another Japanese toolmaker. This design incorporates a pantograph as shown in the schematic in Figure 24 /15/16/. Hydraulic pressure generated by an external hydraulic unit and an accumulator is used for closing the upper and lower die to form the die cavity. The die closing pressure is adjustable. However, if this pressure is too low it could result in flash formation in the die gap and cause chipping in the die. The die cavity composed of the upper and lower dies moves at a half the punch speed by the pantograph mechanism in order to obtain uniform deformation of the material in the axial direction /17/. These multiple action die designs are similar to those developed at IFU, Stuttgart and by European press and tool builders.

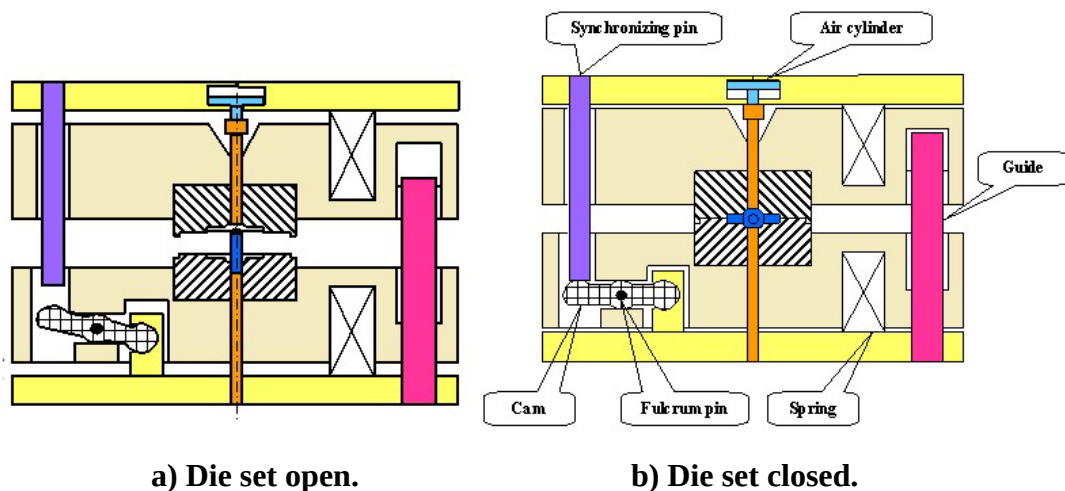


Figure 22: Enclosed forging die set developed by Yamanaka Engineering /9/.

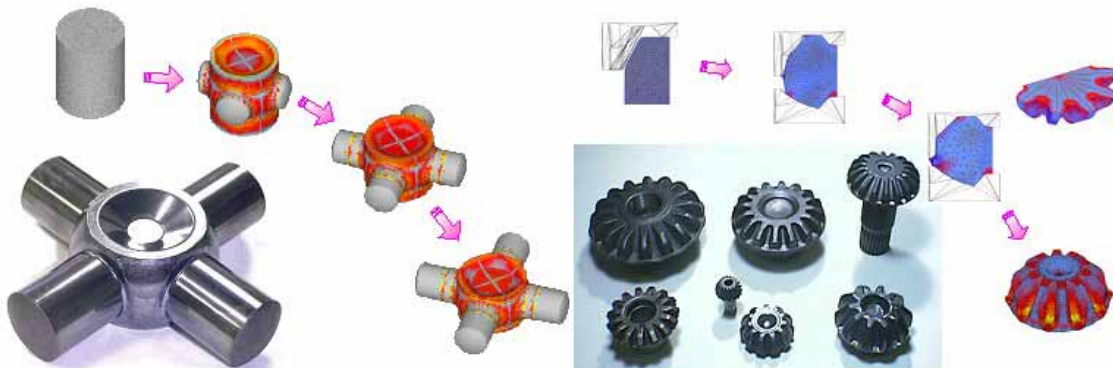


Figure 23: Some example parts forged in the Yamanaka enclosed forging die set /9/.

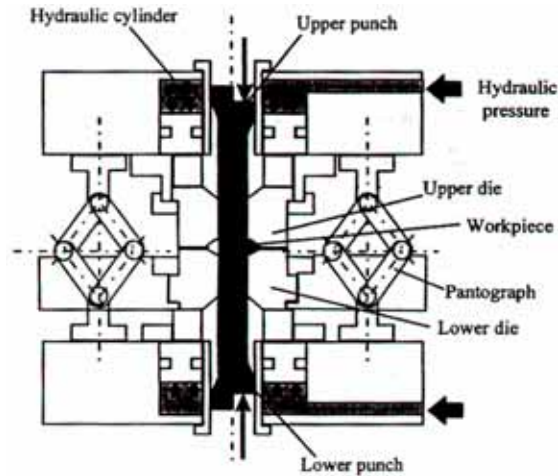
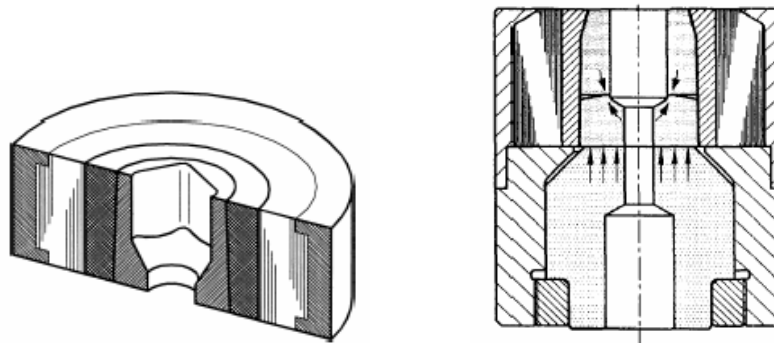


Figure 24: Die set for enclosed die forging developed by Nichidai /16/.

2.4.1 Innovations in compressive prestressing of die inserts

An important factor in enhancing die life is the design of compressive prestressing container systems, which house the die inserts. The conventional prestressing container normally consists of single or double stress rings. Depending on the complexity of the part and the required tolerances, the compressive prestress generated may be too low. STRECON Technology has developed stripwound radially prestressed containers with strength that is 2 to 3 times that of conventional stress rings /20/. The high strength makes it possible to provide an optimum pre-stress for the die, leading to 2 to 10-fold improvement in the die life (Figure 25a). Sometimes, in cold forging dies, fracture may occur because the conventional radial prestressing does not have any appreciable effect on the stress condition in the axial direction. To counteract this effect, STRECON has developed stripwound containers with integrated axial prestressing (Figure 25b) /19/.



a) Standard stripwound container.

b) Integrated axial prestress.

Figure 25: Prestressed stripwound containers developed by STRECON /19/20/.

2.4.2 Reduction of forging pressure by divided flow method

To reduce forging load and tool stresses, Kondo et al /21/22/, have developed the divided flow method and applied this concept in forging a variety of parts such as the gear parts shown in Figure 26. There are two principles of flow relief shown in Figure 26a and 26b viz. flow relief hole and flow relief axis. In the former, a blank with a relief hole is compressed by flat tools resulting in an inward flow as an outcome of the hole shrinkage,

thus creating divided flow. Research results show that the relief hole principle is more suitable for reducing working pressure since the resistance to flow increases gradually during forming. It is however, advisable to provide an artificial relief zone at a location where the contour shape is simple and successive finishing operation is easy to implement.

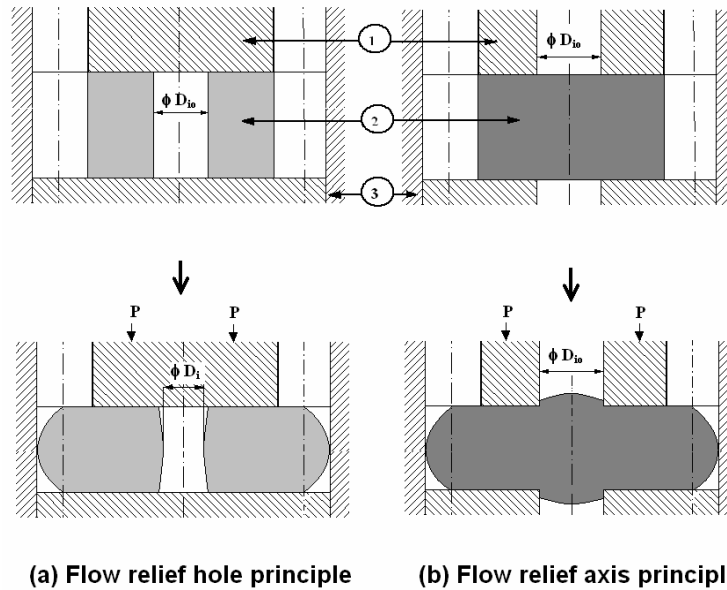


Figure 26: Gear forging process utilizing divided flow /21/.

Manufacture of a helical gear utilizing flow relief axis with back up pressure is shown in Figure 27 /21/22/. The forming process was completed in one step because the inner plate moved down with the die plate until the preset backup load. The final part with the boss is shown.

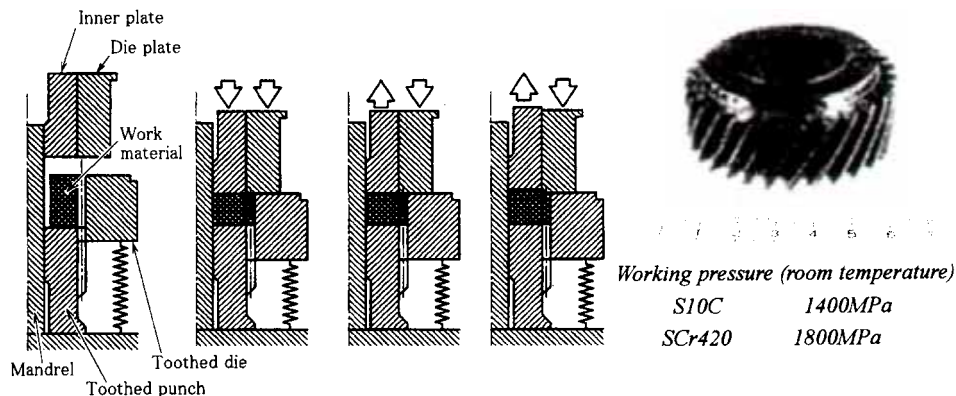


Figure 27:One step divided flow method with back-up pressure /21/22/.

2.5 Information Management in the Forge Shop

Management of complex engineering information in the forging environment plays a big role in ensuring that the desired production outputs are met. A forging company should have the ability to organize engineering knowledge and properly disseminate useful information to the respective departments for implementation. It is necessary to store an abundance of data, to be retrieved when and where desired. A number of forging

companies have gone global with branches in various locations. Thus, information flow becomes complex and difficult to manage efficiently.

To date, companies such as Plexus Systems have developed computerized systems that can assist the management of information flow at various departmental levels e.g. Inventory tracking, shipping, receiving, engineering, purchasing etc /23/. At the engineering departmental level, information management systems can be helpful for storing and retrieving data pertaining to: a) tool designs, b) changing tool materials, c) product specification, d) process instructions, e) just-in-time jobs/rush jobs, f) process control plan, g) tool life tracking, h) machine specifications and drawings, i) press stress analysis, j) engineering drawing management, and k) dimensional control plans.

More sophisticated computerized information management systems will continue to emerge, and the forging companies will be compelled to adopt these systems. Failure to do so might hinder their chances of competing on the global marketplace. The steady growth and development of the Worldwide Web has prompted many forging firms to reassess and redesign the way they share critical business information /24/. The Web can provide cold forging companies with both operational and administrative benefits that can improve the firm's overall competitive position.

2.6 Training of Personnel

Due to global competition, the training of metal forming engineers, who are expected to plan and supervise the design and production of parts and dies, becomes increasingly important. Continuous improvements in forging technology and application of recently generated R & D results require that engineers be continuously updated in new methods, machines and process technology. Professional education in forging and metal forming is necessary not only to upgrade the knowledge level of practicing forging engineers but also that of industrial, mechanical and metallurgical engineers who may be assuming new responsibilities in forging industry /25/26/.

In order to prepare engineers who will work in high-tech forging companies, the current curriculum given in most universities would have to be restructured. It should be noted that most of the material related to cold forging taught at the university level is very basic and may not be of significant value to the high-tech forging industry. Universities may be required to restructure their design courses or develop new ones that address real design issues pertaining to forging. More importantly, for the course to be successful and cost effective, there is a need to link universities to the forging industry in areas such as a) process sequence development, b) die/tool designs, c) press automation and design and d) computational tools such as CAE software, CAD and CAM systems.

2.3 Summary and Future Outlook

The following strategies for technology development have been discussed as a means of handling increased market globalization:

- Use of CAE for virtual prototyping of complicated high value parts (microforming, helical gear extrusion, CVJ inner races) and prediction and elimination of forming defects such as laps and chevron cracks.
- Design and implementation of advanced forging presses and tooling for production of complex components.

- The adoption and development of effective computerized information management systems for cold forging operations.
- Life long learning and training of engineers to equip them with relevant knowledge that can be readily applied to the dynamic technological environment of the 21st century.

In conclusion, the cold forging industry will continue to focus on development of tooling and presses for the manufacture of complex forgings. To facilitate product and process development in minimal time and expense, it is imperative that state-of-the-art CAE capabilities be fully exploited. Furthermore, leading edge forging companies continue to develop strategies and capabilities for producing “ready-to-assemble” parts and sub-assemblies for their customers. Thus, it is expected that high-tech cold forging suppliers in developed nations will remain competitive by producing high value-added parts that require advanced technological expertise.

References

- | | |
|---|--|
| /1/ Bachula, G. | “The global context for innovation: Implications for technology policy”, Council for Chemical Research (CCR), CCR Ninth Annual Meeting, Sept. 29, 1997. |
| /2/ Walters, J.,
Wu, W.,
Arvind, A.,
Li, G.,
Lambert, D.,
Tang, J. | “Recent development of process simulation for industrial applications”, Journal of Materials Processing Technology, Vol. 98 (2000), p - 205-211. |
| /3/ Vasquez, V.
Altan, T. | V. Vasquez and T.Altan, “New concepts in die design – physical and computer modeling applications”, Journal of Materials Processing Technology, Vol. 98, 2000, p. 212-223. |
| /4/ Dixit, R.
Ngaile, G.
Altan, T. | “Measurement of flow stress for cold forging”, Engineering Research Center for Net Shape Manufacturing, ERC/NSM-01-R-05. |
| /5/ Cho, H.
Ngaile, G.
Altan, T. | “Simultaneous determination of flow stress and interface friction by finite element based inverse analysis technique”, Engineering Research Center for Net Shape Manufacturing, Submitted for publication to CIRP. |
| /6/ Ngaile, G.
Schumacher, R.
Gariety, M.
Altan, T. | “Developments of replacements for Phoscoating used in forging, extrusion and metal forming processes”, Engineering Research Center for Net Shape Manufacturing, ERC/NSM-02-R-85. |
| /7/ Palaniswamy, H.
Ngaile, G.
Altan, T. | “Coining of surgical slit knife”, Engineering Research Center for Net Shape Manufacturing, F/ERC/NSM-01-R-26. |
| /8/ Tiesler, N. | “Forming of microparts- effects of miniaturization on friction”, |

- Engel, U.
Geiger, M. Advanced Technology of Plasticity, Vol. 2, Proceedings of the 6th ICTP, Sept. 19-24, 1999.
- /9/ Yamanaka, M.
Sunami, F. “Tool Design for Precision Forging”, Cold and Warm Precision Forging Workshop, November 14, 2002, Canton – Michigan.
- /10/ Vasquez, V.
Altan, T. “Prediction and Elimination of Defects in Cold Forging using Process Simulation”, 10th International Cold Forging Congress, Sept 13-15, 2000, Stuttgart.
- /11/ Lange, K.
Hettig, A.
Knoerr, M. “Increasing tool life in cold forging through advanced design and tool manufacturing techniques”, Journal of Materials Processing Technology, Vol. 35, 1992, p. 495-513.
- /12/ Matsuda, T. “Improvement of tool life in cold forging”, Advanced Technology of Plasticity, Vol. 1 Proceedings of the 7th ICTP, Oct. 28-31, 2002, Yokohama, Japan.
- /13/ Nakano, T. “Presses for Cold Forging”, Aida Engineering Ltd., JSTP International Seminar of Precision Forging, Osaka, March 31 – April 1, 1997.
- /14/ Ishinaga, N. “An Advanced Press Design for Cold Forging”, 3rd International Cold and Warm Forging Technology Conference, 1996.
- /15/ Aida Engineering “The Aida Digital Servo Former: NC-1 and NS-1, Hy-Flex D Series”, Aida Engineering Ltd.
- /16/ Yoshimura, H.
Wang, C.C. “Manufacturing of Dies for Precision Forging”, Nichidai Corporation, JSTP International Seminar of Precision Forging, Osaka, March 31 – April 1, 1997.
- /17/ Yoshimura, H.
Wang, X.
Kubota, K.
Hamaya, S. “Process Design and Die Manufacturing for Precision Forging”, Nichidai Corporation, 2nd JSTP International Seminar of Precision Forging, Osaka, May 15 –16, 2000.
- /18/ Yoshimura, H.
Shimasaki, S. “A study to enclosed die forging”, Journal of the JSTP (1983), p. 24 – 30.
- /19/ Groenbaek, J.
Nielsen, E.B. “Stripwound containers for combined radial and axial prestressing”, Journal of Materials Processing Technology, Vol. 71, 1997, p. 30-35.
- /20/ Groenbaek, J.
Birker, T. “Innovations in cold forging die design”, Journal of Materials Processing Technology, Vol. 98, 2000, 155-161.
- /21/ Kondo, K. “Improvement of product accuracy in cold die forging”, Advanced Technology of Plasticity, Vol. 1, Proceedings of the 6th ICTP, Sept. 19-24, 1999.
- /22/ Kondo, K. “Some reminiscences of the development of precision forging processes”, Advanced Technology of Plasticity, Vol. 1, Proceedings of the 7th ICTP, Oct. 28-31, 2002, Yokohama, Japan.

- /23/ Beatty, R. "Advanced information management in the forge shop", Journal of Materials Processing Technology, Vol. 71, 1997, p. 25-29.
- /24/ Beatty, R., Shim, J.P., Jones, M. "Factors influencing corporate web site adoption: a time-based assessment", Information and Management, Vol. 38, 2001, p. 337-354.
- /25/ Vasquez, V. Altan, T. "State of the Art Technology for Training Engineers for the Forging Industry", Proceedings of Umformtechnik 2000 plus, edited by M. Geiger, Meisenbach Verlag, 1999, p.53
- /26/ Vasquez, V. Altan, T. "State of the Art Technology for Training Engineers for the Forging Industry," presented at the 1999 FIA/FIERF Conference, 1999.