

Innovations in Disk File Manufacturing

This paper discusses the important innovations in disk file manufacturing at IBM over the past twenty-five years. Technology advances in the key components of disk files—the magnetic read/write head, its air bearing support, and the disk substrate and magnetic coating—have permitted almost four orders of magnitude increase in areal recording density since the first disk file, the IBM 350, was shipped in 1957. Manufacturing capability for these basic recording technology components has been the key to realizing the cost/performance promise of each new technology. The evolution of this manufacturing capability is discussed with an emphasis on important innovations in processes, materials, tools, and testing techniques.

Introduction

The progress of the disk file industry has been fueled by an ever-growing demand for on-line storage with improved price and performance, as pointed out by Stevens [1]. The single most important factor in meeting this demand has been the increased areal storage density permitted by the advances in basic recording technology discussed by Harker, Brede, Pattison, Santana, and Taft [2]. The key disk file components reviewed in that paper are simple in concept. But to realize the cost advantages of the advances in technology has presented a continuing manufacturing challenge in the face of ever-increasing precision, decreasing geometrical dimensions, and requirements for more contaminant-free environments in both processes and assembled products.

This paper reviews the manufacturing innovations encouraged by these challenges as well as those of growing production volumes and stringent quality objectives. IBM's General Products Division plant in San Jose, California, was the first site for disk file manufacturing. Today, IBM manufactures disk files at two other U.S. locations and five overseas locations and develops disk files at San Jose and at Rochester, Minnesota, and Hursley, England. Some of the contributions made by overseas locations and individuals are noted. The major topics discussed are the manufacturing aspects of the read/write head and its air bearing support, the disk

substrate and its magnetic coating, and the completion of finished head/disk assemblies.

Magnetic head element and slider bearing manufacture

The characteristics of the magnetic head element and its air bearing slider support determine, to a large degree, the areal density and capacity of a disk file. They also influence the specifications for the disk substrate and magnetic coating, as is discussed in this paper.

The manufacturing cost of head element and air bearing became significant as disk file configurations were designed to utilize multiple heads to reduce data access time. The IBM 350 accessed a single arm with a pair of head elements to serve 50 disks. Each head element was supported by a hydrostatic air bearing. Since the IBM 1301 (1962), all IBM disk drives have used one or more hydrodynamic air bearing sliders per disk surface. The evolution of the volume manufacturing techniques for these components—from the labor-intensive laminated mu-metal head elements manually attached to the slider, to the batch-fabricated film head and integral slider—has presented many opportunities for innovation.

Early slider bearings required precision cylindrical air bearing surfaces, as reviewed by Harker *et al.* [2]. Those

Copyright 1981 by International Business Machines Corporation. Copying is permitted without payment of royalty provided that (1) each reproduction is done without alteration and (2) the *Journal* reference and IBM copyright notice are included on the first page. The title and abstract may be used without further permission in computer-based and other information-service systems. Permission to *republish* other excerpts should be obtained from the Editor.

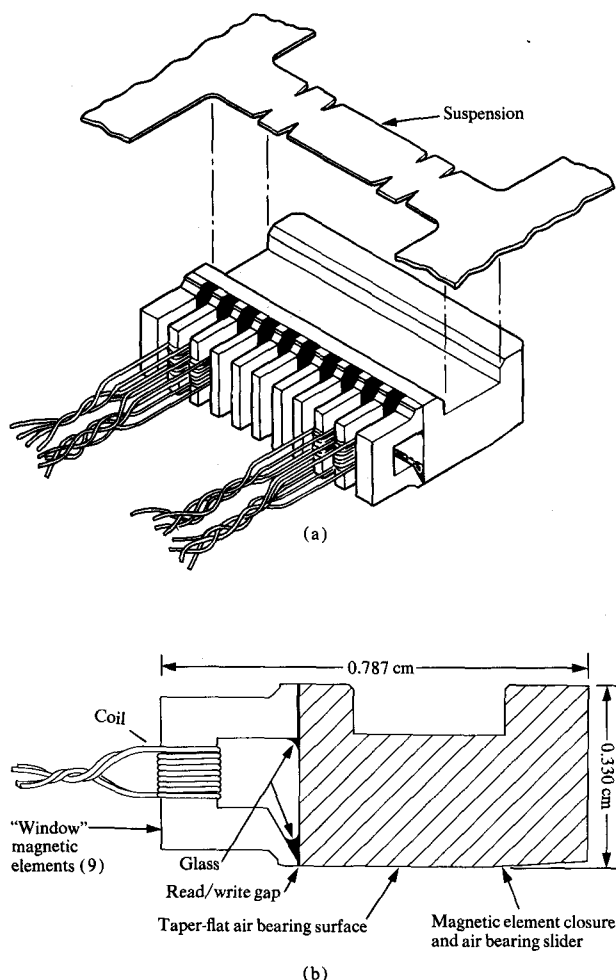


Figure 1 IBM 2305 head assembly: (a) Head and suspension assembly. (b) Cross section of nine-element recording head.

authors also discuss the techniques used to produce these surfaces by means of a cylindrical lap. Both laminated mu-metal and ferrite head elements were used in these sliders. The following section indicates some of the manufacturing process steps associated with the early laminated head elements and the first ferrite head elements. Subsequent sections discuss the significant new batch fabrication techniques introduced in the IBM 2305 (1971) and 3340 (1973) ferrite head sliders and the IBM 3370 (1979) film head.

• Early head elements—IBM 350 to IBM 3330

Hydrodynamic head sliders prior to the IBM 2314 (1966) were machined from stainless steel, and head element cores were constructed of epoxy-bonded mu-metal laminations with separate write and read gaps and coil windings.

Prewound coils were manually placed on a leg of the core by momentarily bending the leg adjacent to the gap out of plane to permit their insertion. A copper shim was placed in each gap, the pole leg reformed into the core plane, and the element epoxied into the slider [or, in the case of the 2311 (1965), retained by ball swaging]. A large number of dextrous operators were required.

Ferrite head elements were introduced in the IBM 2314 (1966) to accommodate increases in bit density and data rate. The head cores were manufactured at IBM Poughkeepsie using ferrite powder which had been pressed into "brick" form. Bar pairs were machined from the brick of compressed powder to form the desired magnetic head core shape and were then glass-bonded to provide the read/write gap. The bonded core rows were later sliced into individual head elements. The read/write coil was placed on one leg of the core and a ferrite bar epoxy-bonded to close the back gap of the core. The 2314 slider was constructed of alumina (for improved air bearing wear durability during head/disk loading) and the ferrite core was epoxy-bonded to the slider. The 3330 (1971) head introduced a ferrite, ceramic, and glass head slider and head element construction without epoxy bonds. The ferrite element was glass-bonded to the ceramic slider by a second glass having a lower melt temperature than that used to form the core gap. The back gap closure bar, with the prewound coil on it, was held in contact with the top side of the core by a spring clip.

Glass-bonded construction, with alignment of ferrite core to slider aided by a microscope/video display, ensured excellent dimensional control and stability of the core gap relative to the slider air bearing surface. Precision assembly of the ten-part 3330 head was, however, time-consuming. The development of simplified head designs and batch fabrication processes is discussed in the following section.

• Batch-fabricated head sliders

Magnetic recording head technology achieved a significant step forward with the introduction of a unique all-ferrite head design in the nine-element IBM 2305 (1971) recording head [3] shown in Fig. 1. The magnetic element for the nine magnetic cores provided an integral taper-flat air bearing slider machined from ferrite.

The simple head slider material system—ferrite and glass—was designed for batch fabrication, high yield, and low cost. A simple and secure snap-in attachment of the flexure suspension permitted mechanized insertion techniques; coils were hand-wound on each of the nine elements after assembly.

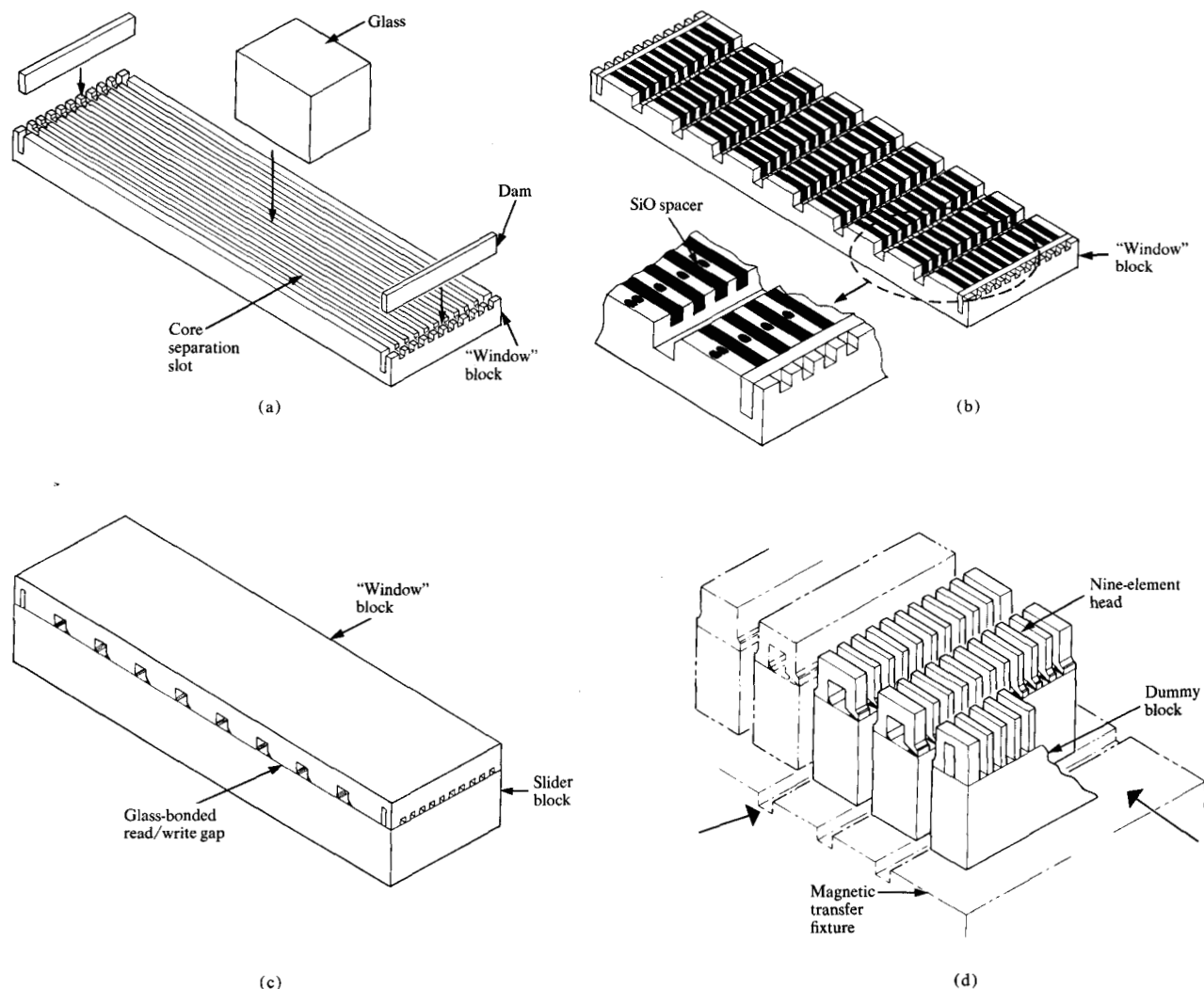


Figure 2 IBM 2305 head batch fabrication process: (a) "Window" ferrite block for fabricating eight heads. Core separation slots (in recording gap face) define magnetic element width. (b) "Window" block after glass melt, form grinding, gap surface lapping, and SiO spacer deposition. (c) Glass bonding of "window" block and slider block. (d) Core and head separation grinding.

Figure 2 illustrates the batch fabrication process. Two ferrite blocks were used; the "window" block was form-ground and then glass-bonded to the slider block. Vacuum-deposited SiO spacers ensured a well-controlled gap spacing.

New and sophisticated lapping and computer-controlled grinding equipment and processes were developed to maintain precise tolerances and surface finishes. A precision grinder, incorporating a stepper motor drive to move the grinder table parallel to the axis of rotation of the grinder spindle, was equipped with a commercial laser

interferometer [4] to measure table position and provide digital input to a control computer. The control computer was programmed to index the grinder table for each cut and control table motion perpendicular to the spindle axis, thus permitting one operator to control four grinders.

Many of the batch fabrication techniques developed for the 2305 were adapted to the Winchester recording head, first introduced in the IBM 3340 and illustrated in Fig. 3. Forty-eight heads are fabricated from each glass-bonded "window" block and slider block set.

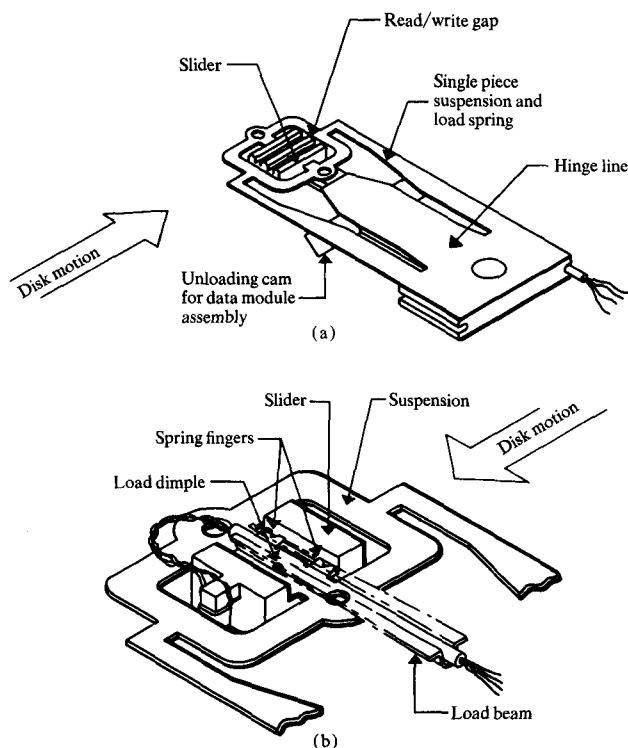


Figure 3 Winchester recording head: (a) Head. (b) Suspension.

In this tri-rail taper-flat design the two outer rails provide the head air bearing surfaces and the narrow center rail provides the read/write element; the rail width defines recording track width. The relatively small air bearing surface of the design is essential to the desired low-load head operation [5].

The beveled center-rail cross section provides a mechanically strong core, reducing core breakage during rail grinding of narrow-track-width heads. The rail bevel grind operation was performed during development with the grinding wheel axis rotating parallel to the bevel plane; an improved surface finish was obtained with the diamond cup wheel shown in Fig. 4. With the circular cutting path of the cup wheel, the finished surface is defined by the highest single abrasive asperity on the cup.

The Winchester grinding process, like that of the 2305, was computer-controlled; however, a Heidenheim optical grating replaced the laser interferometer as a position sensor. The Heidenheim unit, with an accuracy within the resolution of the stepper motor positioning system, offered economies in initial cost and in maintenance cost. Winchester heads were initially machined to a core width tolerance of ± 300 microinches, with later improvements to ± 150 microinches for the 3350 (1976) head.

• Film heads

The IBM 3370 introduced the film element head in 1979. The performance gains available with this technology are noted by Harker *et al.* [2] and are discussed by Croll [6], Thompson and Romankiw [7], and Jones [8].

The film head applies technology familiar to the semiconductor industry to the rear surface of a ceramic head slider. A single plate of ceramic with a thickness approximating the final slider length is used as a substrate to construct several rows of film head elements. Upon completion of the element deposition process the ceramic plate is machined into head slider rows, and the sliders are batch-machined in a manner similar to the Winchester process [8].

Disk substrate and magnetic coating

• Processing of substrates

The disk substrate for the early IBM 350 24-inch-diameter disks was made from an aluminum alloy similar to that used as a substrate for transcription records in the broadcasting industry. Two 0.050-inch-thick disks were bonded together to make the final disk. The first magnetic disk coating was a thin paint film containing dispersed gamma ferric oxide; coating application was made by hand-held paper cup onto the spinning disk substrate. The 1200-microinch coating thickness effectively masked substrate surface imperfections; flatness and dynamic stability of the laminated 0.100-inch substrate were adequate for the 800-microinch-spaced hydrostatic air bearing head.

The advent of the hydrodynamic (self-acting) slider bearing head in the IBM 1301 imposed more stringent demands for flatness, as pointed out by Harker *et al.* [2]. Disk surface curvature of the same order as the slider bearing surface curvature (about 250 in. radius) would cause head instability. Specifications of flatness, local curvatures, and surface dynamics were developed, with improvements in fabrication and measuring techniques continuing as important elements in succeeding programs.

Substrate processing techniques developed for the 1301 24-inch-diameter disk included rough grinding, lapping, polishing, and cleaning. Processing steps were accomplished with manual handling of disks, but as production volumes grew with the introduction of the 14-inch-diameter disk pack, more mechanization of process and handling was required.

Disk surface finish became a more significant parameter as coating film thicknesses were reduced to accommo-

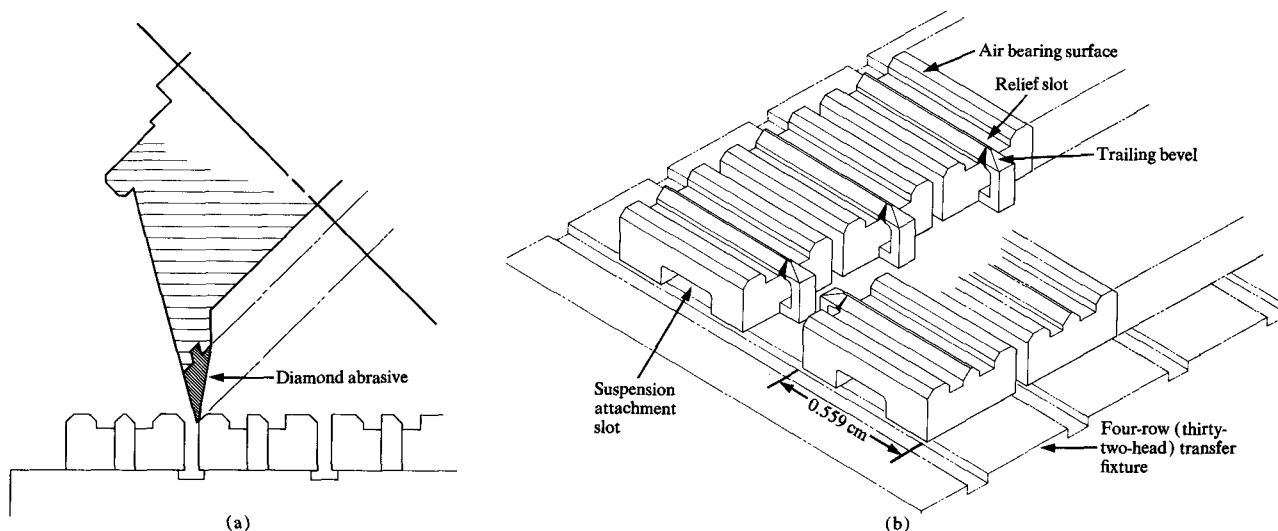


Figure 4 Winchester head batch fabrication process: (a) Cup wheel grinding of rail bevels. (b) Head separation from eight-head barrow. Machining operations with heads mounted in this orientation on transfer fixture include: relief slot, rail side bevel, trailing bevel, and separation grinding, as well as lapping of the air bearing flat and leading taper.

date increasing bit densities. Surface roughness created changes in coating thickness that were reflected in read-back signal modulation and data errors. With the introduction of track-following servo systems, disk surface finish could reduce head positioning accuracy. The following sections discuss this evolution.

Early 14-inch disks—IBM 1311 through IBM 2314

The removable disk pack concept was introduced in 1963, with the announcement of the IBM 1311. To minimize the size and weight of the customer-removable disk pack, the disk diameter was reduced to 14 inches and the disk thickness was reduced to 0.050 inch. To achieve the high-volume disk production required for this product, a new disk substrate finishing facility was built at San Jose to process vendor-supplied substrate blanks. Blanks were first edged to control inner and outer diameter, then wet-sanded, flat-baked, again wet-sanded, fly-cut, lapped, polished, and cleaned.

In the flat-bake process heavy machined steel platens were interposed in stacks of disks and the entire mass was raised to a critical annealing temperature, to reduce the effects of residual rolling mill stresses, and slowly cooled. The processing steps through flat-bake and sand continue today. New processing lines automatically handle disks from vendor blank stacks to flat-bake stack.

To accomplish the lapping, polishing, and cleaning a transfer line polishing machine called "Autotran" was developed. In this tool, disks were held in a vertical plane

by three grooved rolls. The transfer line presented each disk to a series of polishing stages with the disk free to rotate while in contact with rotating polishing brushes. Three rotating brushes contacted each side of the disk at each stage. An abrasive slurry of alumina and kerosene was pumped onto the disk surface at the polish stations and kerosene was used to clean the disk at several cleaning stations. The fly-cut, lap, and Autotran polish process was used for 1311, 2311, and early 2314 disk packs, but was replaced by diamond-turning substrate finishing in the later 2314 disk production. The diamond-turning process is used to produce disk substrates today.

Diamond-turning substrate finishing

IBM Germany entered into disk and disk file manufacturing in 1966 with the production of the IBM 2314. The Sindelfingen Manufacturing group sought an improved-quality, lower-cost substrate process. The lap and polish process, while a high-volume mechanized approach, was costly to maintain and provided modest product yield. The polish stages were not always able to remove lapping scratches and tended to create a radial curvature in the disk surface near the outer diameter.

An improved disk-alloy (Almag 5, manufactured by Alu Singen), diamond-tool machining [9-11], and a precision-lathe spindle and tool carriage were combined to provide a unique substrate fabrication process. Commercial precision lathes—initially Bryant Symons units from the United Kingdom and later Boley units from Germany—were adapted with pneumatic logic to control the tool carriage

and move the special polished diamond tool bit. A vacuum chuck was mounted on the lathe spindle to hold the disk substrate.

The multi-facet diamond tool is shaped to follow cutting with a burnishing action that imparts a mirrorlike disk finish. Chip flow from the surface is continuous and surface velocities are several times that recommended for conventional cutting of aluminum.

The diamond-turning process, using the oil-lubricated journal and thrust-bearing-supported Boley spindle, has continued in use since the adoption of the 2314 process. With two cuts on each surface it is possible to produce a disk surface finish of less than 2.5 microinches arithmetic average (AA) and 8 microinches average peak-to-valley. The typical peak-to-valley standard deviation is approximately 2-4 microinches.

Air bearing spindle lathe

San Jose Advanced Manufacturing Engineering explored improvements in the diamond-turning lathe. A hydrostatic air bearing spindle, developed by Union Carbide for the Atomic Energy Commission [12-14] and later manufactured by the Ex-cell-o Corporation, offered a more stable support for the vacuum chuck and the potential of improved disk surface finishes. The Ex-cell-o spindle was constructed with two opposed half spheres connected by a short shaft. The half-sphere sections were hydrostatically supported in mating concave spherical cavities to provide both axial and radial stiffness. The air spindle was mounted on a special structure that supported a servomotor-positioned precision tool carriage. The combination of this precision spindle and tool carriage provided disk substrate finishes of 0.5-0.6 microinch AA with less than 2.5 microinches average peak-to-valley roughness and a standard deviation of less than 1 microinch.

The IBM 3330 disk file with its track-following servo system provided an application for the air bearing spindle diamond-turning lathe. The amplitude measurement of adjacent track servo patterns in the 3330 servo system (and subsequent track-following systems) was sensitive to disk coating thickness variations induced by the 8-microinch average peak-to-valley turning marks of the Boley lathe diamond-turning process. The air bearing spindle lathe was used to machine all 3330 servo disks and subsequent servo disks for track-following servo system files. The air bearing spindle is today also used for the finishing of some data disks.

• *Disk coatings*

The disk coating formulation developed for the first disk product was an epoxy, phenolic, polyvinyl-methyl-ether

copolymer similar to today's disk binder systems [15]. Early disk coating binder and magnetic particles were mixed in a small ceramic ball mill containing alumina balls. Several hours of mixing as a wet slurry in the ball mill ensured good dispersion of the magnetic particles in the binder system. The resultant slurry was filtered through a nylon stocking and then hand-poured onto a spinning disk. The focus of innovation in coatings since the 350 has been in the selection and control of the particles contained in the binder system, in the application and curing of disk coatings, and in the thickness control and surface finish of the applied film.

Ball milling and the fortuitous alumina particle

The ball mill left a residue of fractured small alumina particles, the quantity depending on milling time, rotational speed, and slurry viscosity. At first the alumina particle residue was small in size relative to the bit cell and created no serious data defect problem. But as bit cells became smaller the alumina debris did present a problem, and an effort was made to minimize or eliminate it from the ball mill. This led to the discovery that the alumina particles were critical to disk durability. It was known that both the hydrostatic and hydrodynamic heads impacted the disk surface upon initial dynamic loading. It was not known that the alumina particles were the ingredient that gave the disk impact resistance. As a result of this new insight a new binder composition was developed that provided an acceptable trade-off between durability and data defects.

The ball-mill process was improved in order to decrease particle breakage and ball-mill debris and to increase dispersion of the magnetic and alumina particles. A hard cylindrically shaped zirconium oxide ball-mill pellet was selected for uniform dispersion and minimum debris generation. Debris generation was further reduced by careful control of ball-mill speed and slurry viscosity [16].

Spin coating

Spin coating provides a rapid and repeatable process to spread the ink and its dispersed acicular magnetic particles parallel to the disk surface; a uniform coating thickness is obtained [16]. The early hand-held pouring cup has been replaced by a moving pressurized coating nozzle that is microprocessor-controlled; disks are today handled automatically. The disk is coated at low speed and then accelerated to control thickness and aid initial drying through solvent evaporation. Magnetic particle orientation, introduced for the 3340, is accomplished by application of a magnetic field of 1800-2000 Oe [$1 \text{ oersted} = (1000/4\pi) \text{ A-m}^{-1}$] during the later phase of the drying cycle while the disk is again rotated at low speed [2].

Particulate contamination can be a major source of coating defects. A small adhered particle can, as an example, distort the radial flow of the liquid coating to create a coating run—a radial ridge of increased coating thickness. While disks are handled in class 100 rooms [17], control of airborne particulate contamination is a continuing challenge. A class 100 horizontal laminar-flow coating booth was developed for the 3330 disk and is now standard for all disks. Typical air flow particle counts within the coating booth are less than ten particles of 0.3 micrometer size per cubic foot.

While the average final coating thickness variation may be held to 3 microinches, particle agglomeration tends to create a waviness in the final coating film. Following a cure cycle at elevated temperature, the disk is buffed to achieve the desired surface finish and flatness.

Disk buffing

The early 350 buffing approach used emery paper hand-held against the rotating disk surface. The process developed for the 14-inch family of disks uses simultaneous two-sided abrasive web buffing with a special grade of kerosene as a lubricant. The abrasive web is continuously fed, at low speed, to supply fresh abrasive while the disk rotates at approximately 1800 rpm. Each abrasive web is backed up with a rubber roll and the dual web/roll system is moved radially in and out over the coated disk surface while the roll pressure is controlled to compensate for disk surface velocity.

Today, the buffer developed for the 62PC 8-inch disk represents the most mechanized implementation of two-sided disk buffing. The buffer incorporates a final disk wash station using surfactants and deionized water. Close coupling of burnish and wash enhances disk cleaning by avoiding dry debris. A microprocessor controls buffer/wash operation and disks are automatically conveyed from an input autostacker (discussed in the next section) through buffing and washing to an output autostacker. Buffer performance is monitored by a three-disk sample in each 150-disk batch. Film thickness is determined by measuring x-ray fluorescence from the iron oxide particles in the coating. Control limits are held to <10 microinches at the outer diameter.

Disk-handling mechanization

● *Autostacker*

Some of the earliest developments of mechanization in disk file manufacturing have evolved in disk handling. Mechanized disk handling was developed to reduce direct labor cost, minimize handling damage, and control particulate contamination.

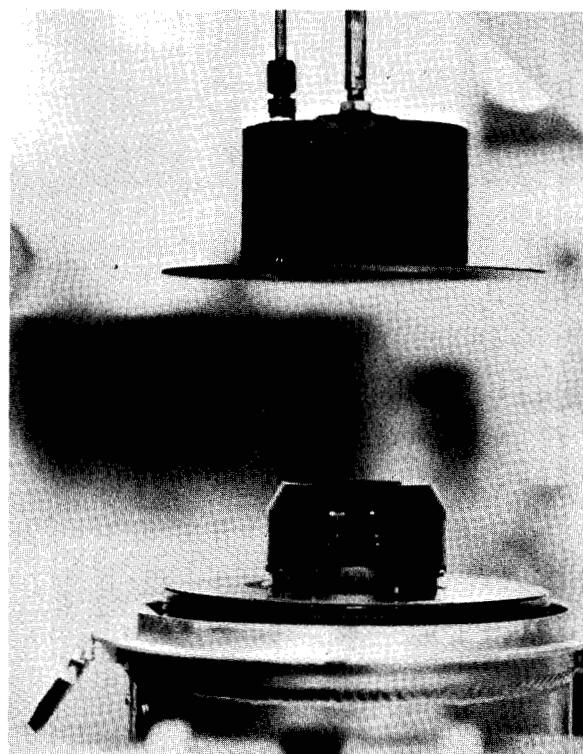


Figure 5 Autostacker for eight-inch disk (shown with a disk buffer's vacuum pick-up head at top).

The earliest mechanized disk-handling tool, the autostacker, was developed to handle groups of 24-inch disks. An example of a current autostacker is shown in Fig. 5, which illustrates an autostacker for 8-inch disks. This tool supports up to 170 disks in a separated stack, with each individual disk supported at its inner diameter by the lands of three screw shafts. The shafts are powered and controlled to lower or raise the stack one disk level to receive or release one disk.

Electrical connectors for power and control are at the base of the autostacker; the unit is designed to align and connect with a receiving station. The top closure of the unit ensures a clean environment for disks and allows the portable unit to be moved through nonclean room environments. The autostacker serves as a convenient buffer storage between process steps.

The autostacker has provided the basis for evolutionary development of mechanized handling throughout the disk process. Manual loading of autostackers is replaced by mechanized handling systems for individual processes.

- *Disk transport and sorting*

An early mechanized handler was developed for testing single disks used for the 2311 disk pack. A rotary transfer arm with a short vertical motion and 360 degrees of horizontal rotary motion was used to transfer disks from an autostacker to a test spindle and then to one of several output autostackers to sort disks by test result.

To reduce space and cycle times, a number of linear disk transfer lines with multiple vacuum or mechanical-disk pick-up heads have been developed. These transfer lines are used for testing and sorting disks to autostackers as well as feeding coaters, buffers, washing stations, and disk lubrication units. The most recent transfer line utilizes a series of arms, shaped like a tennis racket, that grasp the disk at its outer diameter. The arms oscillate in 180° vertical arcs to flip the disk from one horizontal orientation to a second horizontal orientation through a sequence of process stations. The transfer line mechanism is located below the disk path to minimize contamination.

Disk mechanical testing

- *Optical disk scanner*

The mirrorlike appearance of the diamond-turned substrate and the high-gloss finish of the buffed coating have facilitated rapid operator inspection at process steps. With the introduction of mechanized process lines, defective disks could pass through many process steps before defects such as coating runs would be detected at burnish and glide or magnetic testing.

An automated inspection tool called "OPSCAN" was developed to minimize process time invested in defective disks and to provide a means of rapidly detecting and correcting process problems. The laser, rotating multi-surface mirror, and optical system of the IBM 3800 non-impact printer were adapted to project a 0.002-inch-diameter scanning spot onto a disk surface. The optical system provides a radial scan of the disk while the tester rotates the disk at 6 rpm. Direct-reflected light and scattered light are detected by two photodiodes. Both sides of the disk are scanned simultaneously.

Substrate defects such as handling damage and particulate contamination are sensed as a reduction in direct-reflected light, or a decrease (or increase) in scattered light. Coating defects such as pinholes and coating runs are detected by an increase in reflected light or, as in the case of the substrate, an increase or decrease in scattered light levels.

The detection system was found to be noise-sensitive when light amplitude levels were set to detect small

defects. It was determined that small defects could be detected—without false rejects—by comparing the total defect count in a local segment with the total count of the disk or with several adjacent segments. An IBM Series/1 is used to store acceptance criteria, collect and process the data.

- *Burnish and glide-height testing*

With the development of the hydrodynamic slider, thinner coatings, and reduced head spacing, a "tick-tick-tick" sound could be heard as disk asperities contacted the slider. The burnish-head approach developed by Brunner [2] continues as a process tool to remove disk surface asperities. A flying-height margin is provided for the normal product head by operation of the disk at less than normal speed so that the burnish head flies at a closer spacing than normal.

The burnish head has also been used to sense the presence of remaining asperities after burnish. A microphone was used to detect the sound of an asperity contacting the head. A more sensitive detection was developed using a piezoelectric crystal beam sensor that was cantilevered in a plane parallel to the slider bearing and attached to its top surface. Slider accelerations induced by asperity impacts cause beam deflections and piezoelectric signal output. The initial piezoelectric sensor head was incorporated in a 3330 slider. Subsequent designs have been adapted to low-load slider bearings. Disks are burnished and glide-height tested [18] before single-disk magnetic test and are glide-height tested after assembly into disk packs and head/disk assemblies.

Head/disk assembly configuration

The head/disk assembly (HDA) evolved from the 3340 Data Module [5]. The 3340 provided a new partitioning of disk file functions with critical-tolerance and contamination-sensitive components (including heads, head arms, and disks) contained in a small portable sealed unit, the Data Module. This approach permitted improved contamination control during manufacturing and has been used in all San Jose-developed disk files since the 3340. A similar approach has been used in Hursley-developed 62GV (1974) and 62PC (1979) files [19, 20]. File system structures and drive bases for head/disk assemblies may be assembled in conventional factory assembly environments while the HDA is assembled in a class 100 room.

The HDA for the IBM 3350, 3370, 3375, and 3380 includes the following components:

- Disks and disk spindle.
- HDA base plate.
- Head-arm assemblies.

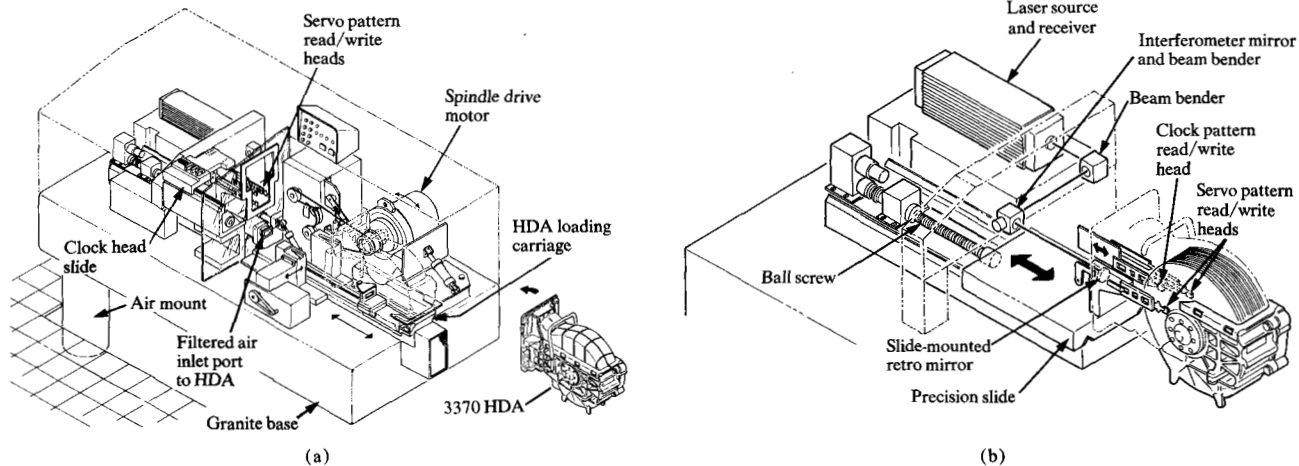


Figure 6 (a) The components of the IBM 3370 servowriter. (b) Detail view of servowriter with HDA in its operating position.

- Actuator voice-coil.
- Actuator carriage and carriage way.
- Enclosure.

The HDA configuration has influenced the servowriter, magnetic, and functional testers that are discussed in the following sections.

Servowriter

Track-following servo control systems were first introduced in the IBM 3330. A precision tool was developed to write servo tracks on one surface of the removable 3330 disk pack. The basic 3330 servowriter design has been extended to accommodate all subsequent disk file products. The servo-track pattern is written as a series of precision-spaced tracks. Position information is derived from the relative signal amplitude detected from a pair of these tracks [21]. The major challenges in developing the servowriter were the minimization of system vibration and the attainment of rapid, precision incremental positioning of the servo head.

Vibration of the disk surface in a radial direction relative to the servo head will induce localized servo track "squeeze" where the effective track pitch will be smaller than desired. Air-turbulence-induced axial motion (flutter) of the disk relative to the head arm will cause the head slider to move in an arc motion about its suspension flexure pivot [see Fig. 3(b)], thus shortening the effective radial distance from the arm to head element and momentarily shifting the written servo pattern. The flutter effect—and rotational vibrations—have been mini-

mized in the 3330 and most subsequent servowriters by operation at less than normal disk file rpm. Rotational vibrations have been minimized by care in spindle designs and bearing specification as well as by balancing disk packs and HDA disk stacks. To isolate external vibrations, the servowriter is built on a large granite block supported by a three-point self-leveling air-mount system. The granite block acts as a seismic mass with the air mounts effectively isolating floor-induced low-frequency vibrations.

The servo head arm is positioned by a Moore precision slide driven by a servo-controlled two-speed ball screw drive. Slide position is monitored by a laser interferometer. Track-to-track moves with a positioning error less than two microinches can be made in less than 100 milliseconds.

The 3370 servowriter is illustrated in Fig. 6. The 3370 HDA has two independent actuators with each actuator's servo head suited to read a band of servo tracks written on an outside surface of the seven-disk stack. Servo write clocking is derived from a clock track written and read by the clock head of the servowriter.

As noted earlier in the section on disk substrates, diamond-turning marks can create false position information because of their effect on signal amplitude. A servowriter technique to minimize position errors caused by both substrate and coating defects and thus improve disk yield was developed for the 3350. The position error of each servo track pair is monitored by the servowriter

after writing with the servowriter head held on the track pair centerline. The position error for each group of 26 servo bytes is stored. The servowriter then repositions the head to the most recently written track and rewrites that track with byte group write amplitude selectively controlled to compensate for the stored position-error information. This technique significantly improved HDA yield.

Head and disk magnetic performance testing

A high level of data integrity—the absence of incidents of data loss or data errors—is an essential element in the design of a data processing system. A permanent data loss or error may interrupt the running of a key customer application and require time-consuming data recovery procedures. A number of innovations in disk file storage design have been made to improve integrity as file areal densities and performance have advanced. These innovations have included functional checking circuits, redundant circuit designs, error detection/correction codes (ECC) [22], disk defect skipping [5], and file error recovery procedures [23].

The most catastrophic loss of data can occur with head/disk contact at full file rotational speed. As head/disk spacings have been reduced from 800 microinches to less than 13 microinches, a number of mechanical evaluation techniques—and careful attention to particulate contamination control—have been implemented. This section discusses some of the magnetic testing techniques that have been developed to ensure product data integrity as areal densities have increased and read-back signal-to-noise ratios have decreased.

• Component integration testing

Data handling reliability in a disk file is a function of the performance characteristics of the data channel, the read/write head, the disk, and the data-head misregistration tolerance characteristics of the file. Each of these elements has a tolerance range and probability distribution. Effective design of tolerance specifications and testing criteria to achieve a desired system hard and soft (ECC or error-recovery-procedure-correctable) error rate requires extensive component testing to determine process distributions and the error rate effect of convolving these distributions into working files [24].

Component testing includes the analysis of data error causes and the development of sensitivity curves for specific tolerance and disk defect types and sizes. This knowledge is then used to define component stress tests that are more efficient in identifying marginal components than are normal data handling tests.

The significance of early component characterization, integration, and iteration was recognized in the 3330 program. To make the required measurements, a precision test spindle with a laser-interferometer-controlled head positioning system was built and dedicated to component evaluation activity. After significant component process variables are identified and tolerance distributions measured, as many as 125 combinations of heads, disks, and channel electronics may be tested today on a technology development program.

Statistical tolerance modeling techniques are used to project the track misregistration (TMR) effect of machine tolerances such as differential thermal expansion, vibration, servowriter tolerances, and head-positioning servo system errors. Error rates increase as heads move off true track centerline at write and read; excessive off-track at write can result in an error that is uncorrectable with read-head repositioning and is of greater length than that correctable by ECC.

• Disk defect considerations

The coated film of the particulate magnetic disk is granular in structure and contains a wide distribution in the size of defect sites. Micro-defects, due in part to the granularity of the coating and non-uniform particle dispersion, directly affect system signal-to-noise ratio [25] and influence off-track error rate. The relationship of off-track error rate *versus* TMR and the statistical projection of machine TMR can be convolved to calculate file error rates. Direct tradeoffs can be made between micro-defect density and required machine TMR performance. It is important to control the disk process so that micro-defects do not degrade the planned off-track capability of the file because of random position coincidence of defect and bit cell.

The use of ECC in the 3330, and of defect skipping and ECC in the 3340, permitted substantial increases in areal density with acceptable disk cost and yield and improved data integrity. These techniques have been used together on subsequent products.

• Single-disk testing

Single-disk testing has always been employed to evaluate the magnetic performance of disks before their assembly into disk packs or HDAs. Single-disk testers have evolved from hardwired control logic to stored program control. Single-disk testing provides process control information and a method of screening disks before their assembly into final products. The selection criteria at single-disk test are an economic tradeoff between “overkill” (the rejection of good disks that would pass final test) and “underkill” (the acceptance of disks that will be

built into product, fail final test, and require disk pack or HDA disassembly and rework).

The newest tester is program-controlled to permit variable-amplitude-level testing of disks in order to better monitor process line quality. Tester efficiency is enhanced by a four-head and four-channel disk scanning system. A variable-motion-increment scan provides finer track-increment testing in the higher-defect-count inner and outer areas of the disk, and coarse track increment motion on the remainder of the disk. The IBM Series/1 controlled tester is connected to an IBM 370 host for data collection, report generation, and graphical output.

- *Surface analysis*

Disk pack or head/disk assembly surface analysis (SA) provides a means of stress-testing the data integrity to be expected in the customer environment. The 1311 disk pack surface analysis was a simple test for extra bits. Disk packs were tested on two different drives with heads offset in two directions about the nominal track centerline to stress off-track capability. The number of pack SA tests increased over time. The 2314 disk pack test added a bit-cell timing measurement to detect bit shift and a positive modulation test to detect head/disk spacing excursions. With the development of the 3330 electronic track-following system, off-track testing and on-track formatting of data tracks could be accomplished on a single test drive.

Surface analysis tests for the 3330 included those for extra bit, missing bit, track modulation range, and bit envelope (change in amplitude between adjacent bits).

The 3340 surface analysis test introduced a means of reducing test time. Each track was initially screened by a special defect-sensitive amplitude test. Those tracks free of significant defect sites then needed only to be tested on-track. This product also introduced defect skipping to provide improved data integrity at high bit densities and better surface analysis yield. This technique is also used in the 3344, 3375, and 3380. The 62PC and 3370 files use fixed-block architecture (FBA) [26] and permit defective block skipping and demarking during SA.

The 3340 and subsequent HDA configuration files have gained enhanced data integrity because of the permanent relationship of individual heads and disks. Each head/disk combination passed at SA remains as a functional unit without the interchange tolerances (head/data track alignments and head/disk performance tolerances) experienced in interchangeable disk pack files.

Functional testing of head/disk assemblies

- *Mechanical integrity and servo stability*

The HDA contains a major portion of the disk file's mechanical elements. Head-positioning servo system performance is, as an example, dependent on such HDA components as spindle bearings, head-arm carriage, voice-coil bobbin, head arms, and head suspensions. Each of these elements, and the quality of their assembly and attachment to other elements, can influence servo system performance. A number of functional tests, such as access seek timings, are typically performed prior to SA to ensure that an HDA is functional.

A mechanical transfer function analysis (TFA) is an effective test for mechanical integrity [27]. The availability of commercial fast Fourier transform equipment has made it practicable to TFA test all HDAs [28, 29] and this technique is currently used on 62PC and 3370 to measure servo system stability. Gain limits are defined as a function of frequency and stored in digital form. A failing HDA can be analyzed with the aid of a plot of frequency *versus* gain (Bode plot). Typical failure modes have distinct resonant frequencies.

- *Automated testing of integrated HDA and file electronics*

The 62PC incorporates its electronics and HDA as an integral package, as contrasted with the large systems files such as the 3370 and 3380 that package the electronics separate from the HDA and drive mechanics. This permits a higher level of functional testing at an earlier stage. To reduce 62PC labor hours and improve test quality, a number of automated program-controlled test functions were developed using programmable test equipment. Test cells were divided into two stations with approximately 140 tests being performed at the drive pretest station where 90 percent of electronics card and HDA failures are detected. Surface analysis is performed at the second station with one operator running up to six stations. The test stations are each controlled by a local dedicated processor with disk storage and are connected to a 370 host system for data collection.

Summary

The innovations described have facilitated the introduction of the advances in disk file technology that have achieved an increase of almost four orders of magnitude in areal density. Batch fabrication, mechanization, automation, and control of test criteria and yield levels have improved disk file cost/performance.

Magnetic head manufacturing techniques have progressed from labor-intensive laminated-head structures,

having manually installed head windings and separate air bearing components, to batch-fabricated air bearing/head structures using film technology.

Advances in areal density have been accomplished by enhancements in the flatness and surface finish of disk substrates, reduction in the flying height of air bearings, miniaturization of head parameters and tolerances, and improvements in the control of disk coating thickness, particle size, and dispersion. Disk flatness, dynamics stability, coating surface, finish, and cleanliness are tested by both electrical and optical methods. The newest test tool, "OPSCAN," has adapted elements of the IBM 3800 non-impact printer and computer data analysis to provide automated surface quality evaluation.

Advancement of areal density has also encouraged the development of new recording system component-integration techniques. These techniques aid in characterizing the data error contribution of component tolerances and file TMR while facilitating the specification of component and completed disk pack and HDA test criteria.

Mechanization of disk handling has minimized handling damage and contamination while enhancing the efficiency of automated disk processing and testing tools.

Defect characteristics of particulate disks required more sensitive testing techniques as bit cells decreased in size and file system signal-to-noise ratios diminished.

Integration of heads and disks into an HDA configuration has eliminated a number of head-to-track misalignment tolerances and has also simplified product contamination control. The permanent relationship of heads and disks in the HDA has enhanced data integrity following surface analysis.

Automation of single-disk testing, HDA functional testing, and surface analysis have necessitated the use of computer programming techniques. This automation approach has provided flexibility in modifying test criteria and efficiency in data collection, analysis, and report preparation.

Acknowledgments

Twenty-five years of disk file manufacturing have been reviewed in this paper. The selected innovations described are only representative of the creative endeavors of many individuals. We would like to acknowledge, at least in part, the generous and patient assistance extended by a number of our associates during the preparation of this paper.

E. R. Solyst prepared the preliminary text and drawings describing the batch fabrication of the 2305 and 3340 magnetic heads. M. W. Warner was helpful in describing the evolution of the 3340 head. L. G. Taft, A. W. Ward, and I. C. McIntosh were most helpful in reviewing their work and the contributions of others in developing improved disk substrate and coating processes. D. S. Cheng, R. L. Costabile, and G. G. Maddams provided useful information on magnetic disk testing, and B. Blythin aided with insights on disk defect characteristics. D. F. Sturtz provided useful perspective on HDA manufacturability and disk test strategies. D. M. Jones, in numerous helpful discussions, provided a perspective on the development of surface analysis strategies and automated functional testing. L. J. Fortunati and J. S. Makiyama contributed perspectives on servowriting. R. P. McIntosh and A. Rusnak aided in describing the rationale for development of automated TFA testing, and L. D. Stevens was a patient and helpful historian, critic, and editor.

We would also like to acknowledge the suggestions and help of S. H. Smith, R. F. Ryon, J. E. Kettman, T. W. Peterson, D. W. Brede, and T. O. Montalbano for their assistance during early drafting of the paper.

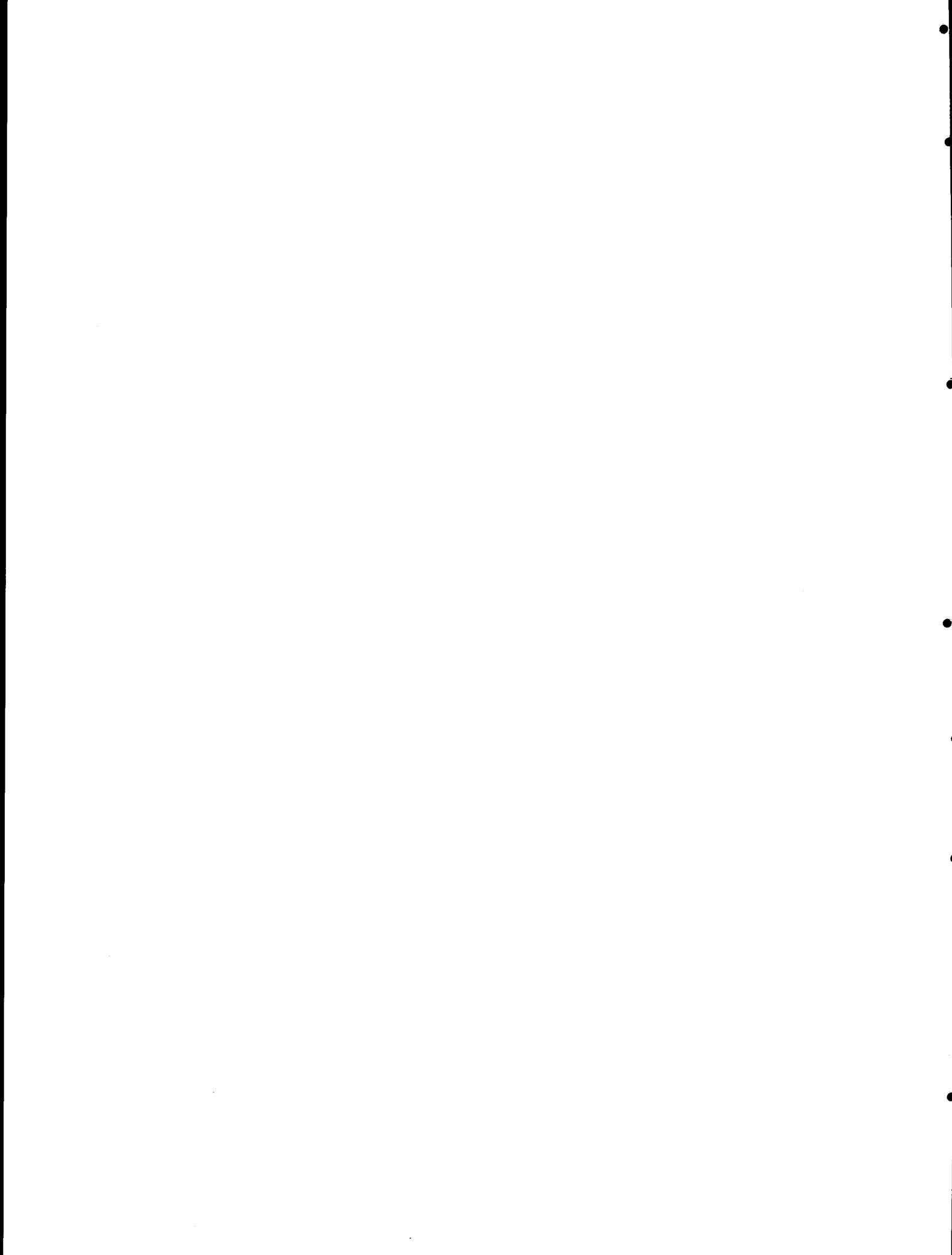
References

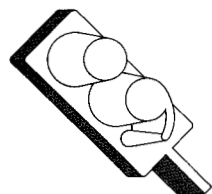
1. L. D. Stevens, "The Evolution of Magnetic Storage," *IBM J. Res. Develop.* **25**, 663-675 (1981, this issue).
2. J. M. Harker, D. W. Brede, R. E. Pattison, G. R. Santana, and L. G. Taft, "A Quarter Century of Disk File Innovation," *IBM J. Res. Develop.* **25**, 677-689 (1981, this issue).
3. E. R. Solyst, "Multichannel Recording Head," U.S. Patent 3,579,214, 1971.
4. A. F. Rude and M. J. Ward, "Laser Transducer Systems for High-Accuracy Machine Positioning," *Hewlett-Packard J.* **27**, 2-6 (1976).
5. R. B. Mulvany, "Engineering Design of a Disk Storage Facility with Data Modules," *IBM J. Res. Develop.* **18**, 489-505 (1974).
6. Ian M. Croll, "Design Philosophy of Film Magnetic Recording Heads," *Disk Storage Technology*, 10-11 (1980); Order No. GA26-1665-0, available through IBM branch offices.
7. David A. Thompson and Lubomir T. Romankiw, "Film Head Development," Ref. 6, *op. cit.*, pp. 3-5.
8. Robert E. Jones, Jr., "IBM 3370 Film Head Design and Fabrication," Ref. 6, *op. cit.*, pp. 6-9.
9. P. Frey, "Surfaçage Lisse des Métaux Légers au Moyen d'Outils Diamantes," *Aluminium Suisse* **10**, 287-289 (1960).
10. G. A. Mittl, "Diamonds as Turning Tools," *Cutting Tool Engineering* **15**, 22-25 (1963).
11. J. B. Bryan, R. R. Donaldson, E. R. McClure, H. A. Whelan, and R. W. Clouser, "Diamond Turning of Parabolic Mirrors," *Seminar Proceedings*, Society for Photo-Optical Instrumentation Engineers, San Diego, CA, August 27-29, 1973, p. 39.
12. J. M. Casstevens, "Development of a One-Microinch (250 Å) Spindle for Diamond Turning of Optics," *Seminar Proceedings*, Society for Photo-Optical Instrumentation Engineers, San Diego, CA, August 30-31, 1978.
13. H. E. Alvey, "Numerical Control in an AEC Installation," *Collected Papers Manufacturing Systems*, ASTM National Engineering Conference, Philadelphia, PA, April 29-May 3, 1968, Vol. 68, Book 2, Paper MS 68-165.

14. T. T. Saito, "Diamond Turning of Optics: The Past, The Present, and The Exciting Future," *Opt. Eng.* **17**, No. 6 (1978).
15. D. D. Johnson, R. Flores, and M. J. Vogel, "Composition of Epoxide Resin, Methylol Phenol Ether, Polyvinyl Methyl Ether, and Acid Anhydride Catalyst, and Metal Substrate Therewith, Especially a Magnetic Signal Storage Device," U.S. Patent 3,058,844, 1962.
16. T. C. Patton, *Paint Flow and Pigment Dispersion*, Wiley-Interscience Publishers, New York, 1966.
17. J. Vseller, "Clean Room Technology," *NASA SP-5074*, Office of Technology Utilization, National Aeronautics and Space Administration, Washington, DC, 1969.
18. Raymond C. Tseng and Gene O. Zierdt, "A Glide Test to Assure Disk Surface Quality," Ref. 6, *op. cit.*, pp. 16-18.
19. J. S. Heath, "Design of a Swinging Arm Actuator for a Disk File," *IBM J. Res. Develop.* **20**, 389-397 (1976).
20. Robert D. Commander and John R. Taylor, "Servo Design for an Eight-Inch Disk File," Ref. 6, *op. cit.*, pp. 90-98.
21. R. K. Oswald, "Design of a Disk File Head-Positioning Servo," *IBM J. Res. Develop.* **18**, 506-512 (1974).
22. P. Hodges, W. J. Shaeuble, and P. L. Shaffer, "Error Correcting System for Serial by Byte Data," U.S. Patent 4,185,269, 1980.
23. Paul L. Shaffer and John W. Hughes, "Design Considerations for Data Integrity in the IBM 3370," Ref. 6, *op. cit.*, pp. 36-37.
24. Charles C. Lin and Gottfried E. Mauersberger, "Component Integration Concepts for the IBM 3370," Ref. 6, *op. cit.*, pp. 19-21.
25. J. L. Su and M. L. Williams, "Noise in Disk Data-Recording Media," *IBM J. Res. Develop.* **18**, 570-575 (1974).
26. David L. Nelson, "The Format of Fixed-Block Architecture in the IBM 3370 DAS," Ref. 6, *op. cit.*, pp. 34-35.
27. O. I. Elgerd, *Control Systems Theory*, McGraw-Hill Book Co., Inc., New York, 1967.
28. J. W. Cooley and J. W. Tukey, "An Algorithm for the Machine Calculation of Complex Fourier Series," *Math. Comp.* **19**, 297-301 (1965).
29. L. R. Rabiner and B. Gold, *Theory and Appreciation of Digital Signal Processing*, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1975.

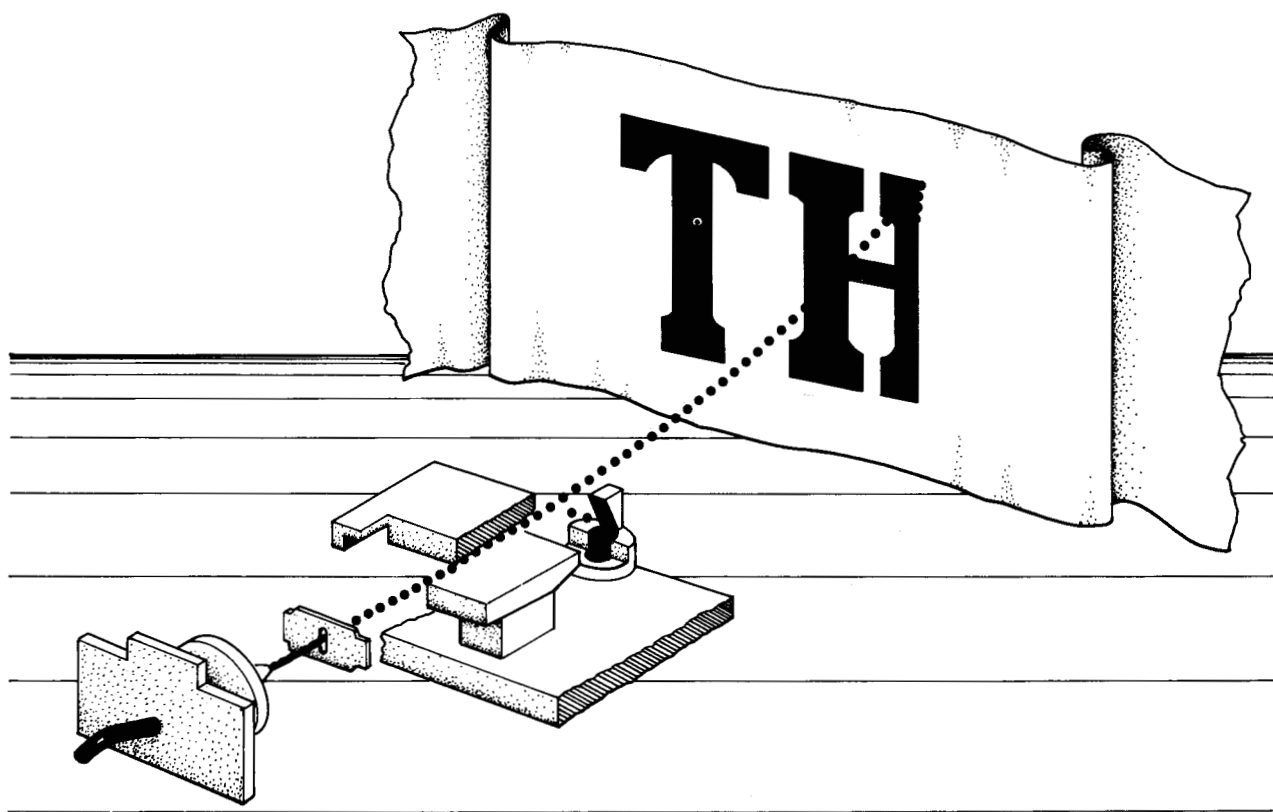
Received December 10, 1980; revised March 20, 1981

The authors are located at the IBM General Products Division headquarters, 5600 Cottle Road, San Jose, California 95193.





Printing Technology



Ink jet printing

The *Journal* acknowledges the contributions of J. L. Hibbard and H. B. Michaelson to the acquisition, review, and editing of the papers in this section.

Editor