Optical Tooling and Its Uses in Industrial Plants

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Development and principles of instruments and accessories designed and built around optical lines of sight and industrial applications of optical tooling.

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PART 1

Background

In view of the varied uses of optical tooling today, perhaps the name "optical tooling" is a misnomer. However, if we consider how optical tooling has been developed, the name is quite understandable. Although optical alignment certainly did not originate within our aircraft industry, it was here that the instruments, methods, and standardizations were developed to the point where optical tooling has become a separate concept in precision alignment. The original need and use of optical alignment in the aircraft industry, was for the erection of the large jigs or tools required for airframe construction. Today these tools are designed and built around optical lines of sight - - - - hence the name optical tooling.

History

We know of instances where optics have been used as much as 35 to 40 years ago in this country to align machine tools. Both the Germans and the British are credited with using optics to check the alignment of the jigs used for airframe construction during World War II. In addition, we know that the British used optics to align the main shaft bearings on the ships built during the same period. However, it is our own Air Force that is responsible for the development of optical tooling as we know it today. Immediately following World War II, the United States Air Force sponsored a development program by the airframe manufacturers for the use of optics in airframe tooling. As a result of this program, there is not a single major aircraft manufacturer today who does not use the method.

GENERAL INDUSTRIAL APPLICATIONS

Although the alignment problems found in other industries may seem to differ completely from those of the airframe manufacturers, the vast majority of these problems, both in and out of the aircraft industry can be reduced to finding the answers to these four fundamental questions:

1 Is it straight?
2 Is it flat?
3 Is it plumb?
4 Is it square?

Actually it doen't matter whether it is a do-it-yourself project at home, the installation and maintenance of equipment in your plant, or quality control and assembly of manufactured units; these four questions must be answered. Obviously, the answers need not always be to the same degree of accuracy, and in optical tooling we are primarily concerned with alignments involving tolerances that are measured in thousandths of an inch and seconds of arc.

Twenty years ago such alignment was not considered critical in many fields; but today the trend is towards larger and faster machines. Because of their size and speed these new machines require more accurate alignment. Perhaps of even greater importance is the fact that many of the machines placed in operation some years back are being operated today at a rate substantially in excess of the original designed capacity. This usually multiplies maintenance problems, and any technique or tool that will improve operation and reduce downtime is a valuable asset to the maintenance engineer. Better alignment through the use of optics is such a tool.

However, greater accuracy is not the only advantage of optical tooling. Occasionally, optical tooling is purchased because there is no satisfactory alternative method available, but usually it is bought simply because the customer is convinced that optical tooling will save him money. Part of the savings may be a

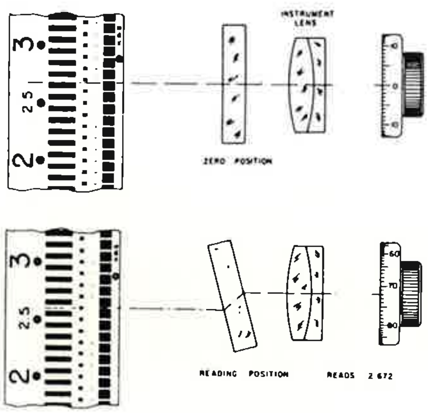

Fig.1 Optical micrometer.

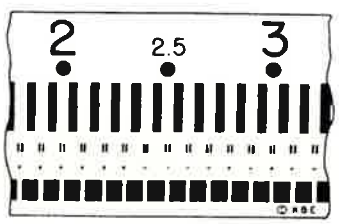

Fig.2 Portion of an optical tooling scale showing paired line pattern.

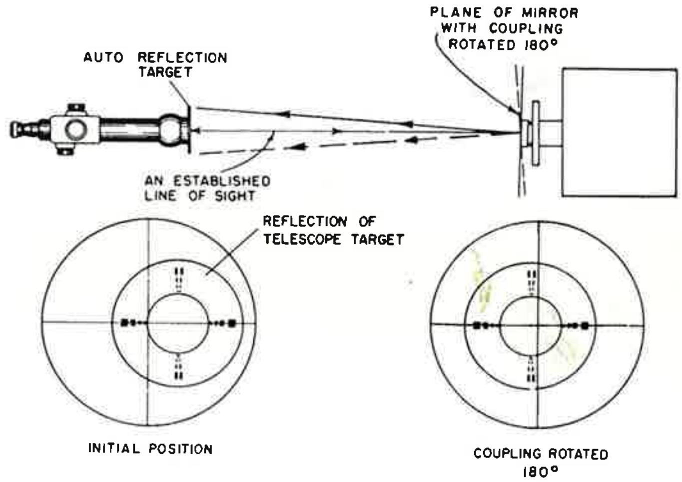

Fig.3 Auto-reflection.

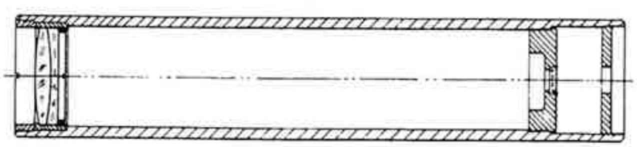

Fig.4 Alignment collimator.

result of the better alignment, but a substantial amount is often due to a reduction in manhours required to accomplish the alignment. In other words, a need for greater accuracy is not the only reason for using optical tooling.

Definitions

Optical micrometer is a device containing an optical flat, calibrated to measure displacement from the line of sight of a telescope. With the optical flat perpendicular to the line of sight, the displacement and the micrometer reading is zero. When the optical flat is rotated, the line of sight is moved parallel to but offset from its original position. The amount of this displacement is indicated on a micrometer drum reading directly in 0.001 in. This is illustrated in Fig. 1.

Paired-line targets and scales. It has been proven that greater pointing accuracy can be achieved with a telescope if the crosshair of the telescope is placed midway between a pair of parallel lines on the target rather than attempting to superimpose the crosshair over a single line on the target. For this reason, optical tooling scales and targets usually incorporate the paired-line principle, as shown in Fig. 2.

Auto-reflection is the process of sighting through a telescope at a mirror and viewing the reflected image of a target placed at the objective end of the telescope. Auto-reflection is accomplished when the center of the image of the target coincides with the center of the crosshairs. This can only occur if the mirror is perpendicular to the line of sight of the telescope so that the line of sight is reflected directly back on itself. Therefore, auto-reflection implies perpendicularity between a mirrored surface and the line of sight of a telescope. Fig. 3 illustrates the principle of auto-reflection.

Alignment collimator is a device that can be made to coincide with an optical line of sight in direction and position to a very high degree of accuracy. Essentially, the collimator is a fixed infinity-focused telescope without an eyepiece. As indicated in Fig. 4, a reticule or tilt target is located at the principle focus of the lens. Since the collimator is focused

Fig.5 Alignment telescope.

Fig.6 Sight level with optical micrometer.

at infinity, the light rays emerging from the collimator are parallel to each other. Therefore, any telscope sighted at the collimator must be focused at infinity in order to view the tilt target in the collimator. Any apparent displacement between the crosshairs of the viewing telescope and the reticule in the collimator is an indication of angular deviation rather than lateral displacement. The collimator also has a displacement target on the objective lens. Therefore, if a telescope is aligned to both the front or displacement target and the back or tilt target of a collimator, it means that the optical axis of the two instruments are collinear. If the telescope is aligned to the tilt target only, it means the optical axes are parallel only.

Collimate:

1 To make light rays parallel.

2 To position an optical instrument so that its optical axis is parallel to the optical axis of another instrument. This is done by focusing both instruments on infinity, placing a light source behind one instrument and sighting through the second instrument into the objective of the first. Collimation is accomplished when the reticules of the two instruments are aligned.

Auto-collimation. The process of sighting through a telescope at a mirror and viewing the reflected image of the telescope crosshairs. Auto-collimation is accomplished when the reflected image coincides with the real crosshairs. This is accomplished by focusing the telscope on infinity, and placing a light source behind the crosshairs to project their image out to the mirror and back. As in auto-reflection, the mirror must be perpendicular to the line of sight of the telescope in order to have the reflected image coincide with the crosshairs.

PRINCIPLES OF OPTICAL TOOLING

Is it straight?

To determine straightness, the line of sight of a telescope is used as a reference line instead of the familiar tight wire. Because the line of sight is intangible many of the problems inherent with the tight wire are eliminated. The optical reference line cannot sag, vibrate, bend, or kink. Equipment can be moved in or out of the area without disturbing the reference lines, and there is no safety hazard due to wires stretched above the floor. Perhaps the greatest improvement, however, is the fact that measurements can be made directly to the center of the reference line without the danger of disturbing the line during the act of measuring.

The instrument used to establish this single, fixed line of sight is the alignment telscope illustrated in Fig. 5. The telescope has two built-in optical micrometers which enable the operator to measure offsets along both an X and a Y-axis directly to 0.001 in. A built-in auto-reflection target on the objective lens, and an auto-collimating eyepiece and illuminating unit are also available. The barrel of the telescope has been ground to a true cylinderical shape within close tolerances, and the optical center has been located so that it coincides with the physical center of the telescope barrel as determined by the outside diameter. With this arrangement, the telescope can be removed from a V-block-type bracket, and returned at some future time with assurance that the original line of sight will be reestablished. In addition, the telescope can be rotated about its center providing an important self-checking feature which is inherent in almost all optical-tooling instruments.

Is It Flat?

For leveling operations, instead of determining flatness with a shop level and a

Fig.7 Jig transit.

Fig.8 Optical square mounted on an alignment telescope.

straight edge, a sight level similar in principle to the surveyor's level is used. However, in this case, by virtue of an optical micrometer and special paired-line optical-tooling scales, it is possible to measure offsets accurately from the horizontal reference plane established by the instrument to 0.001 in.

A tilting level such as the one shown in Fig. 6 is used. This level tilts or pivots directly over the vertical axle of the instrument, thus eliminating any change in the height of the line of sight when adjusting for level from one sighting to the next. Because of the coincidence reading level vial, the instrument has a leveling accuracy of 1 sec of arc. Thus this instrument makes it practicable to level a large machine bed, for example, to within a few thousandths of an inch.

Is It Plumb?

Instead of using a plumb bob to establish a single vertical reference line, a jig transit is used to erect a vertical reference plane. Parallelism between this reference plane and any other surface can then be determined by measuring offsets between the two planes. Again, the use of an optical micrometer and paired-line scales enables these measurements to be made directly to 0.001 in.

The jig transit differs considerably from the surveyor's transit. Aside from the heavier, sturdier construction, perhaps the most striking changes are the elimination of the compass and the vertical and horizontal circles. The jig transit illustrated in Fig. 7 is provided with an optical micrometer. A coincidence reading level vial, an auto-collimating eyepiece, and axle mirrors are also available. The axle mirrors are mounted on the ends of the horizontal axle of the transit and are adjusted so that the surface of the mirror is parallel to the line of sight of the transit telescope. Using auto-reflection or auto-collimation, one of the mirrors can be made perpendicular to the line of sight of another instrument. Thus a 90 -deg angle can be erected between the line of sight of the other instrument and the line of sight of the transit. However, the basic function of the jig transit is establishing a plumb reference plane.

Is It Square?

To establish squareness, we have a choice of two methods. If it is a matter of setting a surface with a relatively small area at right angles to a line of sight, it can be done by mounting a mirror on that surface so that the mirror is parallel to the surface in question. Then by either auto-relection or auto-collimation the mirror and the surface can be set at right angles to the line of sight. This of course establishes perpendicularity only at the point where the line of sight intersects the plane of the mirrored surface.

To establish a large surface perpendicular to a line of sight, or to set up any right angle with relatively long legs; it is best to use an optical square in conjunction with an alignment telescope. The optical square fits over the objective end of an alignment telescope as shown in Fig. 8, and has two objective windows. One provides a straight-through line of sight along the base line, and the other window provides a line of sight at right angles to this base line. The vertex of the 90 -deg angle thus established is centered in relation to the spherical section of the housing. This means that the telescope and optical square together can be rotated about the base line of sight to establish a plane which is perpendicular to the base line. The optical micrometers on the telescope are accurate when used in conjunction with the optical square in both the straight-through and the right-angle lines of sight.

TYPICAL APPLICATIONS

The second part of this paper will describe some actual optical-tooling applications in detail. Therefore, a few typical uses of optical tooling outside of the airframe industry will be mentioned briefly merely to point out the widely varied industries in which optical tooling has been used.

In the shipbuilding industry, optical tooling is being used to align shaft bearings, establish witness lines for boring operations, and controlling the shipboard machining of steam catapults. During the installation of large paper machines, the sole plates are leveled and the crosslines for the erection of columns are laid out on the sole plates using optical tooling. Because of the leveling accuracy obtained, the top surface of the sole plates and the bottom surface of the columns are machined at the factory. No shims or other adjustments are required in the field. A similar method is used to check and realign cylinders on any type of machinery requiring a series of cylinders all to be mutually perpendicular to the longitudinal center line of the machine.

Manufacturers of machine tools are using optical tooling to align machines during manufacturing as well as during final erection in the customers shops. In addition, many shops are using optical tooling for periodic maintenance checks on their machine tools and for gaging completed products. The electronics industry uses optical tooling to set up accurate test fields in order to align the mechanical axis to the electronic axis of radar units.

These are just a few of today's applications. Actually, with a firm understanding of the principals of optical-alignment procedures, the engineer today can save his firm considerable sums of money through faster and more accurate alignment with optical tooling.

PART 2

Mr. Hanold has discussed the development and principles of the optical instruments and accessories used in optical alignment. This portion of the paper will cover some actual applications of optical tooling.

When applying optical methods, or perhaps a better term would be "precise methods," to an alignment job we find that it sometimes uncovers other problems. Actually these problems are not new but have always been with us. However, since optical tooling can provide precise accuracies over extended distances (within $\pm$0.001 in. in 50 ft) we begin to find alignment inaccuracies, due to tolerance build-up or machining, in our component parts. Many times these inaccuracies can be traced to misalignment of the machine that produced the component part. Thus, there are several types of precise alignment problems:

1 Alignment of operating equipment including the installation alignment of turbines, paper machines, cellophane casting machines, and the like.

2 Dimensional inspection of large component parts.

3 Alignment of machine tools (alignment of machines to produce component parts).

The first case history describes the alignment of operating equipment.

CELLOPHANE CASTING MACHINE

Fig. 9 is a photograph of a cellophane casting machine. Cellophane is made by extruding ripened viscose through a narrow slit into a bath of sulfuric acid and sodium sulfate. This forms a sheet which is passed by rolls through several baths to wash, harden, bleach, plasticize and dry it. To perform this continuous operation, a machine of considerable length (approximately 200 ft) consisting of many rolls, a multiplicity of drives, gear reducers, and so on) is necessary. Over the extended distances indicated, it has been proven highly desirable to use optical methods to provide the most accurate alignment possible

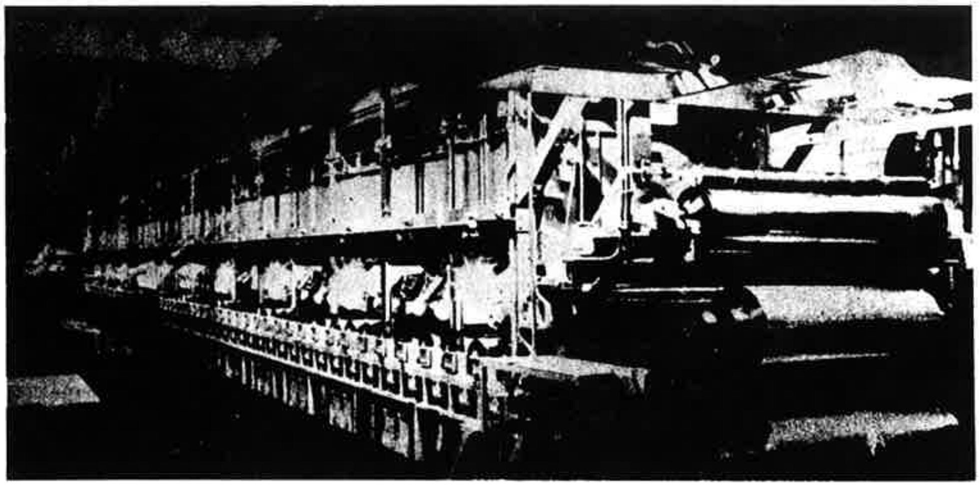

Fig.9 Cellophane casting machine.

for such facilities. The film-handling characteristics are vastly improved; bearing, coupling and gear failures are reduced and present mechanical limitations of speed increases have been eliminated.

Fig. 10 illustrates the optical system used on a casting machine. Several optical sight lines are established, as shown, in order to align the various component parts. The center sight line is used for two purposes; (a) to locate the frames in position, and (b) to align the roll drive shaft. When setting frames, a collimator is held parallel to and at a known distance from the machined surfaces of the frame by a facility gage. Using the collimation method described previously, the frames are set for line, elevation and parallelism with respect to the sight line. Cross level is checked with a precision machinist's level. When aligning the roll drive shaft, a mirror target is held in the bearing housing by means of a facility gage. Using the auto reflection method, also described previously, each individual bearing housing is set for line, elevation and squareness with respect to the sight line.

The upper sight line is used to locate the rolls of the casting machine. A saddle-type facility gage holds a collimator perpendicular to and at a known distance above the axis of the roll. Again by the collimation method the rolls are set for line, elevation, and perpendicularity with respect to the sight line.

The lower sight line shown is used to align the main drive shaft. The bearing housings are located in the same manner as the bearing housings of the roll drive shaft. This sight line also is used to position the transfer-gear boxes, motors and so on. This is done by placing an adjustable spindle mirror target on the end of the input shaft. By rotating the shaft and observing the mirror target through the jig-alignment scope, the mirror target is adjusted so that it is on center and perpendicular to the axis of the shaft.

To provide the original base sight lines along the machine and to be able quickly to reestablish these lines for maintenance purpose, it is most convenient to use jig plates to locate the telescope and target. Fig. 12 illustrates one of these jig plates. It consists of a vertical, welded, tubular frame enclosing a plate in which accurately located holes are bored to support either a telescope or target. By means of hardened locating pins and bushings and permanent base plates in the concrete floor, the jig plates can be quickly and accurately repositioned, thus restoring the original sight lines. Three jig plates are used for a casting machine - one at each end and one in the center. Although the jig plates are approximately 100 ft apart, the telescope and target positions may be interchanged thus reducing the sighting distance to any part being positioned to a maximum of 50 ft. Using the optical system, parts are easily held to within $\pm$0.002 in. for line and elevation and to within $\pm$10 sec of square (within 100 ft).

Incidentally, it is often desirable to offset sight lines from true center lines so that alignment checks can be made at any time without dismantling the machine. Naturally, the offset base line requires the use of a facility gage, (Fig. 12, to provide the reference between the sight line and the part to be located. Although this requires additional

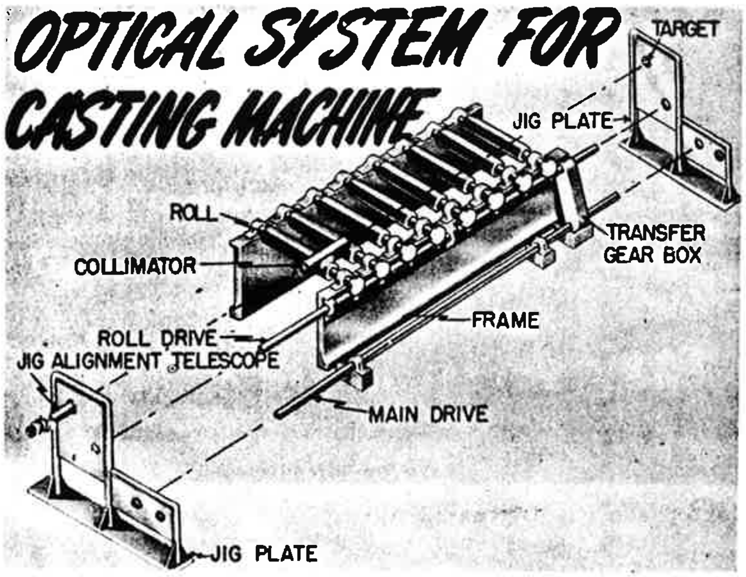

Fig.10.

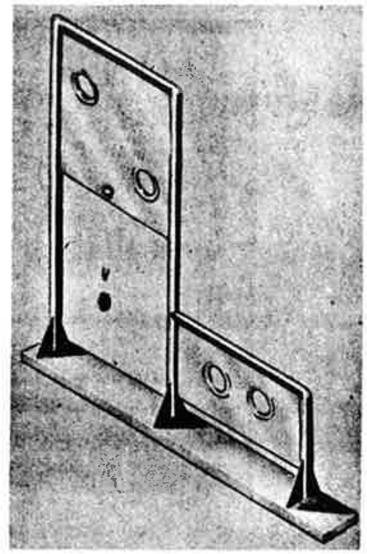

Fig.11 Jig plate.

tooling, the advantage of being able to make a maintenance alignment check in a very short period of time usually justifies the additional expenditure.

Previous alignment methods involving piano wires and straight edges were of insufficient accuracy at the extended length (200 ft) of a casting machine. This necessitated the use of auxiliary means during operation to correct the path of the film through the machine. These were eliminated after optical alignment.

After a short period of training and supervised use, maintenance mechanics have accepted the new alignment method and proven quite proficient in its use. However, the development of the alignment procedure and the design of the facility gages are best handled by engineers with experience in tool design and optical alignment. One thing that optical alignment methods have brought to light, as a result of direct readings and the accuracy with which readings can be repeated, is the necessity for careful shimming and cleanliness on the part of the mechanic. The use of dirty and bent shims increases the number of settings required to obtain alignment. This in turn greatly increases the time required.

COMPONENT PARTS

The next case history is concerned with a component part in fabrication. Fig. 13 illustrates the use of an optical method for dimensional inspection. The drum shown is of fabricated steel 5 ft diam and 12 ft long. Drums of this size are not unusual; however, the close tolerances specified for this drum are unusual. The rotating surface of this drum had to be held within a variation of ±0.001 in.

Because of the required accuracy, optical tooling, rather than the widely used indicating drum gage, was chosen to inspect this drum. To make this optical check, a sight line was located a known distance from the theoretical drum surface, parallel to and at the same elevation as the axis of rotation. To do this the drum was placed in V-blocks on the bearing surface of its trunions. In this case a pit lathe was used which provided a rigid setup and power to turn the drum. As illustrated, the scope and target used to establish the sight line, were equipped with spherical adapters, which were in turn mounted in spherical cups located on steel stands. A precision tilting level was used to located the elevation of the sight line in relation to the axis of the drum. "Wyteface" scales were used to locate the sight line parallel to and at a known distance from the axis of the drum. A facility gage, with a magnetic base, holding an alignment target 6.0000 in. (±0.0001 in.) from the surface of the drum, was used to measure the variation of this surface from the sight line.

Readings were taken at 8 points around the drum and at 1-ft intervals along the drum. The location of these points was not critical. Fig. 14 shows a graph of the maximum and minimum radii of the drum shown in Fig. 13. All other radii

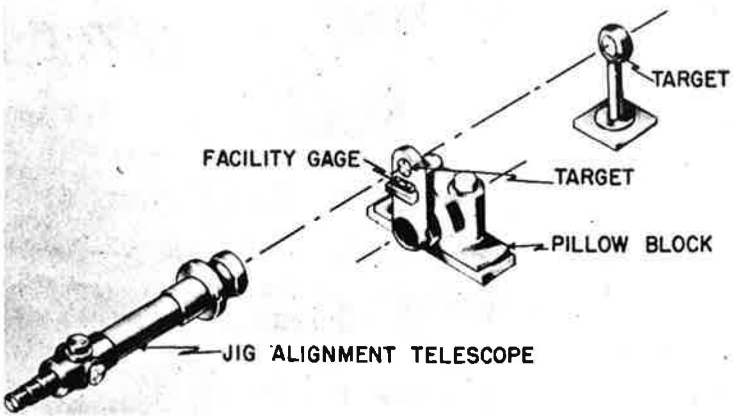

Fig.12 Facility gage.

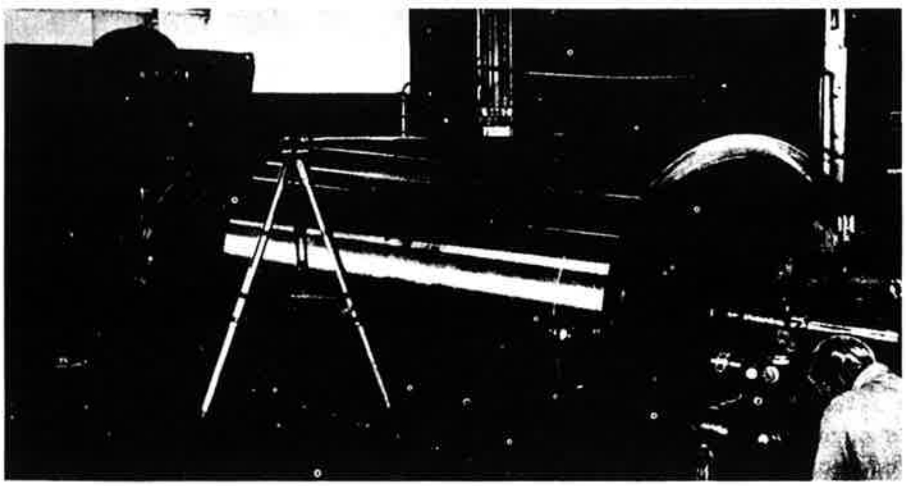

Fig.13 Drum inspection.

fall between these two limits. From these readings the suitability of the drums can be determined.

The requirements of the drum are such that the variations of the radius must remain within a band 0.002 in. wide as the drum rotates. However, the effect of taper can be eliminated by adjusting the position of one drum relative to its companion drum. To determine the width of this band for the drum being inspected, the graph showing the maximum and minimum radii is used. Parallel dotted lines indicating the width of this band were varied experimentally until the amount of taper was at a maximum and thus the band width a minimum. The band width is the net effect of deviations of surface straightness, ovality of the drum and off-center rotation. As indicated by the dotted lines in Fig. 14, the maximum taper was 0.0015 in. resulting in a band width of 0.0045 in. or 0.0025 in. over the required tolerance.

Individual dimensions also can be determined from these readings:

(a) Total run out (combined off-center rotation and out of roundness). At any given point along the drum, the difference between the vertical intercepts of the maximum and minimum curves is the total run out. Maximum in this case was 0.003 in. 60 in. from the drive end.

(b) Surface Straightness and Taper. The difference between the maximum and minimum reading along a curve indicates a combination of two deviations; namely, the variation of the curve from a straight line and the taper along the drum. These can be separated as shown in Fig. 14.

(c) Drum Diameter. Since the optical line is positioned at a known distance from the center

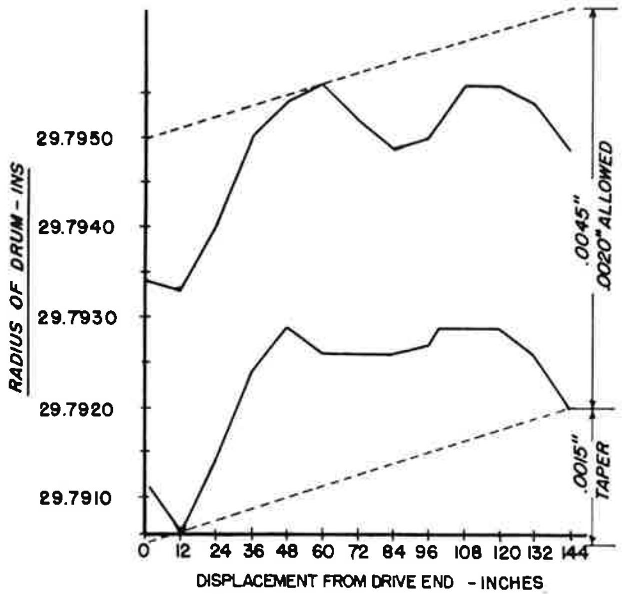

Fig.14 Drum inspection results.

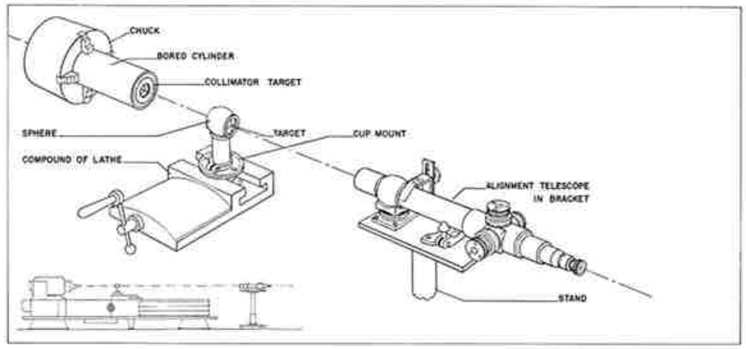

Fig.15.

of rotation of the drum and the offset of the target from the drum known, opposite radii can be added to determine the diameter.

ALIGNMENT OF MACHINE TOOLS

The accuracy of component parts is controlled by the alignment of the machine tool producing them. Thus, it is often necessary to check and align machine tools on which these close-tolerance parts are to be produced.

Fig. 15 illustrates the method used to align a lathe. The method involves two parts:

1 Leveling of the bed.

2 Aligning the bed true to the axis of rotation of the spindle.

Part 1 involves the use of a precision tilting level to locate both ways of the bed at the same elevation. Part 2 involves the use of a collimator, target, and jig-alignment telescope to align the spindle to the bed. The telescope, mounted on an adjustable stahd located at the tailstock end of the lathe, is bucked into a collimator fitted into a prebored cylinder held in the lathe chuck. (The term "bucked" means moving the scope sight line into the same elevation, line, and parallel to the collimator sight line.) A target mounted on the tool post, adjusted to the optical line at a position near the chuck, is read at frequent intervals as the carriage is moved along the bed.

Fig. 16 shows a set of before-and-after readings so obtained. The readings indicate the misalignment between the axis of rotation of the spindle and the bed. Misalignment, in the vertical plane of 0.060 in. maximum is corrected by adjusting the end jacks under the head and misalignment in the horizontal plane of 0.0243 in. maximum by raising the jacks under the back way.

As can be seen, the vertical misalignment was corrected to within 0.0053 in. at the tailstock end. The horizontal alignment was corrected to within 0.0005 in. For our purposes, the vertical alignment was of much less importance than the horizontal alignment.

The optical method has two distinct advantages over older conventional methods; greater accuracy and reduced alignment time. Also, the optical method is the only known procedure that can be used to align the spindle accurately for the full length of the bed.

SUMMARY

The application of optical tools to the alignment of production equipment has many benefits. Among these are better alignment, reduced alignment costs, improved operating performance, and reduced maintenance. However, increased benefits can be obtained by designing equipment to receive optical tools. Not only is the original installation of the equipment more accurate and faster but the alignment may be checked for maintenance without long shutdowns. For instance, a special hydraulic press recently fitted with optical facilities

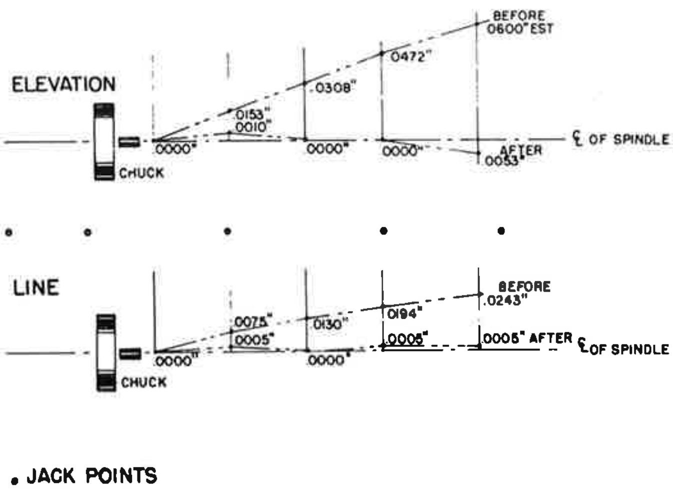

Fig.16 Lathe alignment results.

can be completely checked for alignment in 20 min without removing a single part. Periodic checking and realignment are extremely important for after only a short period of experience with optical tools it is possible to discover the inevitable movement of concrete and steel.

There are also cases where intentional misalignment is desirable. Machines included in this group are, steam turbines, centrifugal compressors, and extrusion presses where elevated temperatures and/or pressures are present. That is to say, the machine is purposely misaligned when cold from known recorded data so that it is in alignment when operating.

One more desirable feature in the design of equipment is the inclusion of leveling and adjusting devices through which alignment may be obtained readily and precisely. Incidentally, on lighter equipment destined to be optically aligned it is unnecessary to provide bed plates. Equipment can be located on studs held in concrete and grouted in. Thus, the cost of fabricating and locating base plates can be eliminated.

Each alignment job requires not only optical instruments but facility gages peculiar to the machine. These facility gages are not inexpensive since they are as indicated - gages having close tolerances. As experience in alignment work continues to expand, the need for additional instruments such as one for the squaring of rolls will be developed to decrease the cost of facility gages.

From the cases cited, it is evident that optical tooling is at present playing an important role in the alignment of existing and new production equipment within the du Pont Company. Beyond its first use in this country by the aircraft industry, only a fraction of the potential of optical alignment has been utilized. The future of optical alignment is limited only by the imagination of the engineers who plan its application. A hint of this future may be visible in the European standard machine tools now available with built-in optical measuring devices. It is quite possible that future equipment will be available from the vendor complete with facilities for optical alignment. Thus, the purchaser of such equipment will benefit through the reduced cost of installation and subsequent maintenance and better operating performance.