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A study in technical improvements in the production of centrifugal pump shafts.

Edward H. Fry

A STUDY IN
TECHNICAL IMPROVEMENTS
IN THE PRODUCTION OF
CENTRIFUGAL PUMP SHAFTS

BY
EDWARD H. FRY

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Date

Mikell P. Groover
Professor In Charge

G.E. Kane
Chairman Of Department

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ABSTRACT

This thesis describes experimental work to improve the quality of centrifugal pump shafts. It was conducted in the modern machine shop of a leading manufacturer of centrifugal pumps.

The experimental work was performed on machine tools that are productive links in the daily output of the end product. It was essential that the productivity of the machines not be seriously impaired while changes were being made to tooling, programming, measuring, and substituting various other experimental factors.

Shafts, because they are simple, cylindrical figures, and because they have been used by people for hundreds of years, are not generally considered to be too difficult to manufacture. However, when shafts become quite long and thin, or when they must be made of corrosion resistant materials, very elusive problems creep in. This study was aimed at isolating and eliminating those problems.

The shop work was made the more interesting because it dealt with actual shop difficulties rather than with purely textbook problems. Also, the psychology of intermeshing the thoughts of shop people and industrial engineers was quite important. By the process of elimination, it was possible to pinpoint definite variables that required modification or elimination.

The study was divided into three broad categories:-

1. The mechanical aspects of shafts, such as machinability, concentricity and manufacturing processes.
2. The metallurgical aspects, such as corrosion resistance.

3. The cost aspects, because of their impact on the selling price of highly competitive pumps.

The study was limited to shafts of single stage, overhung design pumps commonly known as "Refinery Pumps". They are fully described by The American Petroleum Institute [1] and by The Hydraulic Institute [2]. The work was prompted by shaft problems relating to their straightness and to vibrations in the pumps. The API 610 [3] specifications serve as a guide in determining the allowable vibration in this class of pumps.

Several important items came to light during the work:

1. The physical properties of the shaft material, such as tensile strength and hardness are important factors in maintaining straightness.
2. Hardness and chemical constituents of the material must be controlled to insure machinability.
3. The machine tools must be in good working condition; especially important is the concentricity of centers.
4. The use of steadyrests on lathes can do more harm than good if not properly applied.
5. Certain cutting tools work better than others. The tool must be made of the proper materials and ground to the proper geometry to insure maximum metal removal per cutter per unit of time.
6. Shaft material must be selected that is consistent with good machining practice, free machining, remain straight and be

resistant to the corrosive effects of pumped liquids. Thirteen percent chromium stainless steel, in accordance with specification AISI 416, properly heat treated, meets this requirement.

INTRODUCTION AND OBJECTIVES

Purpose Of The Study

The purpose of the study was to improve the performance and reliability of shafts and to reduce their cost.

Importance Of The Study

Modern high speed centrifugal pumps require shafts that have good design, proper metallurgy and straightness. The shafts must also be corrosion resistant and suffciently strong to transmit the power of the driver. The straightness is required to keep the vibration of the operating pump within permissible limits. The API 610 specifications indicate the allowable vibration levels for various types of pumps at different speeds. These values are a criterion on tests in the Hydraulics Laboratory. This study was prompted by difficulties in manufacturing that caused inconsistencies in pump shaft straightness.

Scope Of The Study

The study was limited to shafts of pumps that were of single stage design with cantilevered shaft and bearings. The study concentrated on the turning operations because that is where the eccentricities were believed to be initiated. The terms "unstraight", "eccentric", and "bent" are used synonymously, and simply connote a condition that renders a shaft unfit for service until rectified. A shaft can be bent in a very short length, and is then classified as "kinked". This type of bend is often not correctable and the shaft must be discarded. A long, uniform bow is also a "bent" condition, but usually the shaft can be corrected by utilizing acceptable straightening procedures, such as given in appendix A. Shafts of different materials respond differently to the various straightening methods. Several materials were subjected to experimental as well as production machining.

No attempt was made to study the performance of cutter inserts, except as it pertained to the shaft straightness problem. Many shop tests have been conducted and recorded on carbide tooling, and these records were utilized for guidance in tool selection. The geometry and composition of the tool inserts were changed to observe the differences in cutting and the changes, if any, in the straightness and finish of the machined shafts. One supplier [4] furnished very helpful information on cutting tool inserts, and provided inserts for experimental machining.

Centrifugal pumps are made in an almost limitless combination of:-

1. Sizes--depending upon the amount of liquid to be pumped, such as large volumes for irrigation work and small volumes for feeding steam generators.
2. Pressures--quite low for irrigation and very high for boiler feed or hydraulic service.
3. Materials--iron and bronze for plain water service and stainless steels for pumping corrosive liquids.

4. Designs--

   A. Single stage for low pressure.

   B. Multiple stage for high pressure.

   C. Ball bearings for low speed and light loads.

   D. Sleeve bearings for high speeds and heavy loads.

   E. Rubber bearings for internal water lubrication.

It is apparent that an unlimited number of pump applications leads to an equally large diversification in the design of pumps and their shafts. In order to attack only one phase of pump shaft problems, it was decided to concentrate on a specific line of pumps that are commonly called "Refinery Pumps". Throughout the pump industry, this class of pumps embraces designs that are very similar in design, size and shape. Field reports indicate that manufacturers experience difficulty in making shafts that are satisfactorily straight. The types of shafts under study are usually not more than three feet long, nor more than four inches in diameter.

Previous Studies On Shafts

Owing to their important function, pump shafts have been the object of methods for improving their manufacture. There is very little published information on shafts aside from that which relates to their use in rotating machinery. That information generally concerns the dynamic aspects of unbalance, critical speed, resonance and similar subjects. Methods of improving shafts by changing the material and by using various manufacturing processes have been tried for years, but very little of the work has been documented. This study essentially starts with a "clean sheet of paper".

Importance Of Shaft Straightness

The application of pumps in volatile industries, such as in oil refineries and chemical plants as well as in nuclear power plants has resulted in a substantial upgrading of quality control requirements. Also, the American Petroleum Institute and the Hydraulic Institute specify the allowable vibration permitted on pumps operated at various speeds. Aside from the danger involved in operating vibrating pumps, they cannot be shipped and the revenue is not collectable unless the equipment conforms to the specifications. Additional problems are the costs and delays incurred when in-process straightening of shafts is necessitated. This problem is compounded when an unstraight shaft does not respond to corrective measures and must be discarded.

Straightness is of primary concern in centrifugal pumps that operate at high rotational speeds and have internal liquid sealing clearing of only a few thousandths of an inch. An unstraight shaft can result in:

1. Excessive pump vibration.
2. Seizure of the internal metallic components.
3. Improper coupling alignment between pump and driver.
4. Cyclic bending fatigue and shaft failures.

BACKGROUND INFORMATION

Historical Development Of Centrifugal Pumps

The origin of centrifugal pumps is lost in antiquity, however, they were among the earliest of man's aids, and they were used in ancient Egypt, China, India, Greece and Rome to provide water [5]. This class of machinery did not attain great popularity until the advent of steam turbines and electric motors late in the nineteenth century.

The wide acceptance of pumps diverted them into almost unlimited applications in power plants, paper mills, water supplies, marine and irrigation, to name a few. Originally, pumps were constructed of "garden variety" materials, such as cast iron and bronze, with mild steel shafts. Some of these materials are still used today when low speeds of operation in non-corrosive liquids permit their usage. The present utilization of high speed prime movers to drive pumps at speeds well above 3600 revolutions per minute, dictate that the rotating members of pumps be well manufactured of suitable materials. Extremely well balanced rotors built on very straight shafts are necessary for good mechanical performance. In addition, the shaft and other components that are in contact with the liquid being pumped, must be made of materials that will resist the corrosive effects of the liquid. Figure 1 shows the assembly of a single stage, single suction, overhung type of centrifugal pump, usually intended for service in oil refineries, but also extensively used in a multitude

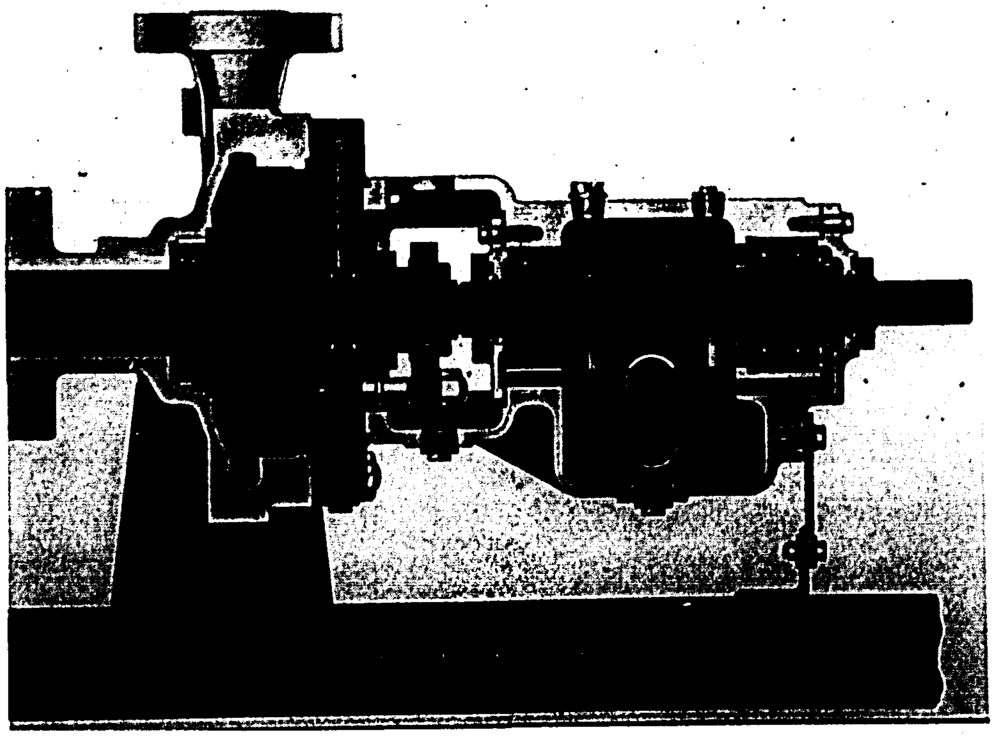

FIGURE 1 ASSEMBLY VIEW OF SINGLE STAGE, SINGLE SUCTION, OVERHUNG, CENTRIFUGAL PUMP.

of other services where hydraulic conditions are suitable.

Uses Of Centrifugal Pumps

The class of pumps being considered are most commonly used in oil refineries, however, they are also extensively used for pumping condensate and other liquids in power plants, and for pumping acids in process industries. These pumps are only one in a large family of similar pumps that employ shafts of very similar size and shape. These pumps are very much in demand and very competitively priced, as evidenced by the forty-five companies that report monthly sales of this equipment to the Hydraulic Institute.[6]

Materials Of Pump Construction

The materials of a pump must be compatible with the liquid to be handled. In addition, the shaft must remain straight when the pump is in service and subjected to the torque and temperature of operation. The shafts with which this study is concerned must therefore be satisfactory with respect to three properties:-

1. Strength
2. Straightness
3. Corrosion resistance.

Several carbon steel or low alloy steel bars will meet the first two criteria, but will not suffice where the shaft must operate in a corrosive environment. Corrosion aspects dictate the use of stainless steel shafting, such as ASTM 300 or 400 series stainless steels. The 300 series stainless steels are more expensive than the 400 series because of the eight percent nickel in the 300, but not in the 400 series. Economics therefore entersthe picture, and the less expensive materials will generally be used provided they are obtainable, readily machinable and produce a satisfactory product.

Determination Of Shaft Concentricity

The American Petroleum Institute specifies the allowable vibration permitted on a pump operated at various speeds. In addition, various users of centrifugal pumps specify the maximum shaft eccentricity acceptable to promote good service life of stuffing box packings, mechanical seals, and bearings. It was during the performance testing of a refinery type pump in the Hydraulics Laboratory that abnormal shaft vibrations were recorded and later traced to an unstraight shaft.

Centrifugal pumps are operated on shop test conditions that simulate field operating conditions. When some feature fails to pass the test, in addition to correcting the problem, it is surveyed to determine whether it is an isolated case or one that exhibits recurrence.

INVESTIGATION AND EXPERIMENTAL WORK

Sources Of Information Leading To The Study

Our primary source of information was the shop "NON-conformance/ Rejection Reports"- Form QCM 587A Rev. 1 - Appendix-B.Hundreds of these reports were screened to sort out shaft problems in the manufacturing facility. A typical "Report" lists, in addition to items of lesser importance, the following:

Report Number	Job Number	Date
Part Name	Drawing Number	Noun Code
Material	Problem Code	Quantity

The reverse side of the report includes over one hundred items of problem codes, defect codes, and performance test code problems. A defective shaft may carry a number of codes, however, in this study the primary interest was in shaft eccentricities. Items such as "bad threads" and "dimensional errors" were passed over.

The reports are issued in 4 copies, 2 of which are of interest:

1. Non-conformance Reports are issued with a :Disposition Report" that instructs the shop to repair the shaft or discard it. The reports that indicated that the shafts were eccentric and required straightening were sorted out for additional study.
2. One copy is sent to the Quality Control Department where it is entered into a computer. Printouts are periodically issued to interested work groups for study. The printouts show the various deficiency codes for which the parts are rejected, and make it quite easy to pinpoint recurring problems.

In the reports that were screened, only twenty-five relevant shaft problems had been noted over a five month period. These reports are initiated by inspectors at "Final Inspection" and relate particularly to shafts that have been completed and are ready for assembly in a pump, or ready for shipment as a spare part. These reports do not tell us how many times a shaft has been straightened, or if it was straightened, prior to its being sent along to the Inspection Department. Some of the reports covered rejections that prohibited the use of a finished shaft for reasons such as: "Runout beyond tolerance. Attempted to straighten, but would not hold. Unstable material." Actually, the conclusion was only a guess, since it had not been determined that there are deficiencies in the raw materials. In some knowledgeable circles, it is believed that machining induced stresses are relieved after a period of time and cause the shaft to bow. To avoid this phenomena, critical shafts are given an in-process stress-relieving operation prior to finish machining or grinding.

A detailed study of the "Non-Conformance Reports" served as a point of departure in the shaft category selected when it was noted that an abnormally large number of refinery pump shafts had recurring shaft runout problems.

It must be emphasized that pumps are never assembled with unstraight shafts. There are methods by which bent shafts can be straightened but these add to the time and cost of the shaft. The final proof of a shaft's integrity is at assembly, since a bent shaft will not permit easy turning of a rotor in an assembled pump. In the case of shafts shipped as spare parts, there is no opportunity for ultimate testing in an assembled unit.

Criteria For Product Improvement

Product improvement is difficult to evaluate as a tangible item. It results in:-

1. Increased product reliability
2. Improvement in meeting shipment promises
3. Improved corporate image
4. Increased sales volume
5. Lower cost due to reduced rework and scrappage
6. Increased profits.

An important factor in product improvements is the elimination of straightening operations on material that has left the mill in a fully annealed condition. If a shaft must be straightened, the operation must conform to an accepted practice that will result in a straight, stable shaft. The material is received at the Manufacturing Department in a fully annealed condition and should not be straightened prior to machining. The allowable runout on the raw material varies according to the specification for particular materials, and in some cases, it is as much as one-quarter inch in a five foot length. The limit set for I-R Spec. 20 material permits a runout of .025" per foot. Since all A-line shafts are less than about 30" long, the total eccentricity of the raw material should be less than .063", total indicator reading. The manufacturing procedure must be so designed that machined shafts are straight within .005" T.I.R. at any location and straightening is not required. In fact, straightening must be prohibited, since various steel materials exhibit the physical property of "memory", which means that stresses incurred in the straightening process may cause it to return to its original geometric form at some later date.

Methods Of Correcting Shaft Runout

Shafts are machined with excess stock left on for grinding. This is .015" on the diameter, and if the machined shaft runs out by more than five or six mils, it must be corrected before grinding in order for it to clean up. There are three ways to accomplish this:-

1. Cold Straightening Method--By means of a hydraulic press and proper supports, the shaft is straightened until it agrees with permissible tolerances. The shaft is stored for 48 hours and then re-inspected. If the shaft is out of tolerance on total indicator runout, it is discarded; no further straightening is allowed.
2. Shifting Of Centers--Center holes may be machined by supporting the shaft on a steady rest and reworking the center holes from a tool post on a lathe.
3. Heat Straightening Method--Explained in Appendix A.

The above methods usually correct the out-of-straight condition, however, they are undesirable and expensive.

Facilities Used In The Study

Two LeBlond Tape II, numerical control lathes (shop numbers 9809 and 9810) were used for the production and experimental machine work. The lathes have 25 horsepower main drive motors and furnish power through 30 horsepower eddy-current drives. These provide variable speeds to the lathe head stock spindles. The electrical characteristics of the drive train is given in Appendix C.

The numerical control unit is a General Electric Style 100S contouring control system that automatically operates from numerical information (and symbols) in the form of an eight channel binary coded decimal punched tape. This tape is in accordance with Electronic Industries Association Standards RS-227 and RS-244 and is prepared on typical business machines such as the Flexowriter model NC-1.

The tape reader in the machine control console is 15 years old and has been repaired on several occasions. Except for the reader being sensitive to imperfect tapes, and that no foreign matter be near the optical element, it works quite well. Throughout our work, a supervisor from the N/C Department assisted when a new tape was needed, the reader malfunctioned, or reprogramming was considered.

The lathes are 15 years old and do not possess the speed, power and clutch capacities to fully utilize modern coated tungsten carbie tools. They have four position turrets on their saddles and four tools are utilized in machining the shafts. The machines have a maximum no-load speed of 1750 revolutions per minute, but operation is limited to about 1000 RPM, primarily because of lack of clutch capacity.

In addition to the lathes and the control consoles, the usual machine shop and tool room facilities were available. Also, the Central Materials Service Laboratories, Purchasing Department and Engineering Department made contributions as needed.

In the opinion of people involved in the shaft study, the age of the machines and relatively low power have no bearing on shaft straightness. Actually, the low power should be conducive to shaft straightness, since there is less tendency to induce machining stresses.

Pump Shaft Materials

Pump shaft materials are commonly made to the pump manufacturers' proprietary specifications and therefore carry its designation. At Ingersoll-Rand Comapny, I-R spec. 379 is AISI type 316 stainless steel, I-R spec. 320 is AISI 1020, spec. 314 is ASTM 4140, spec. 20 is 416, 13 percent chromium steel, etc. The chemical and physical properties are reviewed in detail when their machining is discussed, and in Appendix D.

In additon to the strength, straightness and corrosion resistance requirements of shafts, important considerations are the economies of scale, and inventories. Applications of pumps can be broadly classified as:-

1. Non-corrosive
2. Mildly corrosive
3. Very corrosive.

Pumps handling very corrosive liquids, while they are quite similar to refinery pumps, have certain special features that cause them to be classified as "chemical pumps". These are manufactured for industries listed in the Standard Industrial Classifications of the Bureau of Labor Statistics Indices [6]. This study is interested in the shafts of these pumps, but separately from the shafts of items 1 and 2 listed above, which will be lumped together for reasons of shop practice and economy.

Very few pump shafts are satisfactory when made of carbon steel, simply because they invariably rust, cause problems in sealing liquids against leakage under protective sleeves, and cause maintenance hardships. Quite often, they cannot be reused when a pump is overhauled. The use of 13 percent chromium stain less steel covers a large field of applications and resists mild corrosion. Experience has shown that 13 percent chromium steel will meet the shaft requirements of about 90 to 95 percent of the pump applications, aside from those of true chemical nature that need stainless steels equivalent to AISI 316 or better. By lumping class 1 and 2 together, we can:-

1. Increase the quantities
2. Avoid duplication of setups
3. Avoid tooling changes
4. Eliminate duplication of inventory
5. Avoid mixup in inventory, since the finished shafts are identical in appearance, and both carbon steel and 13 percent chromium steels are magnetic. A common shop method of superficially differentiating materials is to check them with a magnet. Improper substitution of carbon steel for chromium steel has resulted in the premature failure of a part.
6. Avoid mixup in chips and scrap metal, which is essential when returning metal to a foundry for reprocessing.

The ideal material for refinery pump shafts would have the following properties:-

1. Resistance to mildly corrosive liquids.

2. Good physical properties, including high torsional, yield and ultimate strengths.
3. Maintains straightness.
4. Is readily obtainable in economic quantities. Some materials are available only in large "mill" lots, and then, only after long delivery times.
5. Has good machinability.
6. Is satisfactory for the majority of applications.

The details of the specifications for materials used in this study are to be found in Appendix D [7]. Additional information on machinabiltiy and relevant physical properties of the various shaft materials was taken from "Materials Engineering" magazine [8].

Shop Observations And Procedures

Two identical lathes are located face to face, about 15 feet apart, and are serviced by one operator. They are supplied with material by means of an overhead monorail air hoist. The time required for machining is sufficient for one operator to remove a finished shaft and install a bar of raw material without interrupting the productivity of the operating machine. The labor costs are therefore classified as a "two machine rate".

During the various observations and experiments, production continued on one or both machines. The quantities for the various jobs varied from only 4 pieces to 100 pieces. Several different grades of carbon steel, chromium steel and high alloy stainless steels were machined.

Preliminary Steps In The Analysis Of A Shaft Problem

1. Review an assembly drawing, such as No. F6X13A500X3B, Figure 2, which is typical of the pumps being studied. Such a drawing, when drawn quite close to scale size, frequently reveals elements of weakness that require further study.
2. A master routing sheet for a typical shaft. The shaft material is specified on the sheet along with the sequence of operations, setup and operating times. A copy of the routing sheet is shown in Appendix E.
3. The metallurgical aspects with the:

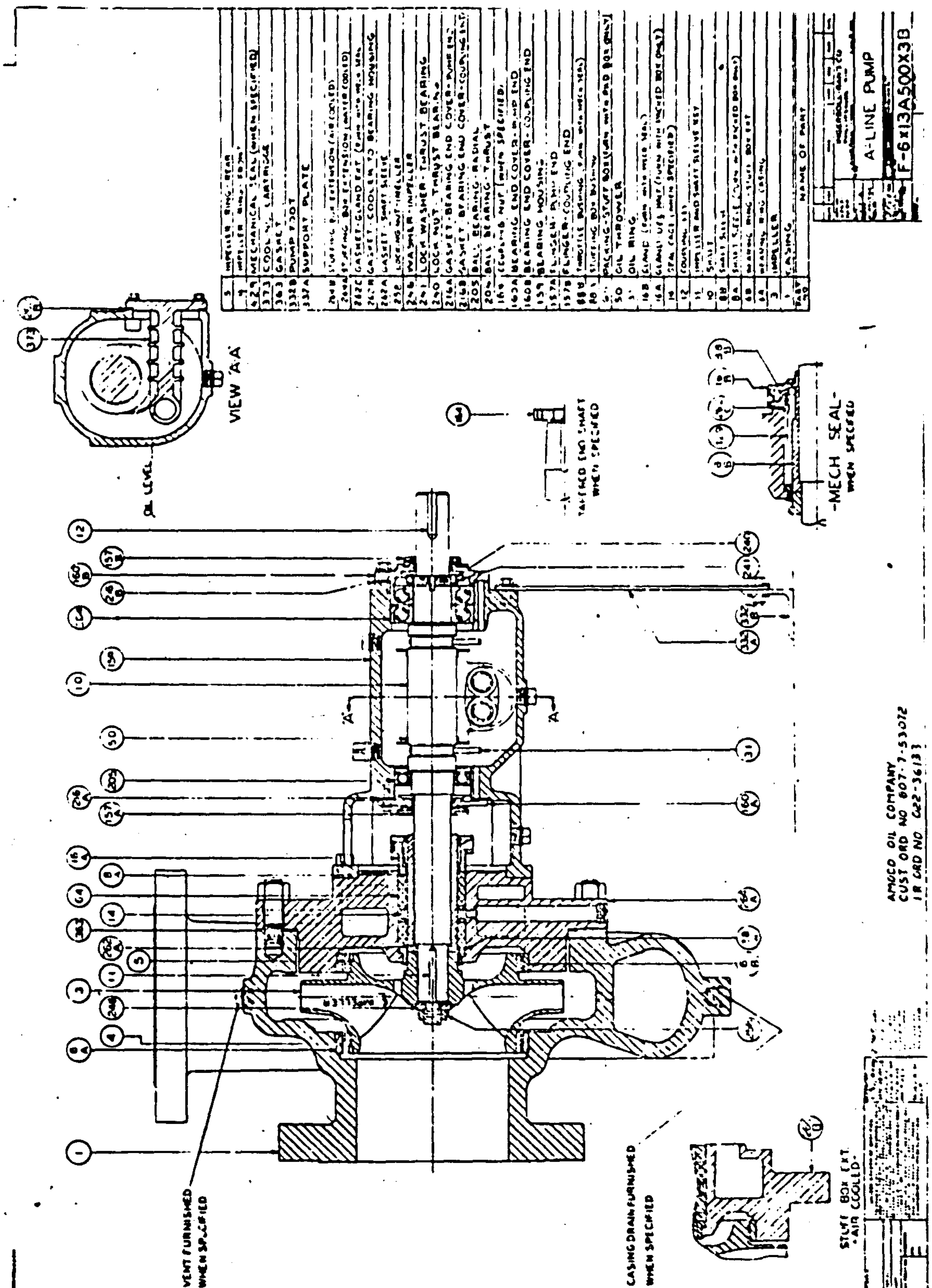

Fig.2 Assembly View of Refinery Pump

A. Ingersoll-Rand Central Materials Service Laboratory,

B. Cameron Pump Division Purchasing Department,

C. Carpenter Steel Division of Carpenter Technology.[7]

4. The physical operations, especially metal removal, being performed on the material.

5. The design aspects with the Engineering Department.

The metallurgists indicated that one of the desirable materials is 13 percent chromium, free machining steel, the industry identification of which is either AISI Type 410 or 416. Seven of the usual shaft materials with their Ingersoll-Rand and AISI designations are (detailed in Appendix D):

I-R Spec.	15	which is AISI - Type - 4140
	320	1045
	348	303
	814	410
	379	316
	20	416
	20HTS	410

As far as possible, the material "pedigree" is traced to insure its conformance to specifications.

The Purchasing Department is interested in procurability and price. They are confronted with engineers and metallurgists who want the best possible materials, and the vendors who raise prices accordingly.

Physical Operations

The master routing sheet in Appendix E shows the operations performed on the raw material. Specific attention was paid to machining operations that were believed to be severe enough to induce stresses in the material. This eliminated operations such as cutoff, center, thread, etc., that are essentially low energy type operations. The lathe work seemed to be the area where eccentricities were initiated. The shaft drawing in figure 3 shows the details of a shaft being studied. The shafts have a threaded end that is used for an impeller lock nut. The other end is larger in diameter and is turned cylindrical to accommodate a coupling that has a straight bore. The rough material is cut to finished length of 28-9/32 inches. The ends are centered on a Sunstrand Cent-Mil that grips the bar stock in a two jaw chuck, locates it in the proper position and drills the center hole. There are some inaccuracies in the machine that cause the holes to be drilled off center by about 1/32 inch. This seems to have only a mildly adverse affect on the machining operations because of the large number of roughing cuts taken, which tend to eliminate eccentricities. This off-center drilling could be important if it is sufficient to prevent cleaning up on finish turning or grinding. The centered bar stock is ground in a narrow band on an external grinder. This band or "spot" is ground at a predetermined location to permit use of a steady rest during machining. The bar stock is loaded into the machine, secured on centers and driven with an ordinary dog, Figure No. 4. A steel wheel, hinged on a trunion, and known as a Vibr-damp, Figure No. 5 rides on the barstock to

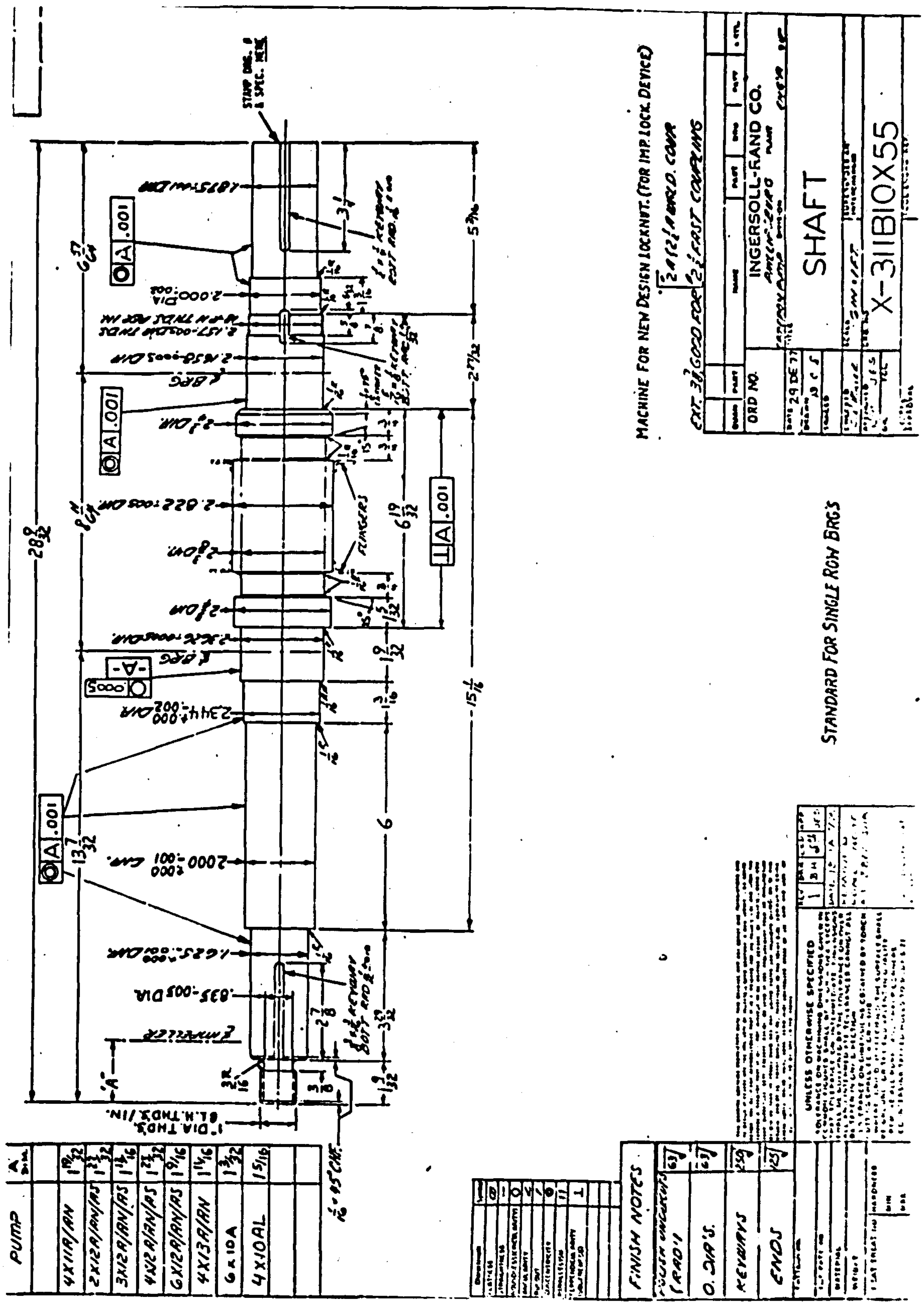

Fig. 3 Refinery Pump Shaft

Figure 4. Steady-rest and "Vibradamp" viewed from headstock.

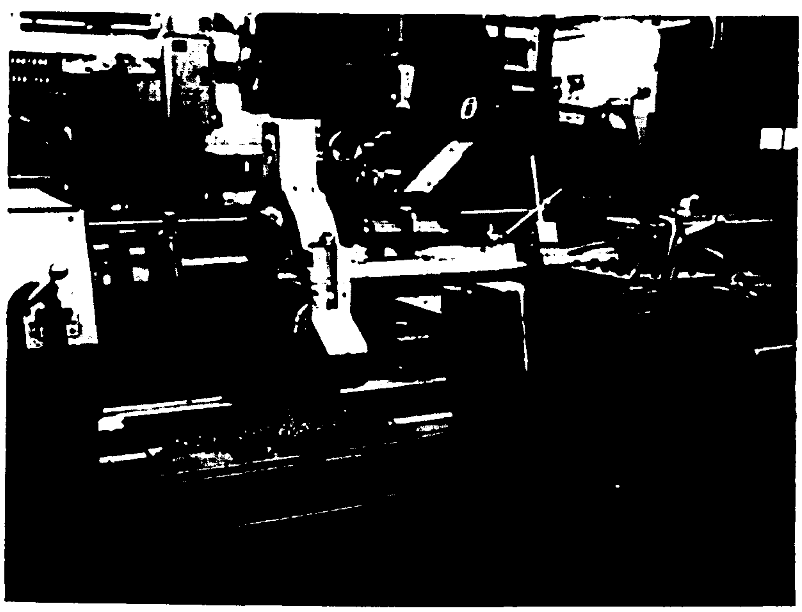

Figure 5. Lathe setup showing driving "dog", "Vibradamp", steady rest and dial indicator location.

supress vibrations. It gets a rough ride on the unmachined surface of the bar until the first roughing cut is made, then it seems to perform its function.

Recent experience on the lathe operation suggested that the runout condition on the finished product was related to the pressure exerted by the tool during plunge cutting of the two 3/4" wide oil ring grooves. For this reason, the groove cutting was eliminated by over-riding the tape and the grooves were later machined on an engine lathe. In addition, the previous history of shaft runout after turning necessitated leaving a .015" of material on all diameters to be removed by grinding.

On the first observation of the machine work, it was noticed that the tail stock live center appeared to be vibrating or oscillating. The machine cover was moved out of the way and a magnetic base dial indicator was placed on the tail stock with the pointer of the indicator resting on rotating live center also shown in Figure 5. It was observed that the live center was running eccentrically by 12 mils, total indicator reading. Our first step was, therefore, to isolate the cause of this phase of the problem.

All of the refinery "A-Line" pump shafts are designed to about the same physical proportions, and all are machined with essentially the same procedures. This particular shaft had been cut to length, centered and spot ground for steady rest at 18 inches. Operation 130 on the route card - "turn coupling end - allow for grind" had been completed. The next operation, #140 turns the opposite end (or impeller end). It was during this operation that the erratic operation of the live center was observed.

It was reasoned that the short stiff raw material bar which was 3" in diameter and 28-9/32" long would be very difficult to align on centers and on a very rigid steady rest without imposing an abnormal radial load on one of the aligning members. Evidently an eccentric load was being applied to the tailstock center, since the center ran very true when the pressure exerted by the steady rest was released. Also, the ball bearing live centers fail frequently and periodically. Figure 7 shows that the discolored bearing support area of the three destroyed ball bearing centers suffered from excessive heating. This was due to:

1. Insufficent lubrication,
2. Excessive axial loads, or
3. Excessive radial loads.

The destroyed bearings appeared to have adequate lubrication and special attention is given to this since the failure of several bearings. Excessive axial loads appear to be insignificant because the tailstock is hand adjusted with no inordinate amount of force, and all cutting of metal is done toward the headstock. A total indicator reading of 12 mils at the tailstock center means that it was pushed off center 6 mils. It would require about 100 pounds of radial force (calculated as a cantilever beam) at the live center to displace it .006". This is assuming that the bar is essentially rigidly fixed in the steady rest and headstock. This is not quite true but is close enough for what is being determined. The only time that a force of this magnitude occurs is during a plunge cutting of the oil ring grooves, and in the present experiment, no grooves were cut. If they had been, it would have been irrelevant because that would have been done on the previous operation and not on the one being observed. The only force that could cause displacement of the tailstock center was that of an incorrectly adjusted steady rest.

As an experiment, the machine operator was instructed to select 10 bars of I-R Spec. 20, AISI 416 at random from a 100 piece job and machine them without the use of a steady rest. The pieces were selected at random so that they would not be from only 2 or 3 mill lengths. Again, the oil ring grooves were not machined, to further eliminate this as a source of bending. Each shaft was dial indicated at 4 locations after machining on centers. The dial readings for all shafts were invariably one mil, a little less than a mil, or slightly more than one mil; perfect score!

The lathe was set up to machine the other end of the shafts. The versatility of N/C was demonstrated by setting up the entire operation in about 20 minutes. The same procedure as outlined above was followed. Nine of the 10 shafts were perfect, and one had an excessive runout of .022" T.I.R. The goal is to limit runout to .003" T.I.R. anywhere on the shaft. The sudden appearance

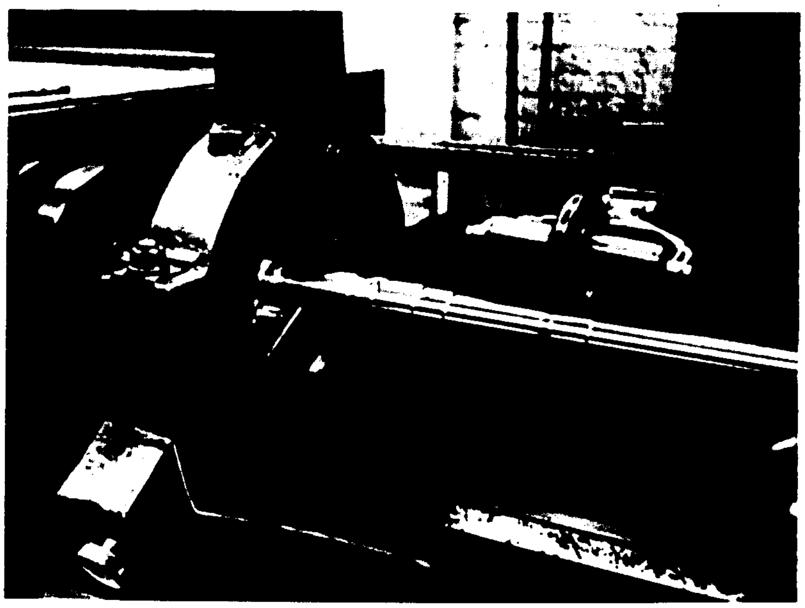

Fig.6 Steadyrest and "vibradamp" from tailstock of lathe.

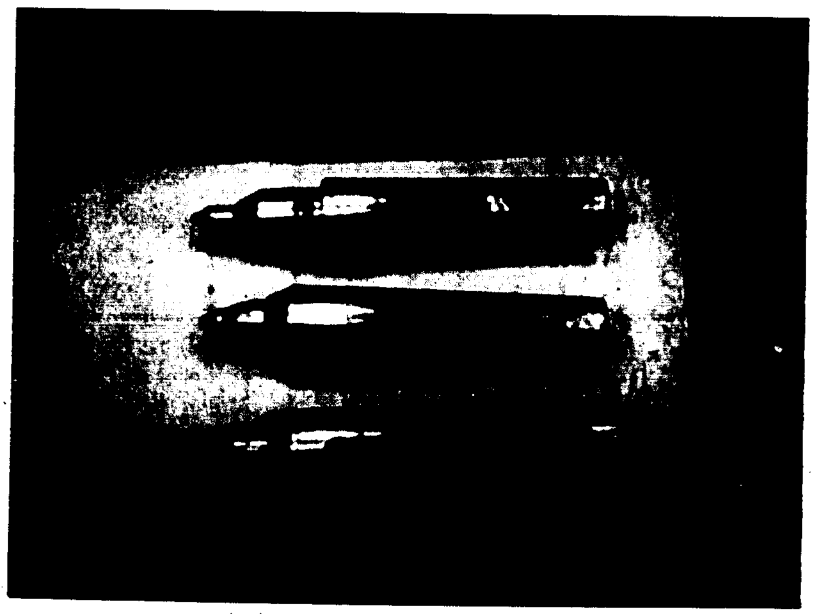

Fig.7 Tailstock centers that failed in service.

of one bad product was not explainable. It could be a characteristic of low yield strength material or some other cause, but much study remained to be done on the metallurgical aspects. Mechanical reasons for the runout could be a small steel chip or other foreign matter in the center hole. The machine operator was instructed to blow out all center holes before placing the bar on centers. In addition, the holes were inspected for size, quality and upset from turning. The holes appear small, however, on the thread end of the shaft; the available end surface is quite small, and limits the depth and diameter of the center hole.

Advantages Of Omitting A Steady Rest

One of the ultimate goals of this study is to simplify and reduce the shaft unit labor costs. Omitting the steady rest would have the following beneficial effects:-

1. It would no longer be necessary to grind a spot on the bar stock for a steady rest.
2. Time saving in not closing, adjusting or tightening of the steady rest.
3. The tool settings could be shortened from 13" to 11" from the center of the tool post. This would improve the rigidity of the tooling.
4. The barrel of the tailstock now extends 11"; thiscould be shortened by 2" for improved support. Even with this long overhang, the barrel is sufficiently long to still be fully engaged in the tailstock proper.

5. Improved tailstock center life and a corresponding reduction in down time for replacement of ball bearing quills.
6. Eliminate the necessity to straighten shafts after machining and prior to grinding.
7. Avoid incorrectly adjusted rollers.

The only disadvantage of the new interim procedure is that the shafts must be put back into the lathes a third time to cut the oil ring grooves.

<u>Additional Machine Work On Production Shafts</u>

Shortly after the quite successful 10 piece run without a steady rest, a similar 15 piece job, also I-R spec 20, was run and only 4 pieces were acceptable (Appendix F). This operation was performed without any changes in machine setup, tooling, inserts or coolant (Appendix G). It seemed that the only item that was changed was the raw material lot, hence, special emphasis was placed on this before the next run.

A third lot of sawed-off bars were observed to have different surface color; some were black and some were gray. No correlation between color, hardness and shaft runout had been made on previous runs. The shop people believed that the black surfaced material runs more concentric than the gray - for some unexplained reason. It was later reported by a metallurgist that the gray bars appeared to be "pickled" versions of the black bars. This was not called for in the specifications, therefore, it was a "plus" feature that was free of charge. It is to be expected that tool life would improve when turning bars that had the mill scale removed by pickling. The bar stock was carefully identified with respect to hardness and color before the next run. The material recorded was I-R spec. 20:-

Bar Number	Brinell Hardness	Color
1	140	Black
2	134	Gray
3	126	Gray
4	148	Black
5	116	Gray
6	143	Black
7	126	Black
8	137	Black
9	126	Gray
10	128	Black

By observation, there is no difference in hardness between the black and gray bars. This material may have a hardness as high as 187, however, in fully annealed condition. The above tabulated values are reasonable. A 40 point spread in Brinell hardness numbers is not unusual and does not cause a marked change in machinability. Also, the machined shafts showed no appreciable difference in straightness, regardless of their initial color.

The success of this project to this point in time was quite insignificant. The machining parameters needed increased vigilance. Accordingly, the feeds, speeds, tool geometry and sequence of machining operations were checked in detail.

The feeds and speeds were studied to insure their agreement with accepted machining practices. According to an article by Norman Zlatin [9], AISI 410 steel with a hardness of 160 to 200 BHN, and using carbide tools, can be machined at a rate of 450 to 1200 surface feet per minute with a feed of .005" to .020" per revolution. This range embraces the 650 SFPM and .020" feed and .150" depth of cut given in "Machining Briefs" [10].

The LeBlond lathes are programmed for revoultions per minute according to an "S" code, the values of which are given in Appendix H. With 3" diameter bar stock, the lathe spindle rotated at 396 RPM. At this speed, the surface speed at 3" diameter was 311 feet per minute. This was below the lower 450 SFPM given above. The feed was .018" per revolution on rough and finish cuts. The depth of cut was .125". These conditions resulted in very little tool pressure.

Figure 3 states that the surface finish should be 63 micro-inches. Armarego and Brown [11] indicate that with a cutting speed of 300 SFPM, and proper tool geometry, the finish will be 60 to 65 micro-inches. The shafts being machined will have ground finishes, but the ultimate goal is to machine finish all surfaces except those having .0005" tolerances at bearing locations. The nose radius of inserts was 1/16".

Increased attention was to be paid to chip formation and chip type. It was especially important that the chips be broken into small pieces since they drop through the lathe bed and are transported in an under the floor conveyor to a scrap container. The carbide cutters had performed chip breaker grooves that promoted plastic flow and shearing stress of the chips, resulting in small, short chips suitable for the conveyor. The chips appear to be consistent in shape and size with those discussed by Vidosic.[12]

Considerations were given to determining the power input to the lathe and to the force exerted on the cutting tool. A watt meter could have been connected to the electrical input leads to the driving motor, but the readings would have had very little meaning since the overall efficiency of the drive train is not known. The eddy current drive is especially susceptible to wide variations in efficiency with a change in speed or load.

The 15 year old lathes are to be replaced with new lathes that will be furnished with solid state instruments that are designed to accurately measure and display power consumption. One such machine is the "Valenite Power Monitor" that can be used to monitor AC or DC motor horsepower or kilowatts. The design and operation of this device is described in the Valenite bulletin.[13]

Facilities were not available to measure the force on the cutting tool. A very satisfactory way to utilize a mechanical dynamometer to measure cutting force and thrust force on the tool is fully described in a book published by the Curtiss-Wright Corporation.[14] The same book illustrates a method of employing bonded wire resistance strain gages and wheatstone bridges to obtain measurements of tool force and thrust. There are probably much more sophisticated devices available today for performing similar work.

Work proceeded on the 10 bars of Spec 20, 13% chromium material. They were to be turned in accordance with Figure 3. For this test run, the rollers in the steady rest were backed off so that they did not touch the barstock. The setup required that the tailstock ram be extended 12 inches, however, it still had good support since 12 inches still remained in the tailstock. The tailstock overhang is shown in Figures 8 and 9. Evidently the overhang did not adversely affect the machining operation since no motion, relative or absolute, could be detected when the machine was operated. The lathe was equipped with a weighted wheel, known as a "vibra damp", which rolls on the bar stock and is supposed to suppress vibrations in the stock. This is also shown in Figure 9.

The bar stock was placed between centers and the tailstock center was screwed into place. Special attention was paid to avoid over-tightening the tailstock, since as the stock diameter is reduced, this could cause bowing of the material. During subsequent inspections, with the lathe dog screw loosened, the bars could be turned by hand on the centers. The center contact areas are quite small, so possibly this test was not too good, but it does appear that the bar stock is not being deformed by axial pressure exerted by the centers.

There had been some question about the roundness of the raw material, so the diameters of 6 bars were recorded at 0, 45, 90 and

Fig. 8. Tailstock Quill and center.

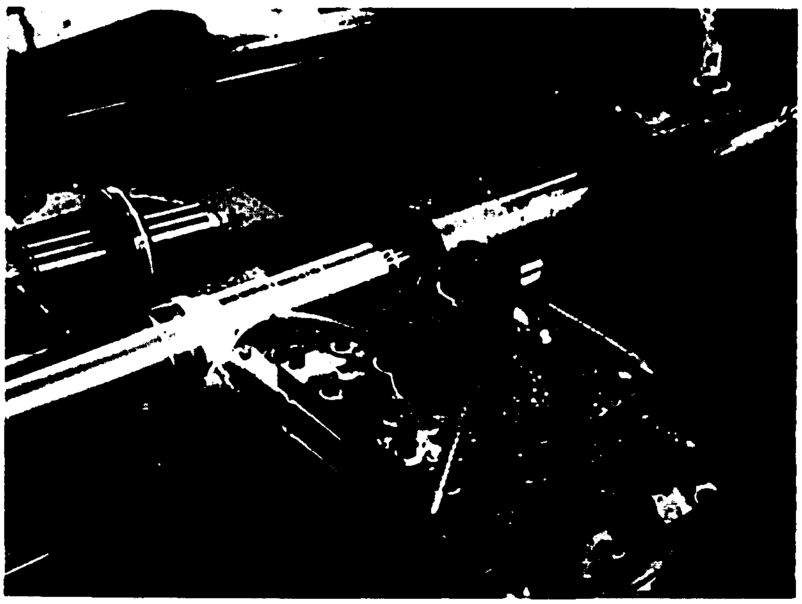

Fig. 9 Tailstock, tool post and "vibradamp".

135 degrees on one end. Bars Nos. 6 through 10 were selected because of their accessibility on a skid. The diametral readings in inches were as follows:

Bar	Location Deg. 0	45	90	135	Deviation In Dia.
No. 5	3.055	3.055	3.055	3.044	.011
6	3.055	3.036	3.050	3.054	.019
7	3.037	3.051	3.053	3.047	.016
8	3.054	3.055	3.050	3.054	.005
9	3.047	3.057	3.054	3.053	.010
10	3.047	3.040	3.039	3.057	.018

These readings are within the material specifications, and only centerless ground stock would be closer to perfectly round as received from the mill.

The bar stock, on centers, was dial indicated in the rough form to determine the eccentricity caused by:

1. Off-center location of centers
2. Out-of-round condition of rolled barstock
3. Out-of-straight condition of rolled barstock.

The total indicator reading for the first piece was .050" at 6" from the tailstock center. The "vibra damp" would probably have run quite rough, so it was not used. The machine operator indicated that the finish machined shaft had a tendency to runout about proportional to the amount of runout observed on the raw material. This seemed unlikely, due to the large number of light roughing cuts which tend to reduce eccentricity with each pass. This suggestion was not discarded, however, because the solution to the eccentricity problem had not yet been found, and no stone was to be left unturned.

The No. 1 shaft was machined in accordance with the standard tape, except that the oil ring grooves were omitted. After two roughing cuts, the material surface appeared to have a "herring-bone" finish. The "vibra-damp" was then run on the shaft and the surface finish was restored to a plain machined finish. N/C lathes are programmed to change spindle speed as the diameter of the work piece changes in order to maintain a nearly constant rate of metal removal.

The machining of the shafts was begun on the heavier, or coupling end. The finish turned shafts (one end) were dial indicated on the lathe centers to determine the concentricity, especially at the center, or barrel section, at the 2.822" diameter. The following readings were taken on the first three shafts:-

Shaft No. 1	.0005" on the barrel
Shaft No. 2	.001" on the barrel
Shaft No. 3	.0002" on the barrel

At this point, it was decided to put shaft No. 1 back into the machine for the purpose of measuring the runout and establishing repeatability. It was surprising to observe that shaft runout was .005", total indicator reading, at the tail stock and .003" at the barrel. The shaft was removed from the lathe centers and shaft No. 2 was installed. The shaft was turned on centers and observed to runout .007" at the tailstock and .003" on the barrel.

It was decided to search out the reasons why duplication of dial indicator readings could not be obtained when a shaft is removed and re-installed in the same machine.

A dial indicator was placed so that the concentricity of the head stock center could be measured. The runout was measured as .005", total indicator reading, so it was decided to correct this problem. Replacement of the centers resulted in no improvement in the runout. It was decided to grind the center while it was firmly in place in the machine spindle. The versatility of the N/C machine was demonstrated in the method of grinding the center. An air powered, high speed grinder was mounted on the machine tool post as shown in Figure 10. This has the advantage of off-setting any eccentricities in the machine spindle, sleeves, etc.

Figure No. 10 Air grinder mounted on machine tool post, grinding head stock center.

A programming supervisor punched a tape to generate a path at 30 degrees to the machine axial centerline, or "Z" axis (see Appendix I). The tape was installed, console properly adjusted, grinding wheel dressed and the grinding of the center proceeded. The finish ground center ran almost perfectly true.

The tail stock center was also dial indicated and found to run out .0025 T.I.R. This condition could not be corrected because no replacement quill was available, nor is there any way to drive the center in order to grind it.

The bar stock for shaft No. 4 was installed in the lathe and finish machined. With the lathe dog screw loosened, the shaft could be turned by hand on the centers. It was tight, but could be turned. The runout was recorded as essentially zero at the tail stock end and at the barrel. The tail stock was loosened, the shaft rotated 180 degrees relative to the centers, and the two locations ran out .0015".

Shaft No. 5 was run and the runout was 0.000 "at the end and .003" at the barrel. This shaft too, was satisfactory on this first turning operation, however, the large diameter at the barrel appeared to have foreign inclusions. The assessment of a metallurgist was that insufficient material had been removed in the machining operation, and that the machined surface actually contained imbedments of mill scale. This will require:

1. Cleaner raw material bar stock
2. Straight bar stock that will clean up in machining
3. Using larger diameter bar stock to insure cleaning-up.

It was also observed that the roughing tool experienced considerable flank wear and had to be indexed to a new cutting edge prior to machining the following piece. The tool changing is left to the discretion of the machine operator, but it is usually done when examination of the inserts shows flank wear of about .015" to .020". A worn tool frequently makes its presence known by:

1. Poor surface finish
2. Abnormally loud or high pitched noise
3. Failure of tool to machine part to proper diameter.

The repeatability of the operation was again checked by putting shaft No. 4 back into the lathe centers and dial indicating it. The poorest location on the shaft showed only .002" T.I.R. runout. Pieces number 6 through 10 were run quite uneventfully except that the roughing cutter had to be indexed after only 2 pieces were machined. The results of machining, indicating, turning the piece 180 degrees relative to the centers and re-indicating were as follows:

Shaft			Turn 180^{o}	
	End	Barrel	End	Barrel
6	0	0		
7	.001	.001	.005	.004
8	.001	.001	.004	.004
9	.0005	.000	.004	.004
10	.0005	.005	.005	.005

This completed work on the first end of the shaft, and except for runout caused by the eccentric tail stock center, the pieces were satisfactory. (Note that all of this machining was performed without employing a steady rest.)

The lathe was re-setup to machine the threaded end of the shafts. Due to convenience in handling, the shafts were machined in the reverse numerical order. Dial indicator readings were taken on the half-finished pieces before and after turning to assist in determining if the material was being deformed during machining. The results were as follows:

Shaft No.	Indicator Reading Taken Before & After Turning	Indicator Reading At Coupling End	Barrel	Thread End
10	Before	.003"	.0025"	
	After	.003"	.003"	.001"
9	Before	.003"	.0025"	
	After	.003"	.003"	.0002"
8	Before	.004"	.002"	
	After	.003"	.005"	.001"
7	Before	.0015"	.0015"	

The roughing cut was started, but trouble developed in the tape or the tape reader. The carriage moved to the right and the turning tool hit the tail stock. The tool was pushed out of the tool post and had to be reset. The shaft was dial indicated and found to run out .045" T.I.R., so it was removed from the machine for straightening prior to finish turning.

The tape reader was cleaned with a small brush and the tape was carefully examined for tears, plugged holes, or other items that might have caused the malfunction. The tape was placed in the console and the machine was run through a "dummy" cycle. The lathe failed to function, so a new tape was made. This too, failed to work properly. An inspection of this odd parity tape showed that one row of holes contained only two holes. This was repunched to get the correct 3 holes and work proceeded. It never was determined why the first tape was inadequate or why the tool post hit the tailstock. The programmer advised that these old readers are very slow and very sensitive to minor tape discrepancies.

The No. 6 shaft, second end, was placed in the lathe centers, tailstock secured, dog tightened and work started. The dial indicator readings for subsequent shafts, before and after turning, without steady rest were:-

Shaft	Indicator Reading Taken	Indicator Reading At		
No.	Before & After Turning	Coupling End	Barrel	Thread End
6	Before	.003"	.004"	
	After	.001"	.008"	.004"
5	Before	.002"	.003"	
	After		.060"	Removed Before Finish Turn*
4	Before	.003"	.004"	
	After	.003"	.008"	.001"
3	Before	.002"	.002"	*
	After	-	.010"	
2	Before	.002"	.002"	*
	After	.002"	.020"	
1	Before	.002"	.002"	
	After	.002"	.008"	.003"

*Eccentricities were too high to permit grinding without inprocess straightening.

Shafts Numbers 2, 3, 5 and 7 required special straightening and remachining:

No. 2 ran out .020", was straightened, remachined, and ran out .012" at the barrel and .002" at the thread end.

No. 3 was straightened to .003" T.I.R. at the barrel. The shaft was finish machined-without a teady rest - and ran out .015" T.I.R. at the barrel.

No. 5 ran out .060", was straightened, finish machined and indicated. It then ran out only .003" at the barrel and .001" at the thread end.

No. 7 ran out .045" and was straightened prior to finish turning. It was finish turned and the final machined shaft ran out .004" at the barrel and .030" at the thread end. This excess runout precluded grinding to drawing tolerances and the shaft was discarded.

Looking back at the accomplishments to this date, the performance cannot be regarded as even approaching satisfactory for a number of reasons:-

1. An 80% or 90% yield of final product as a function of started product is very unsatisfactory, especially on an N/C machine where the human element is reduced to a low level.
2. All shafts are machined .015" oversize in diameter and finished to size by grinding. This adds enormously to the labor and machine cost.

3. The shafts have an excessive number of roughing cuts at low surface speeds.
4. The oil ring grooves are cut in a separate operation on an engine lathe.
5. Straightening operations are required in process.

In addition to "kinked" shafts, and those having a long "bow", an even greater concern relates to twisted shafts. Invariably, these cannot be straightened or made suitable for use. It was considered unlikely that machining stresses were sufficient to cause a permanent twist in the 3" dia bars. An easy way to determine whether or not a shaft is twisted, is to simply dial indicate the shaft in all 4 quadrants at various intervals along its length. A plot of one of the shafts indicated is shown in Figure 11. With the dial indicator set on zero at the zero degrees position, the shaft run out reaches 10 mils and 11 mils at the 90 degree and 180 degree quadrants. At some midpoint, near 135 degrees, the runout reached a maximum, and at a corresponding location halfway around the shaft, the indicator read a negative value. The plot is important in that it does not show maximum values at various shaft locations and quadrants, which would be indicative of a twisted shaft.

<u>Shafting Machined Of AISI 4140 Material</u>

A four piece job was machined of I-R Spec. 15 material (AISI-4140). The dimensions were slightly different, but less favorable, than those of previous shafts. The overall length was 30-7/8" and the diameter was 2-1/2", giving a slenderness ratio of 12.35 to 1

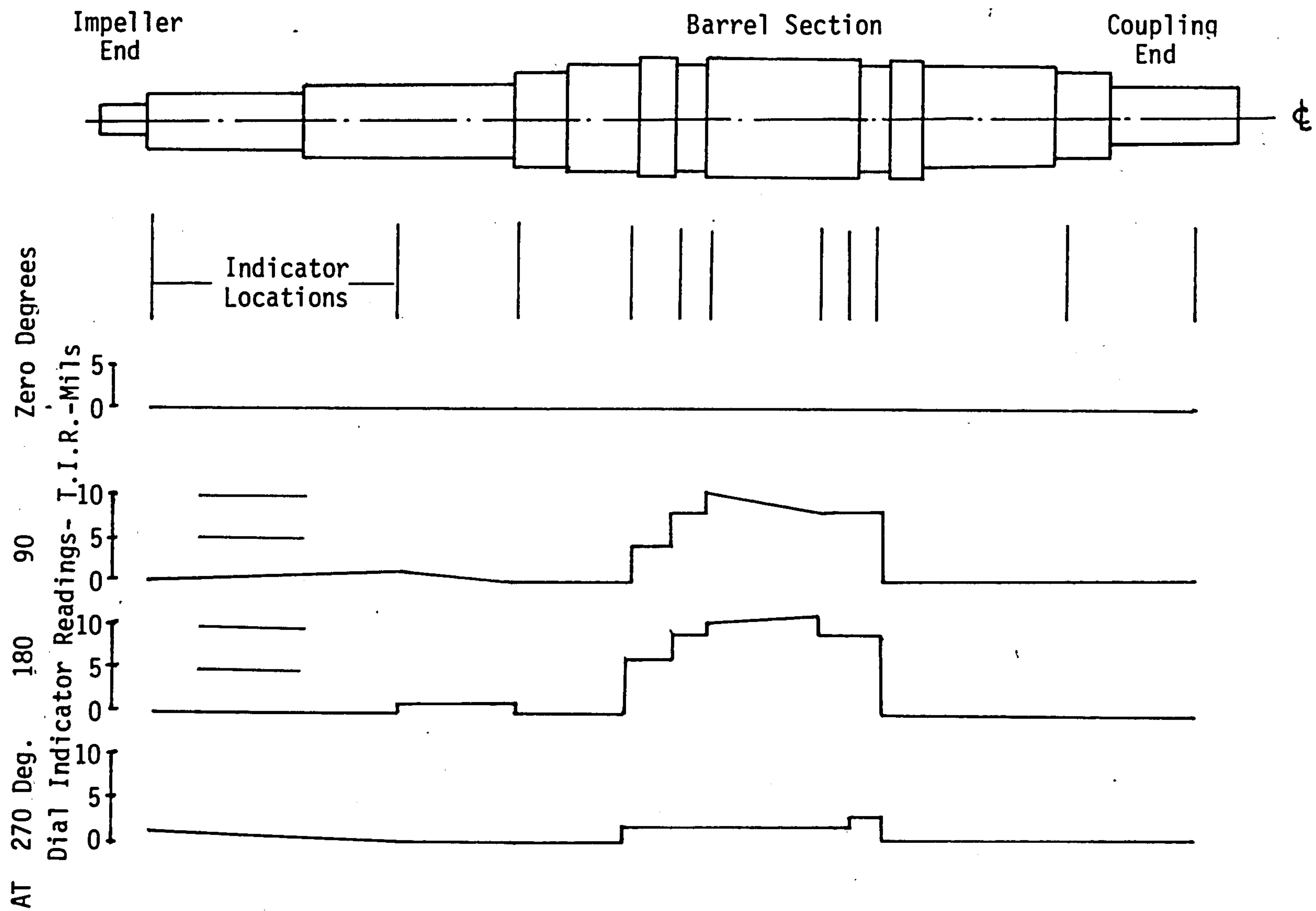

Figure 11 - Eccentricity Plot- Showing runout in four quadrants and demonstrating that shaft is not twisted.

vs 9.17 on the previous shafts. A steady rest was used and dial indication of the finish turned shafts showed:

Shaft No.	At Coupling End	At Barrel	At Thread End
1	.003	.003	.002
2	.005	.005	.004
3	.003	.005	.008
4	.005	.003	.003

Although Shaft No. 3 ran out more than the acceptable 5 mil limit, none demonstrated the excessive runout experienced with 3 of those made of free machining type 416 stainless steel.

Up to this time, a number of the process variations that were employed in machining shafts, failed to yield a superior product. Some things such as misapplication of the steady rest, non-straight condition of raw material, eccentric centering, failure to clean center holes, and failure to change cutter inserts at proper intervals have come to light.

The rather successful run on the 4 pieces of 4140 steel indicate that this material may help solve the physical aspects, but the material is not a good, corrosion resistant material, and therefore not a good stockable material. The improved performance of 4140 material over type 416 can probably be explained by its superior physical properties. One of the problems with I-R Spec 20 (Type 416) is that there is no industry standard, and therefore no limitations on physical properties. The hardness of the bar stock in the as-received condition from the mill can be anywhere from 100 to 262 Brinell. The tensile strength is about 70,000 PSI.

The chemical and physical properties are more than adequate for the applications, but manufacturing shafts from the material creates problems. By comparison, I-R Spec 15, AISI 4140 has a tensile strength of 100,000 PSI and a hardness of about 197 Brinell. Except for the lack of corrosion resistance, Spec 15 is evidently superior to Spec 20. The required shaft material therefore needs to be as good physically as Spec 15, but have the corrosion resistance and machinability of Spec 20. Three material specifications appear to meet these needs, one is I-R Spec 20HTS, another is I-R Spec 814, and the third is I-R Spec 566.

I-R Spec 20HTS has an ASTM equivalent for chemical and mechanical properties. This is ASTM-A582, Type 416 condition "T", stress relieved, free machining, stainless steel bar. It is more expensive than straight 416 material and is used where high strength and some corrosion resistance are desired. The tensile strength of 20HTS material is 120,000 PSI. The hardness is about 262 BHN. Perhaps of greater importance is the 13 percent elongation in a 2 inch length of 20HTS against 22 percent for Spec 20. This should add rigidity to the bar being machined.

I-R Spec 814 material is equivalent to ASTM A276 Type 410, Condition "T", 13% Cr, stainless steel bar, <u>pump shaft</u> quality. The tensile strength is 100,000 PSI, BHN is 262 and the elongation is 15 percent. This material should be essentially as good as 20HTS as a shaft material.

I-R Spec 566 is a 17 percent chromium, 4 percent nickel, 4 percent copper, stainless steel, having ASTM designation A461 Type 630, Condition "H"! It has a tensile strength of 135,000 PSI and 15 percent elongation in a 2" bar. The hardness is about 277 BHN. The physcial properties suggest that the material will remain straight during manufacturing, and such was the actual case. Six shafts were machined to a standard shaft drawing almost identical to Figure 3, the slenderness ratio being the same at about 9 to 1. All of the finished shafts ran concentric within the 5 mil limit and no straightening was required. An effort is being made to reduce the allowable runout to 3 mils T.I.R. and eliminate most of the grinding work.

I-R Spec 379 covers soft, conventional and modified AISI Type 316 and 316 low carbon stainless steel in the form of wrought products (such as shafts) for severe corrosive environments. It contains 16 to 18 percent chromium, 10 to 14 percent nickel and 2 to 3 percent molybdenum. In the as-received condition, the Brinell hardness is about 200 plus or minus 20 points. The tensile strength is 75,000 PSI, yield strength with .2 percent offset is 30,000 PSI and the elongation is 40 percent in a 2" length. Based on previous machining of materials with which to compare physical properties, it was believed that Spec 379 would be troublesome to keep straight. A 10 piece job with geometry similar to Figure 3 was machined on one N/C lathe. The steady rest was used, and the oil ring grooves were machined from the program. The finished shafts were placed on dead centers and dial indicated. The results were as follows:

Shaft No.	Coupling End	First Groove	Barrel	Second Groove	Shaft Sleeve	Thread End
1	4 mils	2 mils	2 mils	2 mils	3 mils	
2	3	8	11	11	10	
3	9	16	17	21	13	
4	8	14	16	16	15	
5	11	20	26	29	32	
6	2	1	1	2	3	
7	5	7	8	9	11	
8	2	2	3	3	3	
9	2	4	5	7	9	11 mils
10	5	7	10	10	13	14

Confirming our suspicions, only shafts 1 and 6 could proceed to subsequent operations without in-process straightening. It is unlikely that shafts Nos. 2, 3 and 4 could be corrected well enough to permit their usage.

Alternate Tooling - Shaft Material: I-R Spec 379.

Subsequent to the previous run, a 57 piece job was run, the only difference being the use of 5 degree positive rake on the insert. No change was required in the program, and the tool insert was microscope-set in the usual manner. After the lot was finished, 10 shafts were selected at random and dial indicated on an inspection device. The results were nearly identical with those observed on the previous run which had utilized negative rake tools, indicating that the use of positive rake tools did not entirely alleviate the straightness problem, but did cause some improvement. Also, the surface finish was better than with the negative rake tools.

A quite significant change in shaft straightness was observed when a 20 piece job was run:

1. First 10 pieces with negative rake inserts.
2. Second 10 pieces with positive rake inserts.
3. No steady rest.
4. One piece with steady rest.
5. I-R Spec 15 - AISI 4140 material.

The log of concentricities is given in Appendix J. The shaft drawing was #311B10X33, which has a threaded end only 5/8" in diameter and lends very little support to the shaft in the final machining cuts. It is significant that shafts No. 1 thru 10, using negative rake inserts experienced 2 shafts whose runouts were excessively large at .016" and .018". This is not satisfactorily explained since the runout was quite close to the tailstock center. The following 10 shafts were machined with positive rake inserts and all 10 were satisfactory. The shafts were machined without a steady rest.

The second, or thread end, of the shafts were machined in reverse order from 20 to 11 with positive rake inserts. Shafts #20, 19, 18, 17 and 16, were turned without a steady rest, and although the barrel part of the shafts ran out as much as .009" T.I.R., they would clean up on grinding without straightening. The other diameters ran within .001" to .0015" T.I.R.

It was decided to run shaft #15 with a steady rest. The runouts increased from 1 mil to 8 mils, 1 mil to 11 mils, and 8 to 9 mils.

This was accepted as conclusive evidence that the steady rest was a misapplication on this operation. It therefore eliminates operation #120 on the master route sheet, Appendix E, which has a production standard time of 0.280 hour and 0.50 hour for setup. The shaft straightening operation is an "average earned rate" (AER) operation, and has labor costs of about $8.00 per hour, and machine time. This too, can be eliminated (operation 150).

There is another operation that does not show on the route sheet, and that is a separate operation for cutting the oil ring grooves. The ultimate goal is to eliminate that also.

The productivity in the manufacturing of shafts is being adversely affected by the utilization of corrective operations that can be eliminated by introduction of several measures listed in "Recommendations" at the end of this Thesis.

CONCLUSIONS

FACILITIES, MATERIALS, METHODS AND COSTS:

I. FACILITIES

1. Existing Facilities - Although antiquated by modern machine tool standards, they are satisfactory for production of pump shafts. The center drilling machine requires maintenance to improve the accuracy in locating the holes in the shaft ends. The LeBlond N/C lathes also need attention to improve accuracy in turning. Due to the age (15yrs) of these lathes, their replacement is imminent. During the various machining operations, especially when erractic shaft behavior was encountered, it was sometimes difficult to establish whether the lathe was performing irrationally or if the material was, in fact, demonstrating that it was non-uniform. This was further complicated by difficulties in obtaining repeatability when turning what appeared to be identical material but yielded entirely different eccentricity readings.

2. Programming - The program for these N/C lathes was written several years prior to our experimental runs. During the initial production runs, the program instructed the lathe to plunge cut the oil ring grooves. With the steady rest in place, the grooves were cut without appreciable tool

chatter or other signs of distress. The steady rest did, however, initiate eccentricities in the shafts. With the steady rest eliminated, tool chatter during cutting of the grooves became objectionable, so the program was overridden to eliminate groove cutting. The program can be re-written to cut the grooves while the bar is at maximum diameter and with narrower inserts taking more cuts with less feed.

3. Steady Rests - These are required for long, slender shafts, but cannot be used for short, thick shafts. Acutally, for shafts having slenderness ratios (length divided by diameter) of 10 or less, a steady rest may be very detrimental. With a short, stiff shaft supported on centers and on a steady rest, the system becomes very difficult to align satisfactorily. This results in deforming the shaft, or the machine tool itself.

4. Cutting Tools - Tungsten carbide inserts were used, but not fully utilized due to the low capacity of the N/C lathe. The inserts were designed with both positive and negative top rakes. The positive rake inserts had longer life (more metal removed per cutting edge), resulted in better surface finish and promoted straighter shafts. The inserts were of several grades and several manufacturers, and no attempt was made to include the results as part of this study. It is important that an excellent grade of

cutter insert be used to reduce downtime brought on by changing of cutters and re-establishing the size being turned (or length). The advantage of a negative rake insert is that it has cutting edges on top as well as on the bottom and has 6 cutting edges on a triangular insert as against only 3 on a positive rake insert. The final decision on insert selection has to be further balanced against cost per insert, power consumed, reliability of vendor, etc.

II. MATERIALS

The various materials from carbon steels thru the chromium steel series, demonstrate different straightness characteristics. The 13 percent chromium stainless steels are ideal for centrifugal pump shaft applications, however, a proper grade must be used. I-R Co. Spec 814, AISI Type 410 properly heat treated to conform to ASTM Spec A276, condition "T" is a satisfactory material. Its high yield strength of 80,000 PSI apparently aids in maintaining shaft straightness. In addition to the shop methods employed to straighten bent shafts, some very sophisticated methods are used in other industries. The Ford Motor Co., Indianapolis Steering Gear Plant uses "analog computer-controlled automatic shaft straightening machines to reduce runout from heat treatment from .020/.040 TIR to .004/.006 in less than 45 seconds with a three point straightening process".[17] The shaft in question is made of AISI 1040 material 23.25" long and 1.00" in diameter.

The straightest shafts are obtained by using AISI Type 410 material, heat treated to attain the properties detailed in Appendix D for I-R Spec. 814.

III. METHODS

The present method of manufacturing shafts is compatible with the quantities and the allowable cost. The shafts could be improved by utilizing in-process heat treatment of material. This would add to their cost, and cannot be given further consideration. Shafts for pumps in critical services have an in-process heat treatment along with other specific requirements.

IV. COSTS

The costs incurred by items in the present process increase the prices of the shafts. These items are:

1. In-process straightening of turned shafts, including straightening of shafts after grinding.
2. Straightening of finished product.
3. Machining of oil ring grooves as a separate operation, or remachining roughed out grooves to true-up.
4. Leaving .015" of stock on all diameters to be removed by grinding entire length of shaft.
5. Grinding a "spot" for the steady rest.

Items 1, 2 and 3 are difficult to assess in terms of shop cost since they are performed on "average earned rate".

The expected output on item 3 is about one piece per hour on an engine lathe. Items 1 and 2 depend upon the success of the straightening operation and can consume anywhere from a few minutes to an hour. An allowance of 15 minutes per straightening, or 30 minutes per shaft would bring the labor time to about 1½ hours for items 1, 2 and 3. Including burden, this represents a shop cost of about $50.00 per shaft.

The excess stock on item 4 adds to the 0.870 hour of grinding time allowed for normal grinding. It adds about 0.30 hour per piece, or roughly $9.00 per shaft. The "spot" for the steady rest is ground in 0.280 hour (Appendix C). Elimination of this results in a standard cost saving of $9.00 per shaft.

Elimination of Items 1 thru 5 inclusive would result in a savings of:

Item 1 }	
Item 2 }	
Item 3 }	$50.00
Item 4	9.00
Item 5	9.00
	$68.00

The set-up times have not been taken into account since their distribution would depend upon the number of pieces. Also, items 4 and 5 are tied in with an incentive system and an increase in productivity would reduce the two $9.00 items to perhaps $6 or $7 per shaft per item. An equitable assessment of added cost per shaft for objectionable items would be $63.00

Additional Material Costs

The above labor savings are not free of additional material costs. In order to eliminate the 5 objectionable items, it will be necessary to start with "dead shaft" shafting quality type 416 stainless steel. The material would cost $.06 extra per pound over conventional Type 416, and special boxing would cost $.07 per pound. In the 3" diameter size for a 10 foot length, this extra cost is $15.00 plus $17.50, which is $32.50, or $3.25 per foot. The 30" long pieces of bar stock would therefore cost $8.12 more than originally. Since material is not "burdened", the savings per shaft would be:

Savings in labor	$63.00
Additional material cost	8.00
Savings per piece	$55.00

With "dead shaft" shaft quality, there should be outstanding production performance for machining and straightness. Further savings could be possible since the stock diameter could be reduced by ¼" due to the precision ground surface which is a specification of this material.

Machining the shaft diameters to size to eliminate grinding all diameters except at the bearing locations will result in further cost reductions, probably raising the estimated saving from $55.00 to $60.00. It is difficult to establish an annual cost savings because the total number of shafts is both unavailable and proprietary. Using a conservative quantity of 2,000 shafts, the annual savings would be $120,000.00. This could be spread to other I-R pump divisions and multiply the savings by a substantial amount.

RECOMMENDATIONS

The shop study has rendered the following recommendations:

1. The machine tools should be put in first class operating condition.
2. The program should be improved to permit machining the oil ring grooves at the first turning operation in the N/C lathes.
3. Steady rests should be eliminated when turning stock having a slenderness ratio of 10 or less.
4. More emphasis should be placed on actual performance of cutting tools and product cost rather than on first cost of tools.
5. "Dead shaft" shafting quality, Type 416 stainless steel material should be used for refinery-type pump shafts.
6. All straightening operations should be eliminated.
7. Grinding of the "spot" will be eliminated when the steady rests are no longer used.
8. Machine all fits to size where tolerance is .001" on diameter. Grind only the bearing location where the tolerance is .0005" on the diameter.
9. Consideration must be given to machining the entire shaft from one setting, rather than turning it end for end to do the second end. This should increase the accuracy of turning.
10. A second approach would be to chuck the bar stock in a collet chuck and eliminate centering, spot grinding and the steady rest. A method similar to this is successfully employed by a vendor of similar parts.

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APPENDIX

APPENDIX-A

Shaft Straightening Procedures

The purpose of this procedure is to (1) list straightness accept-reject criteria for bar stock or shafts, (2) to indicate when it is permissible to straighten bar stock or shafts, and (3) to indicate the permissible method of straightening.

Bar Stock Receiving Inspection

All bar stock to be used for shafts is inspected at time of receipt. The material will be straight within 0.090 inch total indicator run-out within the total length of the piece. Non-conforming material will be:

1. Returned to the supplier, or
2. At option of the shop, straightened according to the following method:

Straightening Method-Cold Straightening

The bar stock is supported on rollers and turned slowly while taking indicator readings to determine the amount and location of eccentricity. A hydraulic or mechanical press is used to exert pressure at the point of maximum deflection to straighten the bar. The process is repeated until the concentricity agrees with the specification. The bar is to remain in storage for 48 hours and then dial indicated again. If the bar is out of tolerance on total indicator runout, the bar is rejected and no further straightening method may be used.

Shaft Inspection, In-process

All shafts are inspected after rough machining and prior to final machining or grinding. If the piece is eccentric, it may be corrected to acceptable tolerances by shifting of centers. The unfinished shaft is supported in a steady rest of a lathe, and the center holes are machined from the tool post.

Heat Straightening Of Pump Shafts

This procedure covers a standard practice for applying heat in the proper amount and location to reduce the runout of shafts, either in-process or finished.

Required Equipment

Dial indicator.

Contact pyrometer.

Tap water at 35 pounds per square inch pressure.

Rollers mounted on a proper stand.

Oxyacetylene gas.

Torch heating tip with 3/32" diameter gas hole.

Restrictions

1. Maximum allowable runout for heat straightening is 0.040".
2. Temperature shall not exceed 750 degrees Fht. as determined by contact pyrometer. This temperature limit means black heat under 900 degrees Fht..
3. The number of heating cycles shall be limited to a maximum of three.

Procedure For Simple Bow

(A simple bow is defined as a gradual runout between bearing supports)

1. Determine and mark the location of the high side runout.
2. Place the high side dial reading at the 12:00 o'clock position. Heat 1-1/2" diameter spot by oxyacetylene with 3/32" diameter or smaller heating tip until shaft moves 2-1/2 times the original runout with black heat. Immediately quench with shop pressure tap water applied by pressure nozzle hose.
3. Shaft must return to the required straightness or it may be reprocessed two more cycles.

Procedure For Kink

(A kink is a runout in a short length)

Repeat the same operations as specified under section for simple bow, except apply dial indicator and heat to the low side of the runout.

APPENDIX B

Non-conformance/Rejection Report

Ingersoll-Rand Company
CAMERON PUMP DIVISION

NON-CONFORMANCE/REJECTION REPORT

QCM 387A REV. 1

1 DIV	2 JOB NO	3 CODE	4 DRAWING NO./PART NO.	5 MATERIAL SPEC.	6 LIST NO	7 0 28314

8 BRANCH ORDER NO.	9 P.O. NO	10 PART NAME	11 LOCATION	12 TOTAL QTY	13 TOTAL REJ	14 DATE REJ / /

15 VENDOR	16 PROBLEM CODE	17 DEFECT CODE	18 R/C	19 OPERATION COST CODE	20 CODE	21 FAULT OF MAN	22 FAULT OF MACH	23 ERROR IN OPERATION	24 INSPECTION MAN NO

DESCRIPTION OF NON-CONFORMANCE

25 SERIAL NO	26 MR HT NO.	27 PROBLEM CODE	28 EXPLANATION	OFFICE USE

29 DISPOSITION ☐ R - REWORK S - SCRAP O - OTHER

30 VENDOR REWORK JOB NO

1980 ____

31 ORIGINATOR DATE / /	32 ORIGINATOR'S SUPERVISOR DATE / /	33 RESPONSIBLE FOREMAN DATE / /

34 **ENGINEERING DISPOSITION**

☐ ACCEPT ☐ REWORK ☐ SCRAP ☐ OTHER

QUALITY CONTROL DISPOSITION

35 A	A	A	A	36 R	R	R	R	37 S	S	S	S	38 O	O	O	O
PC QTY	PC QTY	PC QTY	PC QTY	PC QTY	PC QTY	PC QTY	PC QTY	PC QTY	PC QTY	PC QTY	PC QTY	PC QTY	PC QTY	PC QTY	PC QTY

39 QC/ANI REMARKS

CONCURRENCES — APPROVALS — REQUIREMENTS

40 ATTACHMENTS ☐ DISPO CARD ☐ NONE ☐ OTHER

41 CUSTOMER ACTION REQUIRED ☐ SUBMITTAL ☐ NONE ☐ OTHER

42 DCAS or ANI Requirements ☐ ACCEPTED ☐ REVIEWED ☐ NONE

SIGNATURE DATE / /

43 CONCURRENCES	44 APPROVALS
MARKETING DATE / /	ENGINEERING DATE / /
OTHER DATE / /	QUALITY CONTROL DATE / /

(SEE REVERSE SIDE FOR CODE DESCRIPTIONS)

MFG. COPY

APPENDIX B

Non-conformance/Rejection Report

(Reverse Side)

Performance Codes

PROBLEM CODES:

1 - SHRINKAGE
2 - THERMAL CRACKS
3 - GAS
4 - VOIDS IN CASTING
5 - SAND INCLUSION
6 - INCLUSION (SLAG-DIRT)
7 - SCALE
8 - OPEN GRAIN
9 - POROSITY
10 - HARD WELD
11 - CHAPLET LEAK
12 - LEAK ON TEST
13 - LUMPS/FINS
14 - LACK OF BACKFACE CLEARANCE
15 - POOR SURFACE FINISH
16 - CORE/MOLD SHIFT
17 - PARTS OF CASTING MISSING
18 - THIN CAST WALL
19 - ADD TIME - EXCESS MATERIAL
20 - ADD TIME - EXCESS TOOL WEAR
21 - ADD TIME - OTHER
22 - MISLOCATED FEATURE
* 23 - EXCESS PRODUCTION AFTER DEFECT
24 - IMPROPER GRIND
25 - DIMENSION ERROR
26 - MACHINE MALFUNCTION
27 - OPERATOR ERROR
28 - NO VENDOR SOURCE
29 - HANDLING - HYDRO
30 - HANDLING - OTHER
31 -
32 -
33 - INCOMPLETE OPERATION
34 - BAD THREADS
35 - SHAFT RUN OUT
36 - EXPERIMENTAL PART
37 - DISTORTION
38 - PART BROKEN
39 - PART LOST
40 - BAR STOCK CUT OFF
41 - TRACEABILITY LOST
42 - WRONG PARTS ISSUED
43 - UNMATCHED HALVES
44 - OUT OF CONCENTRICITY
45 - OUT OF PARALLEL
46 - OUT OF PERPENDICULAR
47 - SUPERCEDED DRAWING
48 - ERROR ON BILL OF MATERIAL
49 - CLERICAL ERROR
50 - ERROR ON ROUTE CARD
51 - MATERIAL DEVIATION
52 - DOCUMENTATION NOT RECEIVED
53 - DOCUMENTATION NOT COMPLETE
54 - DOCUMENTATION INCORRECT
55 - DUPLICATE SHIPMENT
56 - OVER SHIPMENT
57 - ERROR ON PURCHASE ORDER
58 - DOES NOT PASS NDE
59 - DOES NOT PASS PERFORMANCE TEST
60 - DOES NOT PASS HYDRO TEST
*61 - GAGES - LOST & SCRAP
99 - MISCELLANEOUS

DEFECT CODES:

A - MACHINING ERROR
B - ENGR ERROR
C - DEF. PURCH. MAT.
D - METHODS ERRORS
E - FOUNDRY ERROR
F - OTHER DIV. ERROR
G - GOODS DAMAGED IN HANDLING
H - RECOND. FIN PARTS
J - REWORK ON FOUNDRY ROUGH MACHINE JOBS.
K - VENDOR CERTIFICATES NOT RECEIVED WITH MATERIAL
L - IMPROPER VENDOR REPAIR DOCUMENTATION
M. - WELDING ERROR
P - PIECE LOST IN SHOP
S - PIECE BROKEN IN SHOP
T - OPERATION OMITTED
X - N/C TAPE MACHINE ERROR
Z - DEFECT CAUSED DURING PERFORMANCE TEST.

*PERFORMANCE TEST PROBLEM CODES

Defect Code by Item

71. Improper Imp. DIA.
72. Full DIA. Test
73. Marginal DIA. Selection
74. Improper Vane Spacing
75. Lumps and Fins
76 Improper Finish
77. Improper throat Areas
78. Casing Mismatch
79. Improper Assembly
80. Improper Clearances
81. Misalignment
82. Improper Balance
83. Improper Machining
84. Vibration
85. Improper Test
86 Improper Test Curves & Data
87 Improper Test Instructions
88 Performance over Quoted
89. Improper Eng'r Drawings
90 Damage in Handling
91. Defective Seal
92 Noisy bearing
93 Defective br'g 'Hot'
94 Bent Shaft
95 Rub-Contacting
96. Defective Driver
99 Unaccountable

APPENDIX-C

LeBlond Motor and Eddycurrent Drive Specifications

Main Drive Motor

Horsepower---------------------------25

Service Factor----------------------1.15

Revolutions Per Minute---------------1770

Voltage------------------------------208/220/440

Phase--------------------------------3

Cycles-------------------------------60

Frame--------------------------------424Y

Field Amperes------------------------31.8/63.6

Eddycurrent Drive

Horsepower---------------------------30 for one hour

Revolutions Per Minute---------------100 to 1710

Torque-------------------------------93.8 Foot-pounds

Amperes------------------------------3.84

Volts, coupling----------------------60

APPENDIX-D

Specifications For Materials

Ingersoll Rand Company Spec. No. 15

This proprietary specification is equivalent to the American Society for Testing Materials specification A322-E4140. It covers alloy steel rounds in the hot rolled and cold finished conditions. It is produced by an electric furnace process and is deoxidized in accordance with the manufacturers standard practice. The material conforms to the following chemistry:

%C	%Mn	%P	%S	%Si	%Cr	%Mo
.38-.43	.75-1.00	.025 max.	.025 max.	.15-.30	.80-1.1	.20

The material is furnished in the annealed condition with a maximum Brinell Hardness Number of 212 BHN. The bars of material have the heat number stamped on one end, or are bundled and tagged for identification. Test reports showing the chemical analysis and the results of the Brilell test are supplied along with the material.

Physical Properties: None are specified, other than the hardness.

CHROMIUM STEELS

These materials are included in the thirteen percent Chromium stainless steels and are covered by Ingersoll Rand Co. specifications #20 and #20 HTS (heat treated stainless). They are also identified as American Iron and Steel Institute Type 410 and 416. Basically, the stainless steels are alloys of iron to which a minimum of twelve percent chromium has been added to impart the same type of corrosion resistance conferred by pure chromium in chrome plate. A thirteen percent chromium stainless steel will not "rust" or corrode when exposed to weather. To obtain greater corrosion resistance, more chromium is added to the alloy. In the manufacture of centrifugal pumps, thirteen percent is the optimum amount of chromium in the vast majority of applications. The problem facing the manufacturer working with stainless steels becomes the difficult one of choosing the right steel for a particular job.

<u>Ingersoll Rand Spec. 20 Material - AISI Type 416</u>

This specification covers a heat treatable, free machining grade of thirteen percent chromium stainless steels. A suffix is attached to the specification number to designate the specific quality required. For shaft materials, the identifications are numbers 20 COM and 20 HTS. The "COM", or common material, is supplied as hot rolled, annealed bars. The "COM" is frequently omitted and the material is identified simply as "20". The 20 HTS material is similar to "20", but is heat treated to a hardness of 262 BHN, maximum.

<u>Chemical Requirements</u>

The chemistry for each heat of material is determined and reported, and must conform to the following analysis:

	C	Mn	P	S	Si	Cr	Mo
Min.,%				.15		12.0	
Max.,%	.15	1.25	.06		1.00	14.0	.60

Physical Requirements- Specification I. R. No. 20

Yield Strength	Tensile Strength	Elongation	Reduction Of Area	BHN
40,000 psi	70,000 psi	16% in 2"	45%	235 max.

Physical Requirements- Spec 20 HTS

Yield Strength	Tensile Strength	Elongation	Reduction Of Area	BHN
80,000 psi	100,000 psi	15% in 2"	45%	262 max

Note: The material is to be processed so as to have minimum residual stress and shall not be straightened after final stress-relief anneal [16]. This is of vital importance in producing straight shafts.

Other material requirements imposed on the vendors are:

1. Surface Requirements- The material shall be free of scale and similar substances.
2. Quality Requirements- The material shall be sound and commercially free from injurious defects.
3. Tolerance Requirements- Dimensional tolerances shall conform to AISI's Steel Products Manual.
4. Certification- Test reports will accompany all shipments.

Ingersoll Rand Co. Spec. 348 Material - AISI Type 303 Stainless

This specification covers free-machining stainless steel bars conforming to ASTM A 582 Type 303. The material is purchased as hot rolled, annealed bars. It is usually produced by electric arc or by electric induction furnaces.

The ladle chemical analysis must conform to ASTM A 582, 303 and is as follows:

	C	Mn	P	S	Si	Cr	Ni	Mo
min.%				.15		17.00	8.00	.60
max.%	.15	2.00	.20		1.00	19.00	10.00	

Physical Properties

Bars are annealed to a maximum BHN of 262. The bars are processed so as to have minimum residual stress.

Yield Strength	Tensile Strength	Elongation	Reduction Of Area
30,000 psi	75,000 psi	35% in 2"	50%

1. Quality Requirements-The material shall not contain any defects which, due to their nature, degree or extent, prevent fulfillment of the requirements of this specification.

2. Tolerance Requirements-Tolerance and permissible variations in dimensions shall be in accordance with ASTM specification A484. Straightness tolerances will be in accordance with current mill practice for deep well shafting. Each shipment from the mill be accompanied by a tag indicating the order number, heat number, number of pieces and weight of bars. (If this is not spelled out on the order to the vendor, it is implied and expected).

I. R. Co. Spec. 379 - AISI Type 316 Wrought Stainless Steel

This spec. covers soft, conventional and modified AISI Type 316 stainless steel for severe corrosive environments.

Chemical Requirements

	C	Mn	Si	P	S	Cr	Ni	Mo
min.%						16.00	10.00	2.00
max.%	.08	2.00	1.00	.045	.03	18.00	14.00	3.00

Physical properties are not specified, however, laboratory tests usually embrace the following:

Yield Strength	Tensile Strength	Elongation	Reduction Of Area
30,000 psi	75,000 psi	40% in 2"	50%

The material is hot rolled, pickled and machine straightened.

Quality and Tolerance Requirements - These are included in those that are within acceptable limits of good manufacturing and inspection practices.

Tolerances - are in accordance with standards of the American Iron And Steel Institute, and any material failing to satisfy the intent and purpose of the specification is rejected.

I. R. Spec.566 -17% Chromium and 4% Nickel

This specification covers 17-4 PH (precipitation hardened) material and is usually made in electric furnaces.

Chemical Requirements

	C	Mn	P	S	Si	Ni	Cr	Cu	Cb&Ta
min.%						3.00	15.00	3.00	0.15
max.%	.07	1.00	.04	.03	1.00	5.00	17.50	5.00	0.45

Physical Properties

Tensile properties are determined and reported:

Yield Strength	Tensile Strength	Elongation	Reduction Of Area	BHN
105,000 psi	135,000 psi	16% in 2"	50%	277

Test procedures to determine the physical properties are in accordance with standards ASTM-A370 of the American Society For Testing Materials.

Inherent Structural Requirements

It is essential that bars be processed through rolling, precipitation hardening and straightening in such a manner that they will remain straight during machining.The bars shall be straight within 0.090", total indicator reading.

I. R. Spec. 814 - AISI Type 410 Stainless Steel

This specification covers quenched and tempered, 12 percent chromium stainless steel conforming to ASTM A276 Type 410, condition "T" with added requirements of "pump shaft quality", defined as a special mill product for designation of bar stock processed to special straightness tolerances and minimum residual stresses. Following conventional processing of hot rolled, quenched and tempered, bars shall be stress-relieved and checked for straightness.

Chemical Requirements

Chemistry is to be in accordance with AISI Type 410:

	C	Mn	P	S	Si	Cr
min.%						11.50
max.%	.15	1.00	.04	.03	1.00	13.50

Physical Properties

The quenched and tempered material shall meet the following minimum tensile properties:

Yield Strength	Tensile Strength	Elongation	Reduction Of Area	BHN
80,000 psi	100,000-psi	15% in 2"	45%	262

Quality and Tolerance Requirements

The material is to be sound and commercially free of injurious defects. The dimensional tolerances shall conform to AISI Steel Products Manual. Bars shall be straight within 0.090", total indicator reading as determined on rollers placed one foot from each end.

APPENDIX-E Cameron Master Routing Sheet

CAMERON MASTER ROUTING 03237

DATE 17DC79 PAGE 1

JOB NUMBER	QUAN	U/M	FINISH	START	PT	SIZE	SYMBOL	NOUN	PL	REV	RTG	REV	EFFECTIVE DATE
					MP	311	B	10			21	00	31JA79

------------- P A R T N U M B E R -------------

DRAWING NUMBER	MATL SPEC	LIST NO.	PART NAME / DESCRIPTION	PIRC
311810X55	20		SHAFT	

BRANCH ORDER	LOCATION	ORD	PRIMARY RTG	WEIGHT	RAW MATERIAL SPEC
			21	56.6 P	20

RAW MATL NAME BAR STK DIAM 3.000 LGTH R U/M IN

RAW MATL PART NBR RAW MATL CLASS CODE ENGR MJM

MATL-PER-PC 28.281 CHUCK LGTH STD CUT LGTH 28.281 U/M IN STD QTY 1

REV	DATE	REV	DATE	REV	DATE	REV	DATE	REV	DATE	REV	DATE	REV	DATE	REV	DATE
00	31JA79														

Q.C. RELEASE DATE :

SIGNATURE :

OPER NUM.	REV	LOD-CTR MACH-NO	PRODUCTION STANDARD	SET-UP STRD	TD/RS STD	OPERATION DESCRIPTION / TOOLING LIST	MACH MAN	SEQ NBR
105	00	91 193				INSPECT & RECORD, IF REQUIRED	01	02
110	00	61 291 M 0049	CE 0.153	0.30		CUTOFF	11	02
115	00	61 303 M 9811	CE 0.140	0.20		CENTER	11	02
120	00	31 084 M 0496	E 0.280	0.50		SPOT FOR STEADYREST AT 18"	11	02
125	00	31 013 9009		2.50		SET UP OPER #130	11	02

CONTINUE NEXT PAGE

CAMERON MASTER ROUTING 03237

DATE 17OC79 PAGE 2

JOB NUMBER	QUAN	U/M	FINISH	START	PT	SIZE	SYMBOL	NOUN	PL	REV	RTG	REV	EFFECTIVE DATE
					MP	311	B	10			21	00	31JA79

PART NUMBER

DRAWING NUMBER	MATL SPEC	LIST NO.	PART NAME / DESCRIPTION	PIRC
311810X55	20		SHAFT	

BRANCH ORDER	LOCATION	ORD	PRIMARY RTG	WEIGHT	RAW MATERIAL SPEC
			21	56.6 P	20

OPER NUM.	REV	LOD-CTR MACH-NO	PRODUCTION STANDARD		SET-UP STRD	TD/RS STD	OPERATION DESCRIPTION / TOOLING LIST	MACH MAN	SEQ NBR
130	00	31 013					TURN COUPLING END ALLOW FOR GRIND	21	02
		9809	T	1.000					
135	00	31 013					SET UP OPER #140	11	02
		9809			2.00				
140	00	31 013					TURN OPPOSITE END ALLOW FOR GRIND	21	02
		9809	T	0.470					
145	00	91 193					INSPECT FOR STRAIGHTNESS	01	02
150	00	31 008					STRAIGHTEN, IF NECESSARY	11	02
		M 9066	AER						
155	00	91 193					INSPECT FOR STRAIGHTNESS	01	02
160	00	31 081					GRIND, INCLUDING SHOULDERS	11	02
		9743	CT	0.870	0.80				
165	00	31 003					UNDERCUT FOR THREADS	11	02
		9058					THREADS		04
			E	0.200	0.50		SFPM 400		
170	00	31 003					THREAD	11	02
		9058	E	0.600	0.50		SFPM 400		
175	00	31 064					LAYOUT & MILL KEYWAYS	11	02
		0471	CE	0.890	1.20		SFPM 400		

CONTINUE NEXT PAGE

CAMERON MASTER ROUTING 0323/

DATE 17DC79 PAGE 3

JOB NUMBER	QUAN	U/M	FINISH	START	PT	SIZE	SYMBOL	NOUN	PL	REV	RTG	REV	EFFECTIVE DATE
					MP	311	B	10			21	00	31JA79

PART NUMBER

DRAWING NUMBER	MATL SPEC	LIST NO.	PART NAME / DESCRIPTION	PIRC
311810X55	20		SHAFT	

BRANCH ORDER	LOCATION	ORD	PRIMARY RTG	WEIGHT	RAW MATERIAL SPEC
			21	56.6 P	20

OPER NUM.	REV	LOD-CTR MACH-NO	PRODUCTION STANDARD	SET-UP STRD	TD/RS STD	OPERATION DESCRIPTION / TOOLING LIST	MACH MAN	SEQ NBR
180	00	91 193				INSPECT	01	02
TOTAL			4.603	8.50				

APPENDIX - F

Experimental Run On 15 Pieces Of Spec. 20 (416) Material

Drawing No. 311B10x52, Job No.94-1195.

Tungsten carbide inserts, negative 5 degree top rake.

Special care was taken to dial indicate the various shaft locations before and after machining to determine whether or not eccentricities were being initiated at particular phases of the machining operations. The spots had been ground on the bar stock so that a steady rest could be used, however, the machining was performed without a steady resy. The spots served as convenient reference locations for measuring runout.

First Turning Operation

Dial Indicator readings in thousandths of an inch

Shaft No.	Spot before machining coupling end	Spot after machining coupling end	Barrel after machining coupling end	Coupling end after machining
1	2	20	1	2
2	3	3	1	1
3	1	17	2	1
4	1	2	1	1
5	2	10	1	1
6	2	4	1	1
7	3	8	1	1
8	3	6	1	1
9	2	16	1	1
10	3	14	1	1
11	3	23	2	1
12	3	2	1	2
13	1	4	1	1
14	3	2	1	1
15	3	4	1	1

The lathe was re-setup to turn the opposite ends of the shafts:

Second Turning Operation

Dial Indicator readings in thousandths of an inch (mils)

Shaft No.	Spot before turning thread end	Spot after turning thread end	Barrel before turning thread end	Barrel after turning thread end	Thread end after turning
1	15	-	11	7	1
2	-	2	-	-	-
3	13	1	29	2	2
4	2	1	8	0	1
5	9	1	13	1	1
6	3	1	2	3	1
7	5	1	10	2	2
8	5	1	2	3	1
9	10	1	9	4	1
10	13	1	5	3	1
11	25	2	38	4	2
12	5	2	2	2	1
13	3	2	9	3	2
14	4	2	9	2	1
15	5	1	8	3	1

APPENDIX G

Coolant Specifications

The coolant used on the LeBlond Tape II, N/C lathes is Shell Dromus B, organic type that is diluted with one part of Dromus to nineteen parts of water. In the concentrated form as received, it is a white liquid that is one hundred percent soluble in water. When mixed with water, it has a pH value of about 9.0. It exhibits good corrosion control and protects iron and steel from rusting. It also has low foaming tendency. It is a standard coolant in the shop coolant system.

The LeBlond lathes have reservoirs beneath the floor to which coolant returns after being used on the work piece.

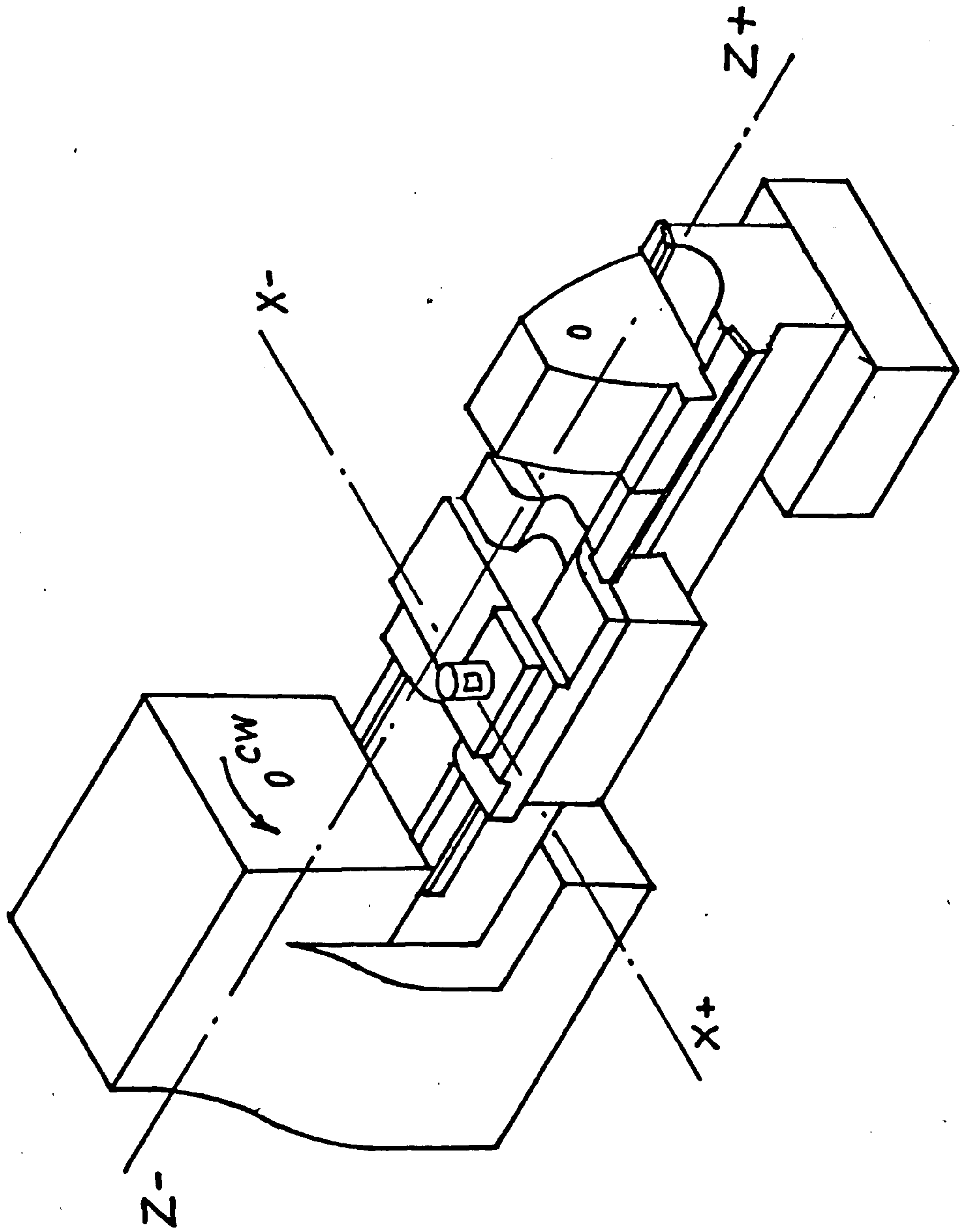
APPENDIX H

LeBlond Lathe Speed vs Diameter

Material Diameter Inches	Program S-Code	Revolutions Per Minute
1.00 to 1.25	529	1000
1.25 to 1.75	528	793
1.75 to 2.25	527	628
2.25 to 2.75	519	500
2.75 to 3.25	518	396
3.25 to 4.0	517	314
4.0 to 5.0	516	249
5.0 to 6.0	515	197
6.0 to 7.0	514	156

APPENDIX I

Axis Nomenclature



Axis Nomenclature LeBlond Tape II Numerical Control Lathe

APPENDIX J

Production Run On 20 Pieces Of Spec #15 (4140) Material

Drawing No. 311B10X33, Job #9809, 95-0127

Tungsten carbide insert, Negative 5 degree top rake.

Pieces machined without a steady rest.

Total dial indicator readings of shafts machined on coupling end were:

Shaft No.	At Barrel mils	At End mils
1	0	0
2	1	1
3	3	16
4	0	1
5	0	1
6	1	1
7	7	18
8	1	0
9	0	1
10	0	0

Inserts changed to positive 5 degree rake:

11	0	1
12	0	2
13	1	4
14	0	1
15	1	1
16	1	1
17	1	1
18	1	0
19	1	1
20	1	1

The positive rake inserts produced a better surface finish, produced more shafts per cutting edge (about 3 to 1), and yielded more consistency in shaft straightness.

The machine was re-setup, and the opposite, or threaded end of the shafts were machined. For convenience, the shafts were machined in the reverse order and the following readings were taken:

(Machined with positive rake inserts)

Shaft No.	At Thread End	At Barrel	At Bearing
20	1 mil	4 mils	1 mil
19	1	9	1
18	1	7	1
17	1	8	1
16	1	8	1

At this time, it was decided to again machine a shaft using the steady rest. The resulting shaft showed:

15	8	9	11

The poor results indicated that the steady rest should not be used, so it was removed for the remaining 14 pieces:

14	1	8	1
13	1	7	1
12	1	5	1
11	1	5	1

The inserts were changed to 5 degree negative rake for the remaining 10 pieces:

10	1	10	1
9	1	8	1
8	1	13	1
7	1	3	1
6	1	7	1
5	2	11	1
4	2	10	1
3	1	8	1
2	1	8	1
1	1	10	1

The shafts machined with positive rake inserts are evidently straighter than those machined with negative rake inserts. It was not necessary to in-process straighten the shafts from number 11 to 20, inclusive.

VITA

Edward H. Fry, the author, was born in Phillipsburg, New Jersey on November 9, 1915 to John and Mabel Fry. He graduated from Phillipsburg High School in 1933, and after working in industry for four years, attended Lafayette College where he earned his Bachelor of Science Degree in Electrical Engineering in 1941. He was awarded a Masters Degree in Business Administration by Lehigh University in 1965. He is presently employed as a Senior Engineer in the Cameron Pump Division of the Ingersoll Rand Co.