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Deep Rolling of Crankshafts

by

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INTRODUCTION

The ultimate goal in crankshaft manufacturing is to reduce the cost related to manufacturing while maintaining or increasing product strength and reliability. This fact holds true whether the crankshaft is for an automotive engine, a tractor, diesel, or small utility engine. Undercut fillet and tangential fillet deep rolling are manufacturing processes that produce both cost savings and fatigue strength reliability.

An undercut fillet with subsequent deep rolling will provide savings of hundreds of thousands of dollars while increasing fatigue strength up to 300%. A tangential fillet, deep rolled, is the most economical processing method when fatigue strength is a major consideration in the crankshaft design. Fatigue strength increases of up to 160% have been realized through tangential fillet rolling. Whether strength increase or cost savings are desired in the manufacturing of crankshafts, the deep rolling process must be considered.

DEEP ROLLING CONCEPT

In order to make this paper more comprehensive, the writer believes it advisable to review the principles of deep rolling and cold working. Deep rolling is basically an extension of the roller finishing or the roll burnishing process. Roller finishing is a process through which a premachined cylindrical component is cold worked, under relatively high working forces. These forces just exceed the yield strength of the metal and cause plastic deformation of the surface metal. Any type of plastic deformation performed cold is cold working, and generates a residual compressive stress.

Roller finishing is primarily employed to generate particular surface characteristics. These characteristics are:

- fine surface finish
- high bearing area (more load carrying surface)
- increased wear resistance
- surface hardness increase
- low coefficient of friction
- uniform surface structure
  - a.) compressive stress
  - b.) no irregularities, therefore no stress risers

Roller finishing primarily works on the peaks of the surface finish generated by the previous operation. The peaks are not bent over or broken,rather the high force causes cold flow of the peaks and expands them to fill the valley voids.

The compressive stress generated by roller finishing is the key to the deep rolling process. Because deep rolling utilizes forces up to five times greater than those forces used in roller finishing, the residual compressive stresses become deeper, hence "deep rolling". Many fatigue failures result from tensional stresses, therefore, having a surface in compression offsets any tendency towards such a failure. It is this deep compressive stress that resists the fatigue loading on many component parts such as the fillets of steering knuckles, tensile bolts, fasteners and crankshafts.

All of the surface characteristics produced by roller finishing are produced by the deep rolling process. Moreover these characteristics are even more profound. Specifically a much more uniform and penetrative compressive stress is generated. Xray defraction tests have shown that the effective depth of the residual compressive stress exceeds 0.12 inches. Another dramatic characteristic is hardness increase in the fillet. It is a fact that cold working will produce a hardness increase (work hardening) and generate compressive stresses. Cold hardening often occurs in machining operations when it is not desired. The work hardening of fillets in various component parts is desired because it protects the fillet from damage in subsequent handling. The following chart shows hardness increases on various metals that have been deep rolled:

Material	Hardness (Brinell)	
	Before Rolling	After Rolling
Aluminum	102	122
Brass	116	155
B-1112 Steel	140	195
Carbon Steel (1040)	176	222
Stainless Steel (416)	210	273
Cast Iron	185	260
Forged Steel 1045	Rc34	Rc55

The technique of cold working is almost as old as metal working itself. Blacksmiths employed it to improve physical properties of sabers, swords, and sickles. The hammering process soon became known as hammer-peening, and was used exclusively in industry for increasing longevity of various component parts.

From hammer-peening developed the process now called shot peening. This method of cold working was developed to improve strength of metal components. Shot peening is carried out by blasting or hurling a rain of small steel shot at high velocity against the surface to be peened. An advantage of shot peening is the various configurations which can be cold worked. However, it is not completely effective for parts which are subjected to reversing stresses. In addition, the compressive stress level imparted is not easily reproduced and is not uniform.

The consistency of stress level generated by deep rolling is assured by the hydraulic control of the input force on the tool and the fact that the work rollers are uniform in size. Low hydraulic pressures are required because the small area of the contact between the work roller and the piece part. These low hydraulic pressures produce high unit or cold working pressures. Again it is this high unit pressure causing plastic metal flow that develops the residual compressive stress.

TANGENTIAL CRANKSHAFT FILLET DEEP ROLLING

Tangential fillet deep rolling was first employed by a U.S. Automotive Manufacturer in 1962 after long, successful history in Europe. This process is carried out by forcing a special work roller against the fillet of a finished ground crankshaft. Figure 1 shows this principle. The radius on the roller conforms to the radius of the fillet for perfect cold working. A back up roller counters the force exerted by the work roller. Applied hydraulic pressures up to 320 psi to the lever arms, that retain the deep rolling tools, yield work contact pressures of approximately 400,000 to 500,000 psi. These pressures vary with changes in material and fillet size. Rotating the crankshaft provides cold working 360^0 around the fillet. (See Figure 2.) The force required can be determined as follows.

Special Rolling Force Calculation

The rolling force required for deep rolling is a function of compressive stress desired in the fillet, the tensile strength of the material, the length of rolling zone, and the diameter of the work roller and workpiece in contact with the roller. The rolling force calculation is developed from the Hertz stress theory for contacting cylinders or balls. The formula is a means of determining the proper force required to develop the specific area pressure. It has been determined experimentally that the specific area pressure should be approximately four times the ultimate tensile strength of the workpiece.

The following empirical formula applies:

$$G = \sqrt{.175 \times \frac{F \times E}{B} \left(\frac{1}{\frac{D_1}{2}} + \frac{1}{\frac{D_2}{2}} \right)}$$

G = specific area pressure in psi,
F = rolling force in lbs,
E = modulus of elasticity in psi,
B = contact area in inches,
D_1= diameter of work roller in inches,
D_2= diameter of workpiece in inches.

Like all deep rolling operations, the high unit pressures on the fillet produces high residual compressive stresses in the surface. In recent crankshaft tests compressive stresses in the magnitude of 60,000 psi were measured by Xray defraction. The material measured was a C1045 steel. These same deep rolled crankshafts showed a fatigue strength increase of 95%. Figure 3 shows an S-N diagram and the fatigue strength increase.

The PSI values on the chart are the actual hydraulic pressures used to force the deep rolling tools into the fillets. Note that lowering the hydraulic pressure on the tool arm decreases the fatigue strength but not in proportion to the pressure decrease itself. It is this pressure-fatigue strength relationship that enables manufacturers to select the degree of fatigue life increase or strengthening factor. Therefore, controlling the system pressure controls the product reliability.

The deep rolling (cold working) process also improves the surface finish and fillet geometry. These characteristics eliminate any surface stress rising effect. Stress risers are potential failure areas since they are tensional stress zones. Deep rolling eliminates these zones. Fretting corrosion and general resistance to corrosion are also eliminated by cold working the surface.

The following case studies are specific examples of crankshaft deep rolling applications:

CASE STUDY I

In the early 1960s one automotive manufacturer experienced crankshaft fatigue failures on a newly developed engine.

Their design program called for increased power without redesign of the crankshaft. The increased power meant more loads on the crank. Major redesign of the type needed for engine safety factor would prolong the engine production and add prohibitive costs.

Two basic fatigue strength increasing techniques were studied and tested; they were shot blasting and deep rolling. This manufacturer found various shortcomings with the shot blasting process. It was rejected because of the large equipment size and high maintenance cost. Perhaps the most important reason, though, was the uneven forces produced in the crankshaft radii. The basic design of the crankshaft also made shot blasting unpredictable and unreliable. The sidewalls and the counterweights interfered with the line of shot.

The other method studied was that of deep rolling. Test results of a deep rolled crankshaft were much more consistent and impressive than any previous method used to increase fatigue strength. Figure 3 indicates these results. Deep rolling of this steel crankshaft showed an average increase in fatigue strength of almost 100%. The fatigue tests were conducted on a resonant tuning fork apparatus, setup to operate at 200 cycles per second. These results convinced the manufacturer to deep roll their crankshafts.

CASE STUDY II

Another automotive manufacturer producing steel crankshafts for a high performance engine considered switching to nodular iron. The switch to nodular iron would save manufacturing costs due to ease of machining, but more important it would provide substantial savings in material. This manufacturer estimated these savings at $10.00 per shaft. The main consideration was, could a nodular iron shaft be made to comply with engineering strength specifications.

Tuning fork tests were conducted with results showing that tangentially deep rolled fillets produced a minimum fatigue strength increase of 50%. As a result of extensive tests showing that the crank would not fail, the manufacturer made the decision to install deep rolling equipment. This decision allowed material and manufacturing savings.

CASE STUDY III

Tractor and diesel engine manufacturers have the same crankshaft strength and life problems as automotive manufacturers. One such manufacturer attempted to increase the power output of an engine, and ran into crank failures in the fillet. Employing the deep rolling process (described earlier in this paper) enabled them to increase horsepower without the concern for failure.

Not only was reliability gained, but manufacturing cost savings was realized. (The induction hardening equipment necessary to increase the strength would have been extremely more expensive than the deep rolling equipment invested in.)

CASE STUDY IV

Fatigue problems are not confined to the automotive and tractor industries. A manufacturer of single piston utility engines (lawn mower, snowmobile, etc.) also experienced a crankshaft failure. A combination of pin bearing and foundry problems caused a particular engine crankshaft to fail. The bearing problem was solved by induction hardening; however, it created a fatigue point in the fillet of the crankshaft. The crank failed the 1000 hour test. A deep rolled crankshaft with induction hardened bearings surpassed the 1000 hour test. Even deep rolled crankshafts made from sub-standard castings surpassed the required engine test. It is easy to see why this manufacturer specifies deep rolled fillets.

CASE STUDY V

Another method of providing strength increase to a crankshaft is tuftriding. This technique is a salt-bath nitriding process. Compared with the cold working technique, a tuftriding installation is an extremely expensive capital investment. It is also costly to maintain and operate. Users of the process have said that its effects are inconsistent and produces cranks which fail prematurely.

One manufacturer who was sending his nodular iron crankshafts to an outside source to be nitrided investigated the deep rolling process. The investigation revealed that rolling produced a substantial increase in fatigue strength over the nitrided shaft. Figure 4 discloses the fatigue test results. Nitriding increased fatigue strength 50% over that of an untreated crank; while deep rolling produced a fatigue strength of 160% over the base line crank. This increase is 82% greater than nitriding produced.

SUMMARY OF TANGENTIAL DEEP ROLLING

Tangential crankshaft fillet deep rolling not only provides fatigue strength increase, but offers a crankshaft manufacturer appreciable cost savings. Add to this product reliability and the process becomes extremely attractive.

UNDERCUT FILLET DEEP ROLLING

The application of the undercut fillet technique has been used in Europe since World War II. More than 25 engine manufacturers in Europe and Japan employ the method for economy and/or strength. In the United States, however, the majority of crankshaft bearing fillets are produced by tangential grinding. All of the advantages described in the previous section on tangential fillet rolling apply to undercut rolling with the addition of substantially higher cost savings.

For purposes of this paper, the present industrial grinding process as well as undercut fillet rolling will be evaluated.

FILLET GRINDING PROCESSING

Pin bearings and some main bearing fillets are predominantly produced by grinding. Figure 5 indicates how this method is carried out. A critical part of the operation is the grinding wheel dressing. Two typical dressing methods employed are single point (or rotary diamond) and diamond impregnated rotary form dressers. (See Figures 5 and 6.)

The single point type dresser forms the proper shape by following a tracer attachment. One problem can occur on the return dress cycle. This return will leave a stress riser near the bearing tangent point on the crank pin when the pin diameter is ground. (See Figure 6.) It should be pointed out that this method of dressing is employed on pin bearing diameter grinders. Single point dressing is also time consuming and frequently cuts into the time cycle. Diamond form or plunge dressing provides a more accurate fillet; however, it requires a much greater dollar investment. Either wheel dressing method costs valuable machine down-time.

Since the grinding wheel is called on to perform three grinding operations, i.e. sidewall, fillet, and bearing diameter; wheel breakdown and wear is high. Many crankshaft manufacturers find it necessary to dress a grinding wheel after grinding each pin bearing. This frequent dressing is especially required to eliminate side wall burn.

UNDERCUT FILLET DEEP ROLLING PROCESSING

The object of the undercut fillet deep rolling technique is to eliminate side wall and fillet grinding. This allows the grinding wheel to do the job it is supposed to perform, that of grinding on the periphery only. Eliminating the fillet and sidewall also simplifies and speeds up the dressing cycle. It further, and most important, decreases the grinding cycle time.

Undercut fillet rolling requires preliminary turning of the bearing fillets. (See Figure #7.) The side walls are turned to the proper width and finish with the same button tools that produce the undercut fillet. All four pins are turned simultaneously. The pin bearing diameter is also turned with a broadface tool as the fillets are being cut. This procedure decreases the amount of stock normally remaining on the diameter and, therefore, further decreases the grinding time. Proper turning equipment is necessary to locate and turn the side walls and fillet as shown in Figure 8.

Following the turning operation, the crankshaft fillets are deep rolled. Figures 9 and 10 show the position of the work roller during the operation. The type of fillet radius produced by the button tool reduces the fatigue strength of the crankshaft. Applying fillet rolling, not only restores the original fatigue strength level, but increases it to a minimum of 40% and up to 300%. The residual compressive stress setup in the fillet reach 60,000 psi. This stress is generated by the high working pressure on the rolls exceeding the elastic limit of the material as previously discussed in this paper.

With the fillet undercut and rolled, the crankshaft is prepared for a simple grinding operation. Figure 11 shows why the grinding cycle is decreased. Instead of grinding 3/8" to 5/8" of sidewall, there is none to grind. No grinding obviously reduces the cycle time and eliminates sidewall burn. The tangentially processed ground fillet is also gone. All that remains to be ground is the bearing diameter.

With the reduction in grinding cycle time, there is a reduction in capital investment for grinders. The grinder reduction is proportional to the cycle time reduction. Reducing capital equipment also means a tax base decrease. Less grinding equipment provides more floor space. There is also a favorable labor reduction factor to be considered.

Since sidewall and radius dressing have been eliminated, the number of dressing cycles is also reduced. Reducing the number of wheel dressings accomplishes two more cost savings advantages. First, wheel life is substantially increased. Wheel selection can then be made to grind one surface more efficiently. The other savings is reduced diamond dresser cost. Less dressing means more overall diamond life.

Providing a favorable condition for the grinding wheel enables a finer surface finish to be generated on the pin bearing diameter. Controlling this surface finish enables the pin bearing and main bearing finishing equipment to perform more economically and to conform to part print specifications more easily. The following case studies all verify the above comments; i.e., cost savings and fatigue strength increases.

CASE STUDY VI

One automotive manufacturer indicated in a previous case on tangential fillet rolling, investigated the undercut fillet rolling technique. The investigation determined that deep rolling an undercut fillet on a nodular iron crankshaft produced fatigue strength increases from 40 to 120%, depending upon the rolling force used. Cost savings of well over $1,000,000 was realized by reducing the number of pin grinders required by 50%. Instead of purchasing grinders, four completely automatic pin lathes were purchased as shown in figure 12.

Once in operation, more cost savings became apparent. After one year and no engine failures, grinding wheel use dropped to less than 1/3 of what it had previously been. This alone provided a savings of tens of thousands of dollars. Combined diamond dresser savings and grinding wheel savings amounted to well over $100,000. The manufacturer stated that a much higher quality crankshaft was being produced by employing the undercut rolling technique.

CASE STUDY VII

A study was conducted by Motor Institute Reasearch Association (MIRA), an independent research organization, to determine the bending fatigue strength increase and the effect of radius size related to undercut fillet deep rolling. The data obtained from their fatigue tests are tabulated below.

Material	Fillet Radius	Fatigue Strength in 1000 lbs/sq.in. at 10^7 test cycles	
		Not Rolled	Rolled
Steel (1046)	1/16"	26.0	51.2
	1/8"	34.0	53.4
	3/16"	38.8	54.
Pearlitic Nodular Cast Iron	1/16"	15.6	53.0
	1/8"	22.0	48.0
	3/16"	21.2	48.0

(See Reference #2.)

Before rolling the strength of the samples showed a marked decrease with a reduced fillet radius. But after rolling, the nominal size of the fillet was of little significance with regard to the bending fatigue strength. Therefore, when designing and processing an undercut fillet little concern has to be placed on the nominal fillet size.

MIRA further stated, "it has also been shown that the strength of rolled components is not reduced by prolonged heat cycling and aging". (Reference #2.)

CASE STUDY VIII

A particular European automotive manufacturer practically doubled the horsepower of an engine by making the transition to undercut fillet rolling. After selling for many years in the United States, it was decided to increase the power output of the engine. One way was a design change; make the engine larger. Such an undertaking would cost an unpredictable sume of money. The company, aware of the strength generating capabilities of the cold working process, was able to utilize deep rolling to eliminate the redesign.

Instead of applying deep rolling to existing tangential fillets in a nodular iron crank, management decided to implement cost savings with undercut fillet rolling. This decision paid off for manufacturing in cost savings and engineering by eliminating costly redesign. Because of the almost two-fold increase in horsepower, the automobile became more marketable.

CASE STUDY IX

In a translation of German paper written in January, 1964, entitled "Deep Rolling Improves Fatigue Strength of Nodular Cast Iron", (test source unknown), the beneficial effect of deep rolling as applied to crankshafts was discussed. Fatigue tests were conducted on nodular iron test bars and crankshafts.

The test bars used were standard for Schenk Rotary Bending Fatigue Test Machine. Carefully prepared, ground and unrolled bars were selected as were deep rolled test bars. The sample pieces, Figure 13, held firmly at either end, were rotated at 12,000 RPM on the Schenk testing machine. Various stresses were applied as shown on graph, figure 14. The graph clearly shows that at 10 million cycles the fatigue strength of a deep rolled specimen is 42% higher than the unrolled specimen.

Fatigue testing of crankshafts was also carried out on standard resonant tuning fork equipment. Dramatic results of fatigue strength increase are illustrated on graph Figure 15. Again at the endurance limit of 10 million cycles, the fatigue strength of a deep rolled crankshaft is 4 times that of an unrolled crankshaft (or 300% increase in fatigue strength).

CASE STUDY X

Another manufacturer of large displacement engines invested in the undercut fillet deep rolling process on a nodular iron crankshaft purely for economics. Their justification was primarily geared to eliminate the need to replace old grinders. The cycle time savings by employing the undercut method resulted in the elimination of up to 50% of the normally required grinders. By eliminating sidewall and radius dressing, the proper wheel selection could be made. So instead of dressing after every pin, the dress cycle could be extended to every two to every five complete crankshafts. This meant a substantial reduction in grinding wheel use and diamond dresser replacement.

Employing the undercut technique eliminated the critical problem of relying on one grinding wheel to generate the proper size on the pin bearing diameter and the width of the same pin from sidewall to sidewall. This more accurate method of producing size by two independent operations produced less crankshaft rejects. Surface finish on the undercut pin and main bearing diameters resulted in relaxing the demand on the final bearing diameter finishing operation. Product Engineering conducted resonant vibration tests on crankshafts for fatigue strength and reported substantial increases in fatigue life over the previous crankshafts. No fatigue strength figures were made available by this manufacturer. There was no change in crankshaft design, except the adding of undercuts to the pin bearings.

(NOTE: At the writer's discretion no absolute dollar savings values were presented in these case studies; likewise, no manufacturers'names were mentioned.)

CRANKSHAFT DEEP ROLLING EQUIPMENT

Whether tangential or undercut fillet deep rolling is applied, the machines would be identical (See Figure 16). There are only minor differences in the configurations of the work rollers. All pin and main bearing journals are rolled simultaneously. The crankshaft is automatically loaded and contained on the main bearing diameters.

Once in position, the tools are closed under hydraulic pressure. When the proper rolling pressure has been reached, the crankshaft is rotated at 60 RPM, basically as it is driven in an engine. The driving motion is provided by the pin bearing tools and holders. The pin tool holders are mounted to two master crankshafts (standard engine crankshafts) which are rotated, causing the work piece to rotate.

Rolling continues for approximately 17 revolutions (overrollings) on an undercut fillet or for approximately 35 revolutions (one revolution per second) on tangential fillets. At the end of the cycle, the working pressure on the tooling is slowly reduced; the tools are opened, and the crankshaft is automatically unloaded from the work area. The machine cycle is fully automatic.

Lubrication is provided during rolling for various reasons. It acts as a flushing agent at the beginning of the cycle to flush dirt away from the rolling area. Longer work roller life will be experienced because of the cooling and wetting effect. This wetting effect of the work rollers eliminates the threat of galling. The surface finish in the fillets is also reduced when a lubricant is used. This fine finish makes the deep rolled fillet easy to spot and differentiate from an unrolled fillet. The oil being of light viscosity equivalent to mineral seal oil (55 to 60 SSU at 100°F) is filtered continuously. It should have high e.p. (extreme pressure) characteristics in order to withstand the high area pressures of rolling without being squeezed out from between the roller and the fillet.

SUMMARY

It has been shown that deep rolling will eliminate such processes as tuftriding (nitriding), shotpeening, shot blasting, and induction hardening. Major design changes can be eliminated since fatigue strength can be restored. Less expensive nodular cast iron can be used without fear of crankshaft failure. The fact that cold working of fillets results in substantial fatigue strength increase, means product reliability. The reduction in grinding time with the undercut fillet technique produces substantial cost savings. All of these reasons, summed up into three words "savings, quality and reliability", substantiate the employment of crankshaft fillet deep rolling.

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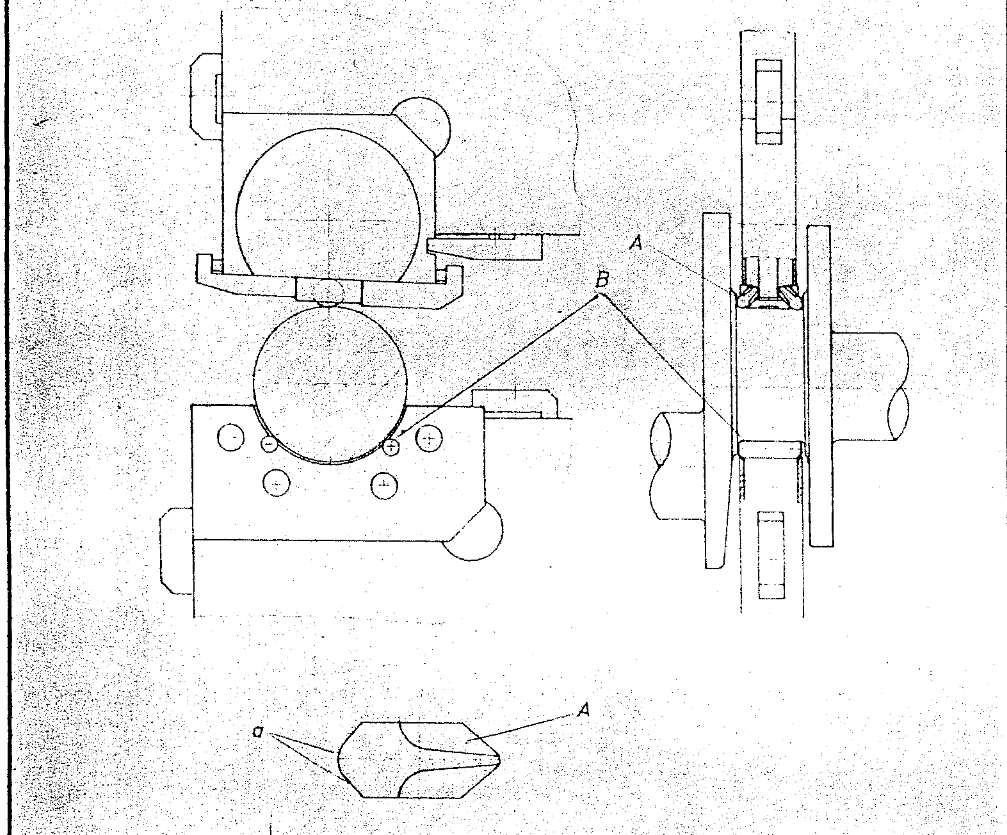
6.) Naumann, Hans J. "Deep Rolling of Highly Stressed Components", ASTME Technical paper MF68-169, p. 1-7.

7.) Author unknown "Deep Rolling Improves Fatigue Strength of Nodular Cast Iron". Translation of German paper, Jan., 1964- p. 4-20.

CRANKSHAFT DEEP ROLLING

TOOLING

Tooling for the Tangential Fillet Rolling Process



A = Work Roller in Assembly

B = Back Up Roller in Assembly

a = Full Fillet Profile

Figure 1.

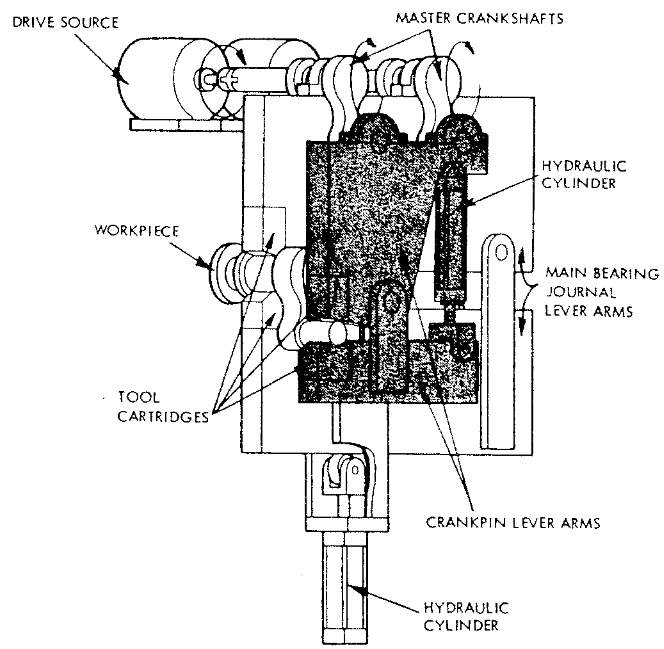
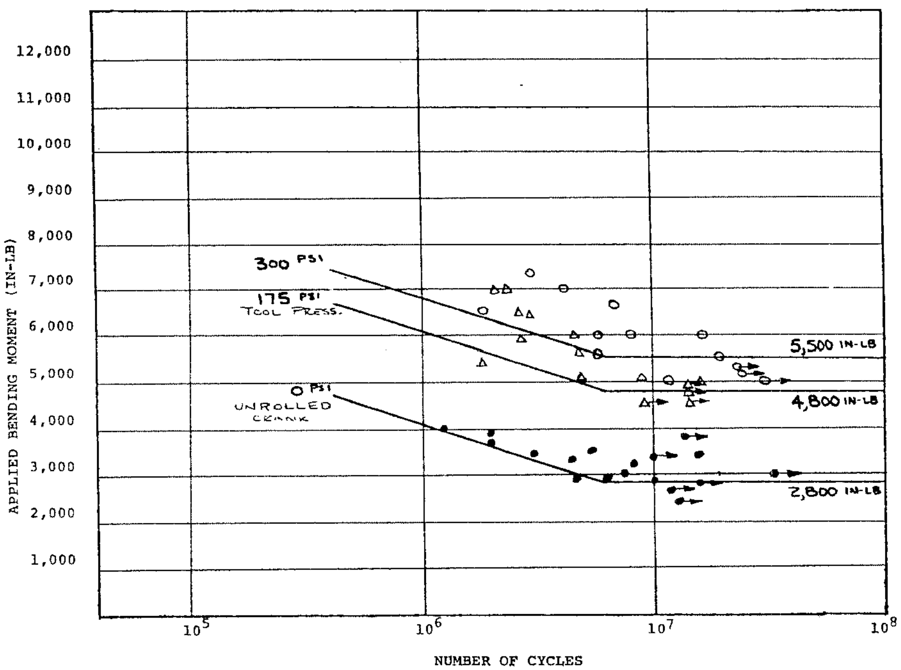


Figure 2.



RESONANT TUNING FORK TEST

Figure 3.

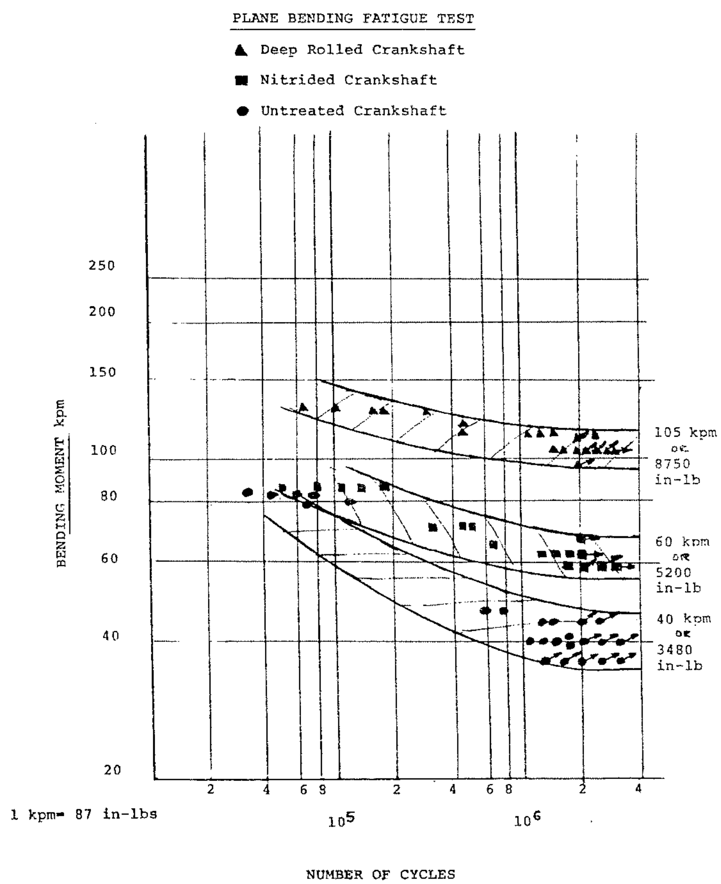


Figure 4.

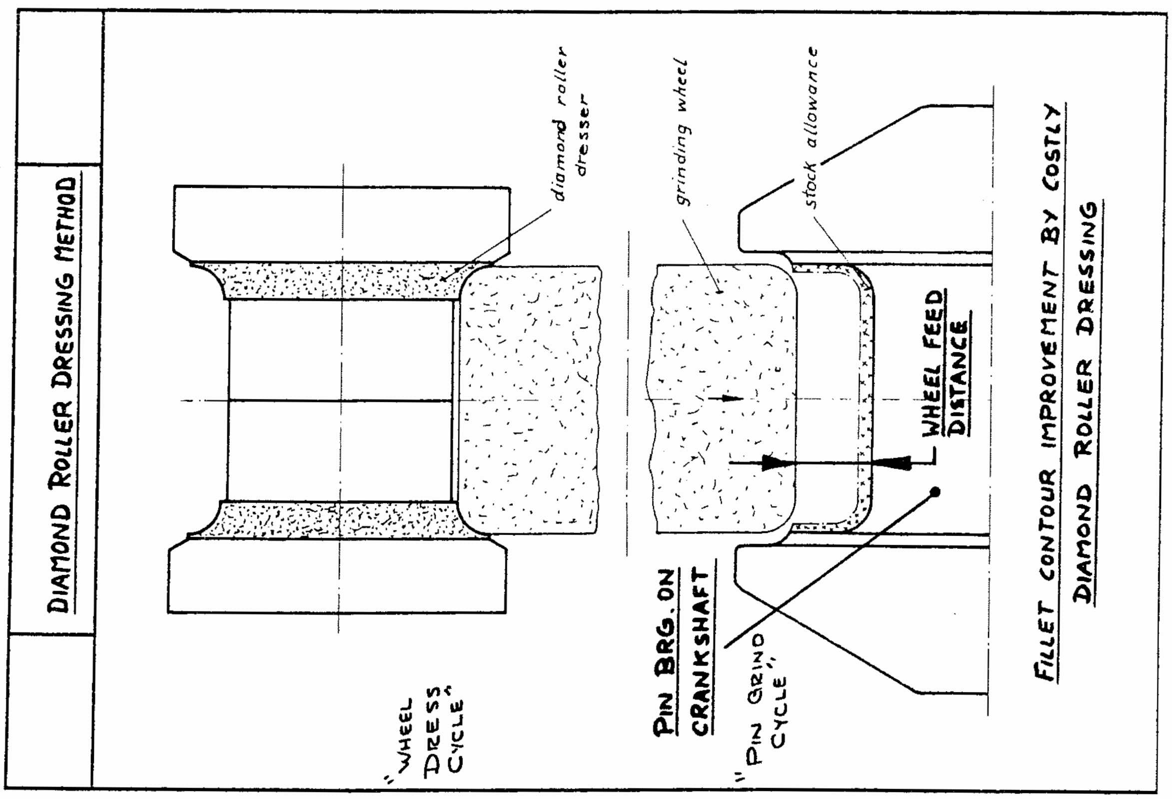


Figure 5.

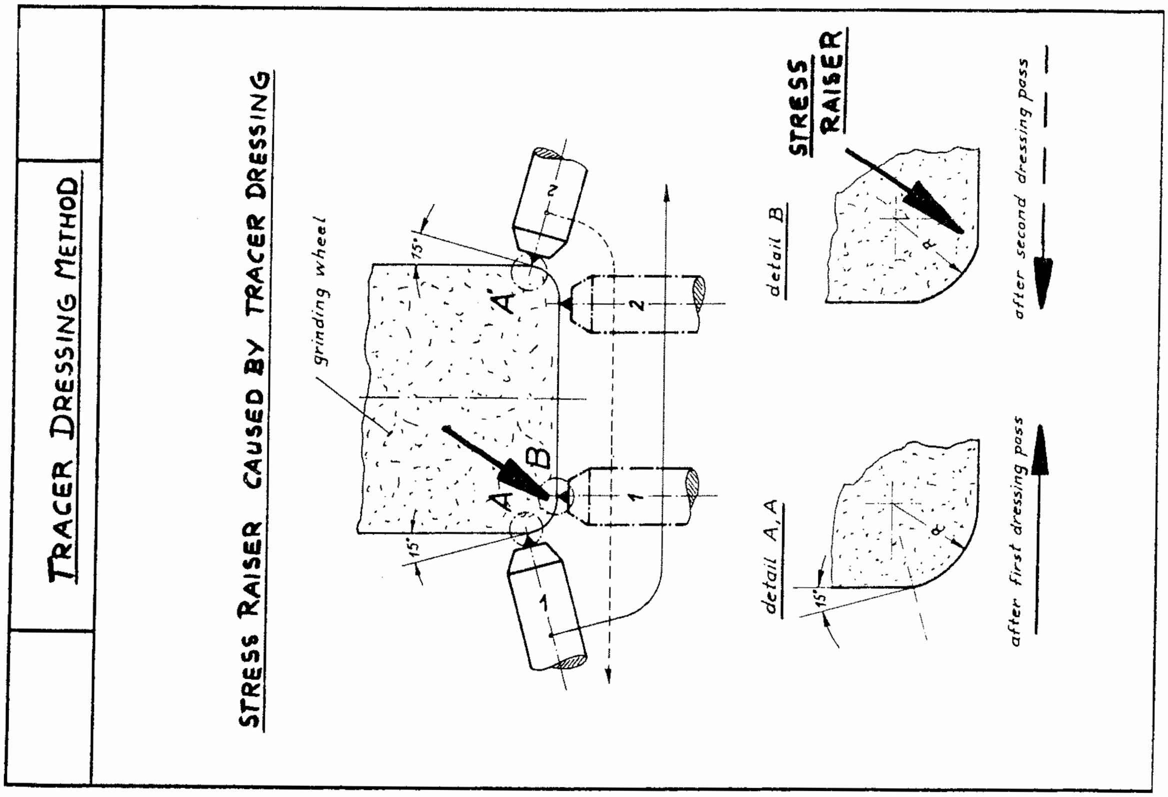
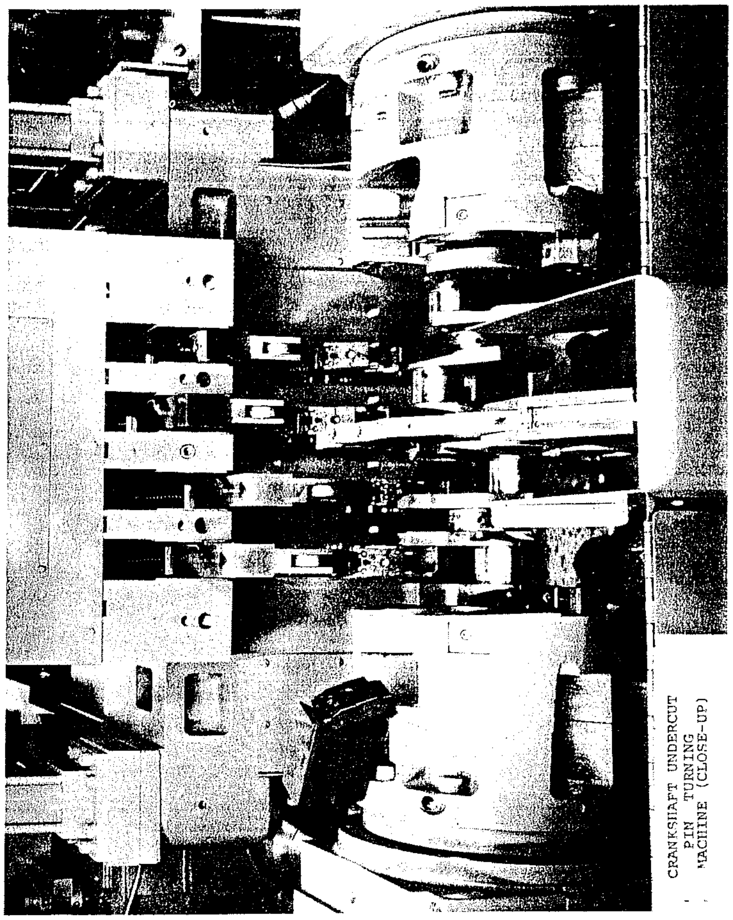


Figure 6.



CRANKSHAFT UNDERCUT PIN TURNING MACHINE (CLOSE-UP)

Figure 8.

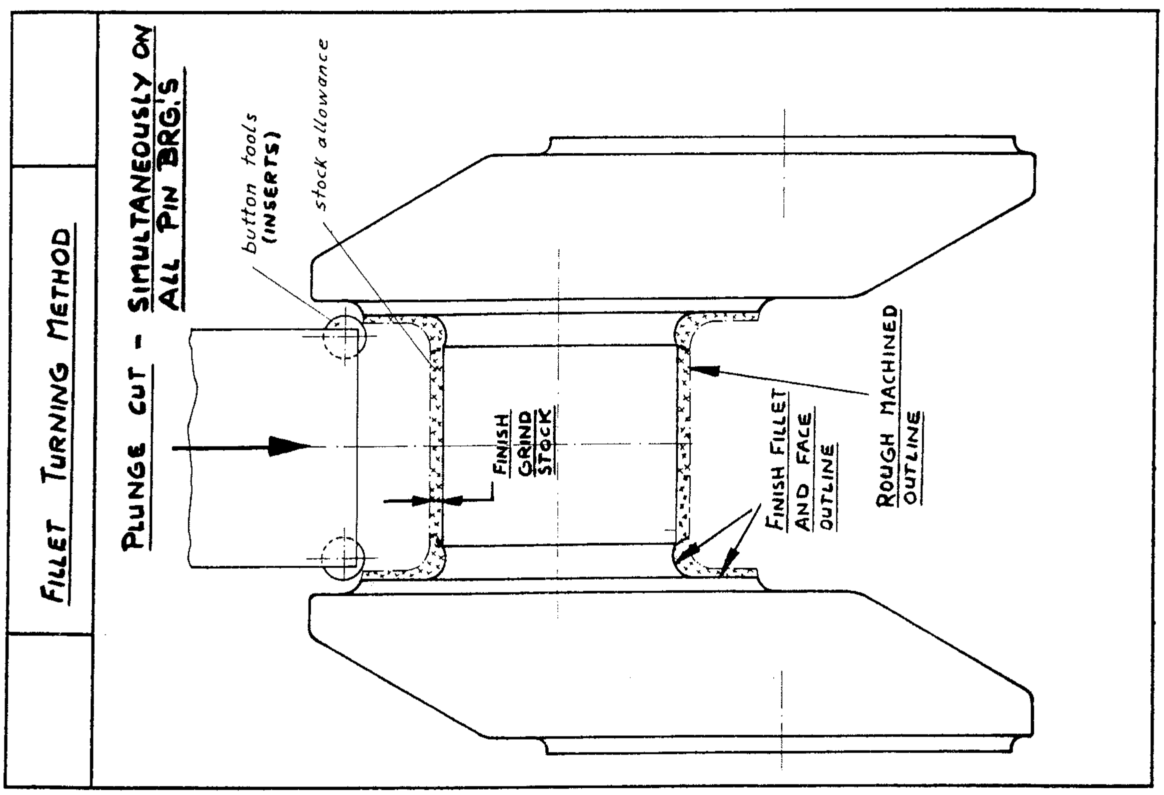
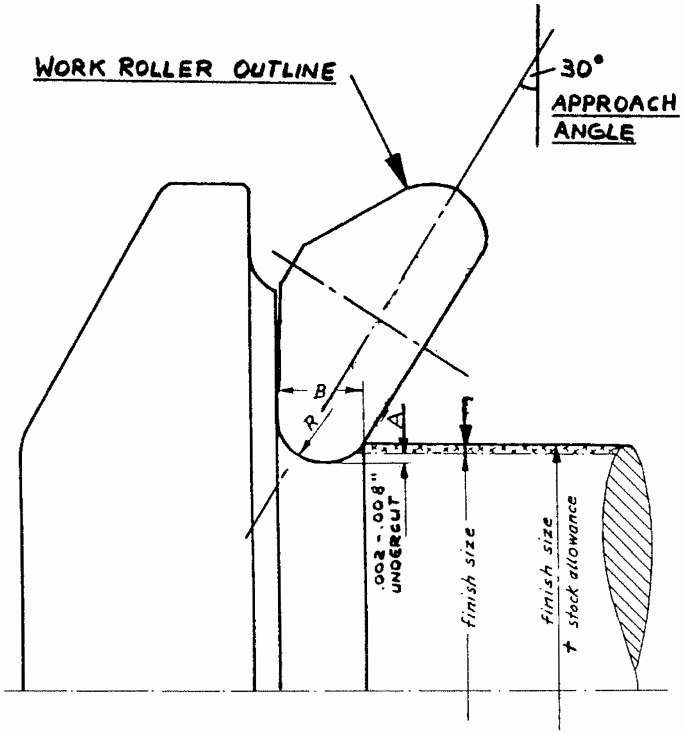


Figure 7.

UNDERCUT FILLET ROLLING



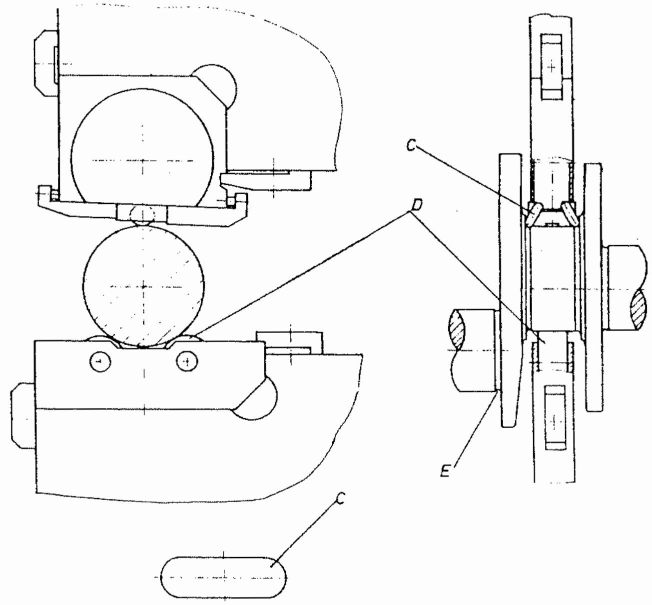
UNDERCUT FILLET ROLLING PRIOR TO FINISH GRINDING.
THIS PROCESS HOWEVER CAN ALSO BE PERFORMED AFTER FINISH GRINDING.

Figure 9.

CRANKSHAFT DEEP ROLLING

TOOLING

Tooling for the Undercut Fillet Rolling Process



C = Work Roller in Assembly

D = Lower Back Up Roller in Assembly

E = Undercut Fillet

Figure 10.

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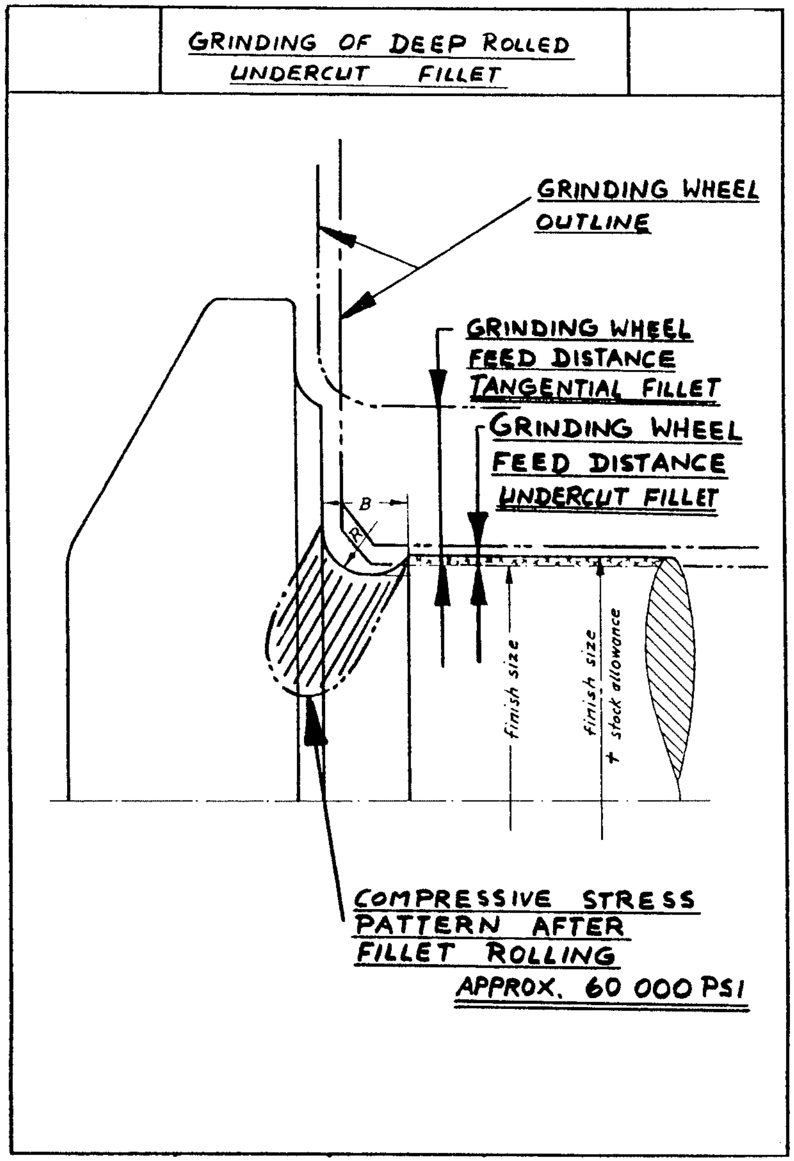


Figure 11.

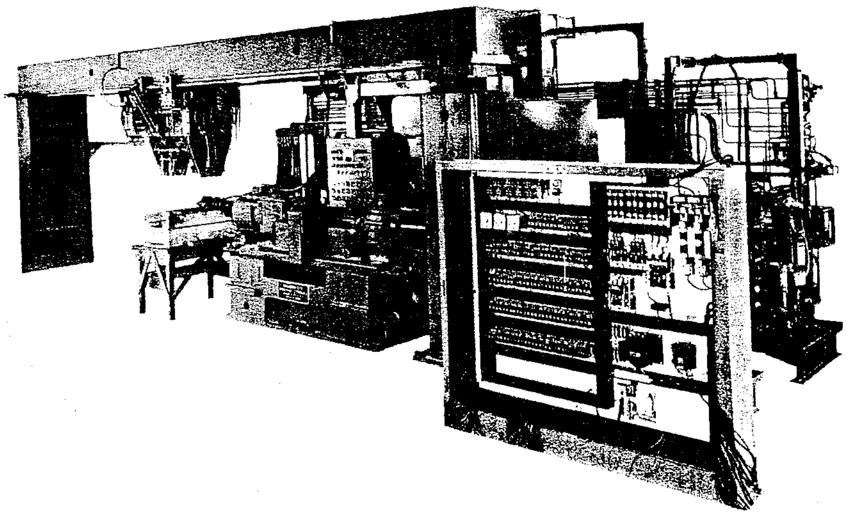
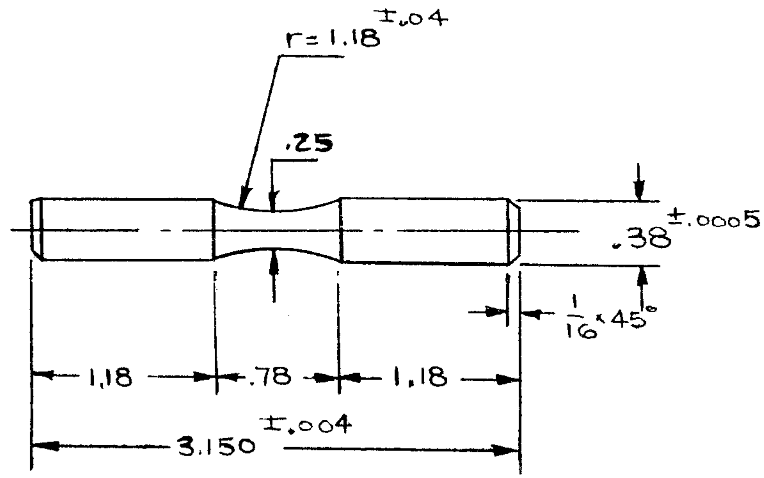


Figure 12.



SCHENK ROTARY STRESS TEST-BAR

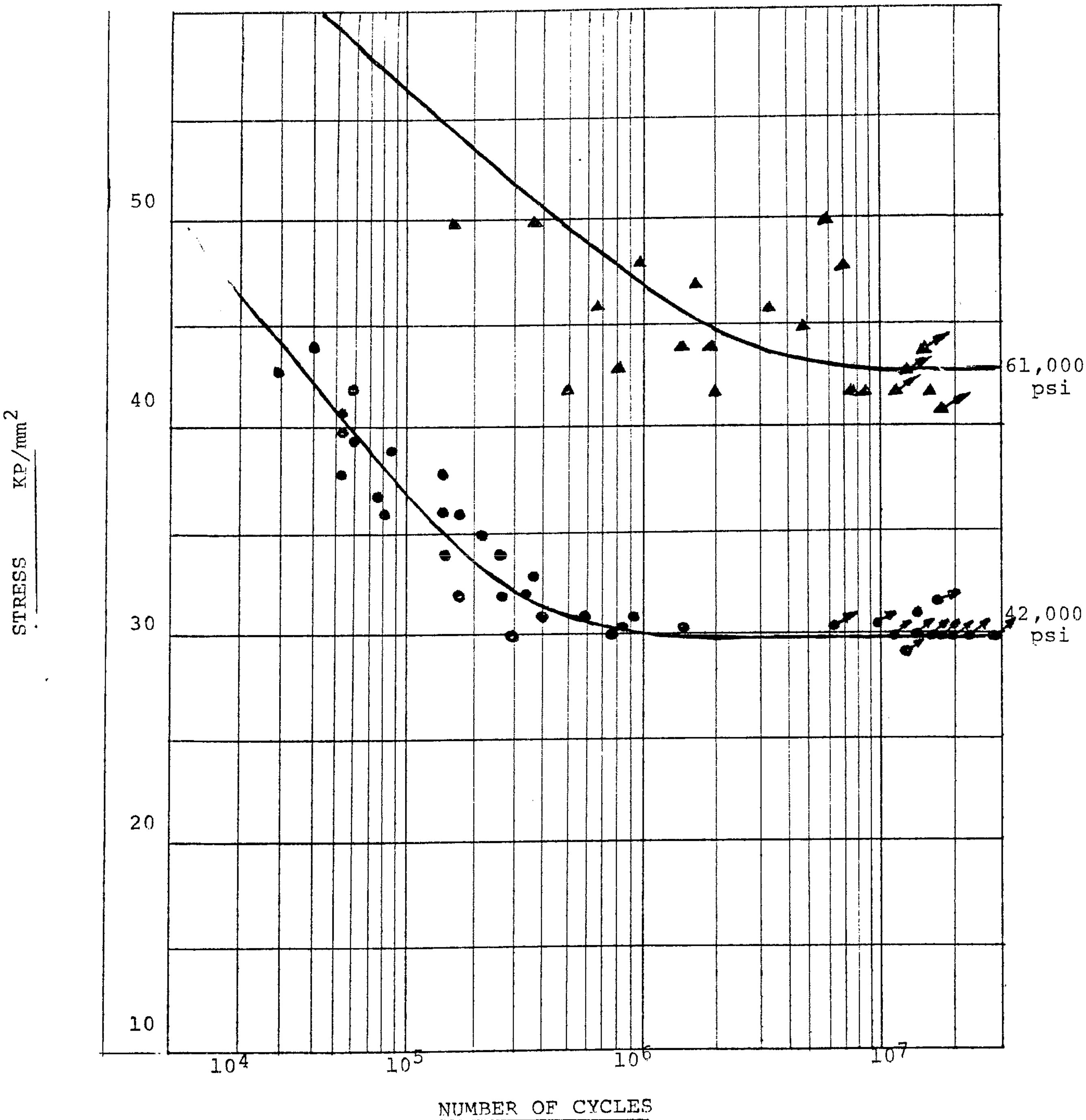
Figure 13.

S-N DIAGRAM

ROTARY BENDING FATIGUE TEST ON TEST BARS

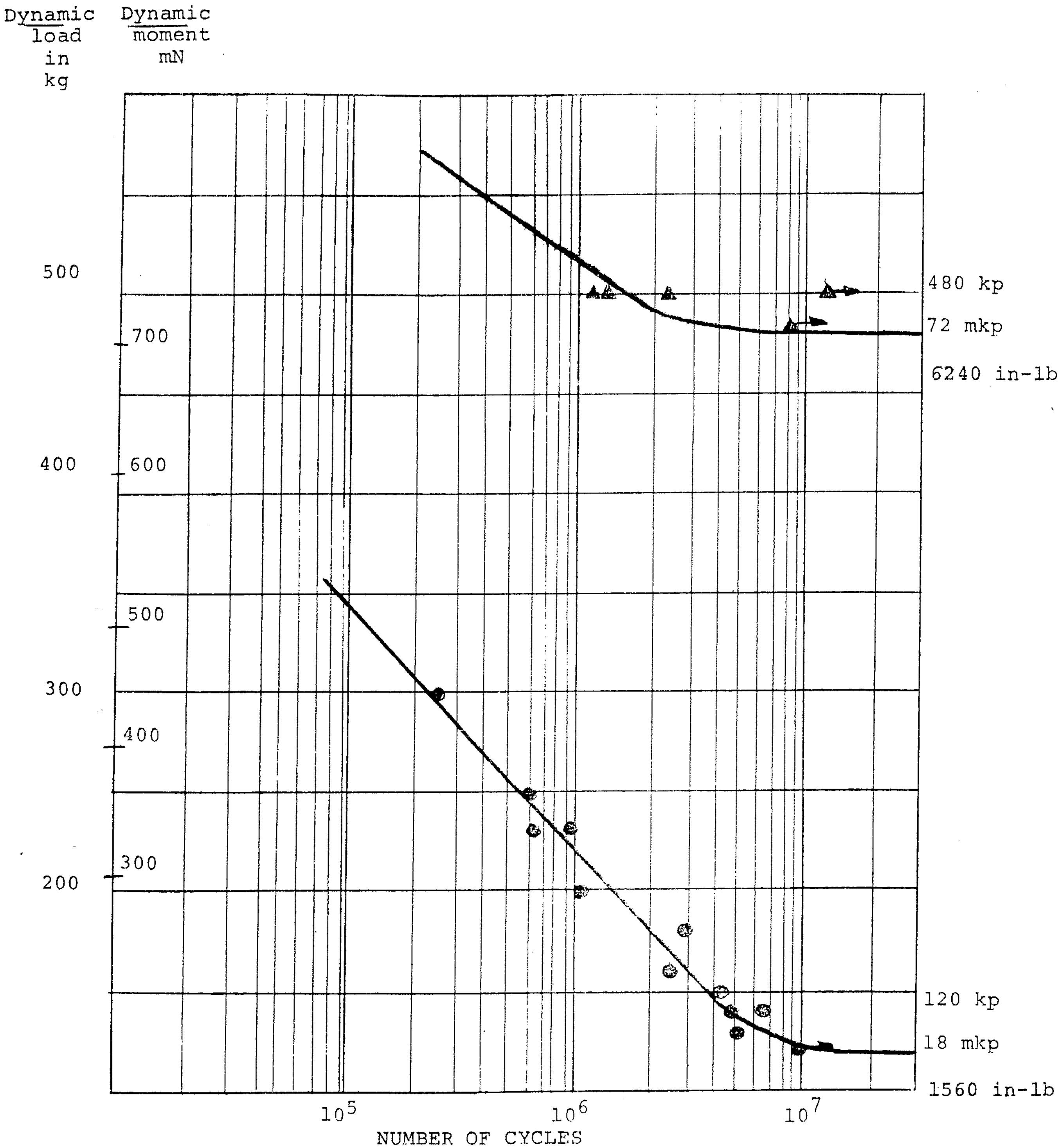
● Stress on Unrolled Bars

▲ Stress on Deep Rolled Bars



(1KP/mm^2 = 14,22 psi)
(Reference No. 3)

Figure 14.

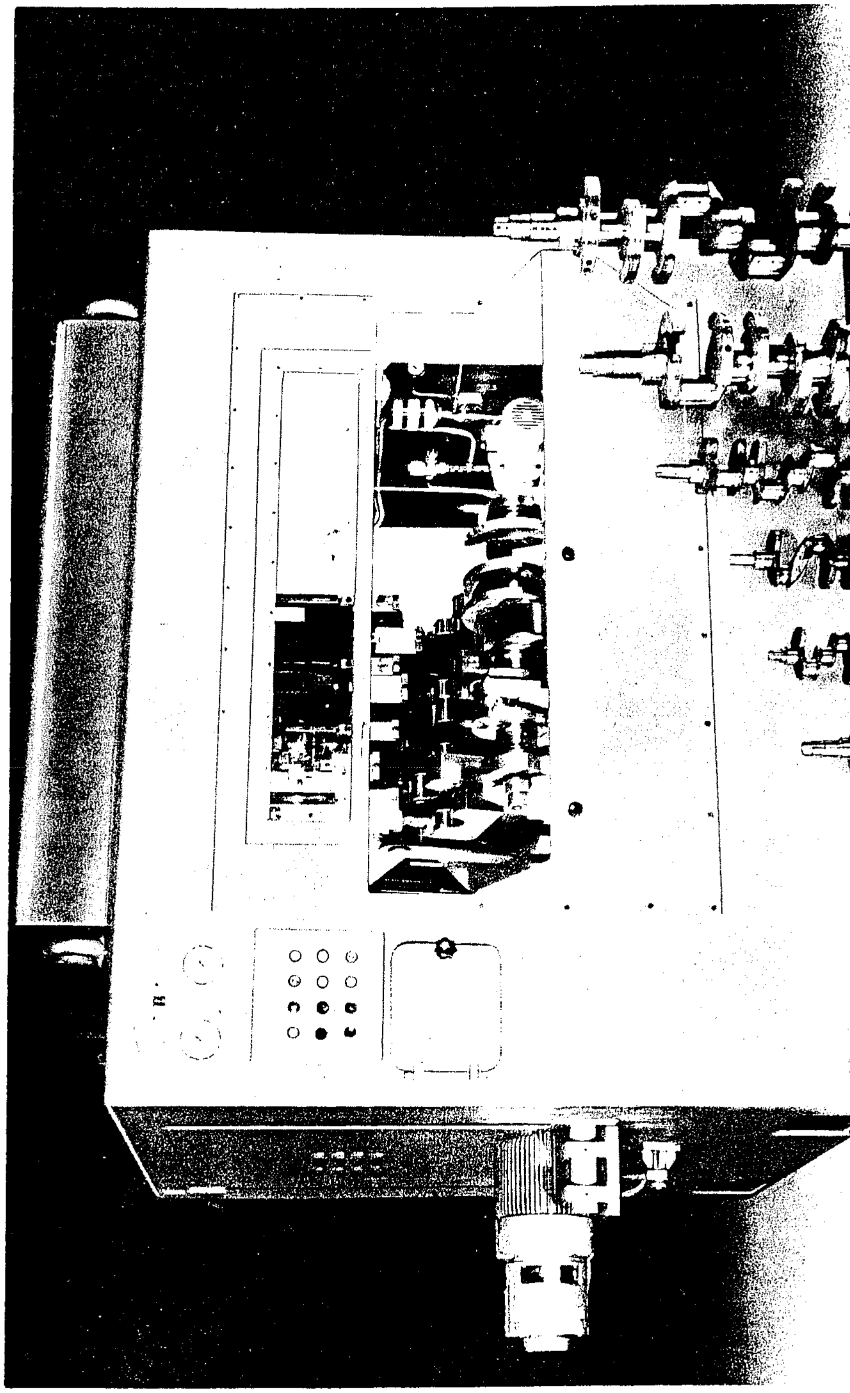


▲ CRANKSHAFT FILLETS DEEP ROLLED

● CRANKSHAFT FILLETS UNROLLED

WOHLER CURVES - BENDING FATIGUE TEST

(Reference #3)



CRANKSHAFT DEEP ROLLING MACHINE

Figure 16.