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Surface Rolling and Other Methods for
Mechanical Prestressing of Metals

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1. Scope

2. References

2.1 Applicable Publications—The following publications form a part of the specification to the extent specified herein. Unless otherwise indicated the latest revision of SAE publications shall apply.

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3. *Applications of Mechanical Prestressing (by George A. Butz)*

- 3.1 Introduction**—The word "prestressing" implies that a stress is applied prior to service. For the purposes of this discussion this is true, but insufficient, definition. It must be extended to say, by virtue of a localized pressure on the surface of a part, that the surface of the part in the vicinity is stressed in tension beyond its elastic limit. When the pressure is removed, the surface elements tend to retain part of the total deformation experienced under pressure. Since this is resisted by subsurface layers which did not exceed the elastic limit, the surface and adjacent layers are left in a state of compressive residual stress.

The two most widely used methods of mechanical prestressing probably are surface rolling and shot peening. Since the process of shot peening has been rather widely discussed in previously published literature, the greater part of this manual is concerned with surface rolling and its theory, load specification, tooling, control, and effects. Methods briefly considered include hammer peening, cold pressing, and treatment of small holes with balls or tapered pins. The general aims of this manual are:

1. To give the reader a general understanding as to what mechanical prestressing is and whether it may be expected to help him with his product.
2. To help him choose a process.
3. To help him get started in tool design and preparation of test samples. At this stage of development of the art, the optimum prestressing conditions and degree of performance improvement should be established by objective and destructive tests, unless one has ample previous experience on similar materials and products.

Mechanical prestressing methods affect the surface layers of a part in at least three ways, the relative amounts being affected by the process and the material:

1. Compressive residual stresses.
2. Cold work or strain hardening.
3. Surface geometry or finish.

It is usually quite difficult to assess the individual contributions of these effects on the improvement in performance attained. The consensus, however, is that the compressive residual stress is the most potent of the three. These effects are discussed in later sections of this report.

While mechanical prestressing methods are now used in many various industries, most of their development and application has occurred in the transportation industry. This might be attributable to the intense competition which fosters development work, continually driving toward the attainment of maximum strength in minimum space and weight with low-cost alloys and processing. In meeting these goals, prestressing methods have made some of their most impressive accomplishments. The following list of parts is not intended to be comprehensive, but rather gives an idea as to the variety of parts where worthwhile gains in performance have been obtained:

1. Aircraft—Propellers, engine parts, wheels.
2. Marine—Propeller shafts, engine crankshafts.
3. Automotive—Coil and leaf springs, torsion bars, front axle spindles, crankshafts, wheels.
4. Railroad—Car axles.

Significant increases in performance have been obtained by prestressing techniques. Under certain conditions, the fatigue strength of specimens has been more than doubled (3).¹ Improvements of this order are not possible in all fatigue situations, nor in all materials. Furthermore, where they are possible, the optimum prestressing conditions must be worked out by objective performance tests. Once these are established and production specifications are set up, the processing engineer must insist that these specifications be met on every piece processed. Mechanical prestressing is unique because there are no simple, nondestructive, or even destructive, tests which can be routinely used to check whether a particular part has been properly prestressed, although certain laboratory methods can be used to measure residual stress. One must inspect the process rather than the part. Even then, subsequent processing steps can reduce or cancel the benefits obtained. These steps could include honing or other finishing, straightening, overheating, and so forth.

1. Numbers in parentheses in text and tables refer to references at end of report.

3.2 Improving Fatigue Resistance—An overwhelming majority of prestressing applications are aimed at improving performance under fatigue loading conditions (cyclic stressing). A detailed discussion of the relative contributions of residual stresses, strain hardening, and surface smoothness to fatigue resistance is beyond the scope and intent of this report. Although it is admittedly oversimplified, acceptance of the premises that initial fatigue cracking is associated with stresses in surface layers and that fatigue cracks are propagated by tensile mean stresses will lead to at least a qualitative understanding of the role of prestressing.

The fatigue situations in which prestressing might be considered may be divided into four arbitrary classes as follows:

1. "Normal" Conditions—No high stress gradients, no surface degradation from processing or service.
2. "Designed" Stress Concentrations—Fillets, grooves, transverse holes, and so on.
3. Surface Degradation From Service and Environments—Corrosion, fretting, wear, mechanical abuse (nicks, gouges, and related misuses).
4. Negative Effects of Fabricating Processes—Machining, grinding, unfavorable heat treatment, plating, anodizing, straightening, and so forth.

The data in Table 1 is illustrative of all these classes. Rolling increased the strength of the smooth specimen by 21%. The harmful effect of a sharp notch was cancelled when the specimens were rolled before notching. Exposure to a corrosive medium before testing reduced the strength of a machined specimen to 69% of the baseline. Companion specimens, which were rolled before exposure, not only exceeded the base line, but were equal to those which were rolled, stored, and tested in laboratory atmosphere. An overbending (intended to simulate a straightening operation), in which the smooth specimen was statically loaded in the test machine to a total strain of 2.5%, left a very undesirable situation on the side of the specimen which was in compression under the static load. The fatigue strength was reduced to 55% of the baseline, a more harmful effect than was caused by the sharp notch. Although the strength of a similarly bent specimen was raised 73% by rolling, it was not brought back to the baseline.

TABLE 1—RELATIVE IMPROVEMENTS IN FATIGUE STRENGTH OF A HIGH STRENGTH ALUMINUM ALLOY PROVIDED BY A PARTICULAR SURFACE ROLLING, 1.5 IN. DIA. SPECIMENS IN REVERSED BENDING (1)

Treatment Specimen	1,000,000 Cycle Strength, % of "As Machined"	Improvement Due to Rolling, %
As Machined	100	—
As Machined + Roll	121	21
As Machined + Notch (0.020 in. deep)	61	—
Roll + Notch (0.020 in. deep)	105	71
As Machined + Corrosion	69	—
Roll + Corrosion	122	77
As Machined + Overbent	55	—
Overbent + Roll	95	73

Table 2 shows how the bending fatigue strengths of steel crankshafts and specimens with fillets were increased by rolling. Increases of 19% for the mild steel specimens and of 25% for the alloy steel crankshaft were noted. A computed maximum contact pressure of 400,000 psi was used in rolling the specimens of mild steel.

**TABLE 2—IMPROVEMENTS IN FATIGUE STRENGTH OF STEEL:
(A) SPECIMEN OF 1.5 IN DIA WITH 3/8 IN FILLETS AND
(B) CRANKSHAFT FOR 4 1/4 × 5 IN DIESEL WITH 0.145 IN FILLETS.
EACH TESTED IN REVERSED BENDING (2)**

Results From	Steel	Max Fillet Stress (ksi) For 1,000,000 Cycle Life	Max Fillet Stress (ksi) For 1,000,000 Cycle Life	Improvement Due to Rolling, %
		Not Rolled	Rolled	
Specimen (A)	UNS No. G10430			
	SAE/AISI 1043 (Normalized)	42.0	50.0	19
Crankshaft (B)	UNS No. G41400			
	SAE/AISI 4140 (300–340 Bhn)	55.0	69.0	25

Another case history is illustrated by Table 3. Mild steel shafts were first tested as normal type (rotating bending) fatigue specimens, where it was established that 20% higher strength was obtained by rolling. Specimens were then tested while held in a bushing where fretting was undoubtedly present at the maximum stress area. The effect was to drop the strength of the ground specimen to less than half of those tested in more conventional fashion. The fatigue strength in this environment was doubled by rolling. This almost brought the strength back to that of the original ground specimen, tested without bushing.

**TABLE 3—ENDURANCE LIMIT OF NO. 45 STEEL
(0.48% C, TENSILE STRENGTH = 92,500 PSI) (3)**

Test Specimen	Fatigue Limit (ksi)	Strength Improvement Over Ground Specimen, %
Conventional Rotating Beam:		
Ground	39.0	—
Rolled	45.7	20
0.69 in dia Cylindrical, Tested as Cantilever Beam Held in Steel Bushing, Causing Fretting Corrosion:		
Ground	18.0	—
Rolled	36.2	101
Rolled + Light Grind	37.2	106

A comprehensive study of surface rolling was made by Atkin and Mezoff (4). It is concerned with the effect of rolling on magnesium alloys and the development of a prestressed magnesium wheel for military use. Some of the results are summarized in Table 4. Markedly different degrees of improvements were indicated for the three alloys tested, ranging from 8–77%. No obvious pattern is established relating the relative degree of improvements from rolling when loaded under complete reversal and zero-to-tension.

**TABLE 4—FATIGUE STRENGTH OF MAGNESIUM ALLOY TEST SPECIMENS,
1.0 IN DIA WITH 5/16 IN RADIUS:
TESTED IN REVERSED AND UNI-DIRECTIONAL BENDING (4)**

Magnesium Alloy UNS No.	Magnesium Alloy SAE No.	Loading	1,000,000 Cycle Fatigue Strength	1,000,000 Cycle Fatigue Strength	Improvement Due to Rolling, %
			As Machined	Rolled	
M16600 (ZK60A)	524-F (Wrought)	Reversal	±18.7	±22.7	22
		O-Tension	25.4	27.5	8
M11800 (AZ80A)	523-F (Wrought)	Reversal	—	±25.7	—
		O-Tension	21.0	30.5	45
M11810 (AZ81A)	505-T4 (Cast)	Reversal	±11.5	±19.0	65
		O-Tension	13.0	23.0	77

In this same reference, the improvement in fatigue life of actual wheels is also reported, as shown in Table 5. It is characteristic of this product and test method that fretting and other surface damage may occur at high-stress regions. This test showed that the life of a particular wheel design could be extended more than ten times by surface rolling. Because of prestress due to tire inflation, the stress ratio in the critical regions would be positive, i.e., from one level of tension to another. The specific amounts of improvement quoted are only intended as representative figures. The actual amount possible in a given situation can vary widely in response to many effects including specimen type, stress level, rolling techniques, and others.

**TABLE 5—LIFE OF 20 × 7.50 MAGNESIUM WHEEL, CAST SAE 505-T4 [UNS M11810 (AZ81A)];
UNDER ROLL TEST WITH INFLATED TIRE AT 8,000 LB LOAD (4)**

Wheel Description	Life Cycles (Single Specimen)	Location of Fracture
Not Rolled	326,000	Bead seat radius of fixed flange
Bead Seat Rolled	2,018,000	Gutter cracks, bead seat OK
Bead Seat and Gutter Rolled	3,946,000	Wheel OK—Test halted

In summation, these examples show that fatigue strength can be improved by important—but widely varying—degrees with prestressing methods. While worthwhile increases are observed on smooth or mildly filleted specimens, the most impressive accomplishments are in protection against rather superficial surface damage, typified by corrosion, fretting, or shallow notches. This type of damage can be surprisingly effective in reducing fatigue strength of engineering structures where the surface is not prestressed.

3.3 Other Users for Prestressing—Stress corrosion cracking is a mode of failure that is influenced by surface stress, environment, and time. A prerequisite to the start and growth of these cracks is the presence of tensile stresses on the surface. Stress corrosion has been observed in many metals, including copper, lead, stainless steel, iron, brass, magnesium, aluminum, and zinc. It has usually been associated with residual or assembly stresses. Since it is strictly a surface phenomenon in its early stages and is entirely dependent upon the presence of tensile stresses of considerable magnitude, considerable protection is offered by appropriate prestressing. The major factor in this protection is certainly the introduction of compressive residual surface stress.

There are uses of prestressing techniques for reasons other than, or supplemental to, strength improvement. These, however, are usually so specific in terms of interest and material that they will be only briefly described here. The following list is typical of some of these possible uses:

- 3.3.1 **SURFACE HARDENING**—When materials subject to work hardening are mechanically prestressed, the surface layers may be significantly hardened. This may be useful in enhancing resistance to wear or other surface damage.
- 3.3.2 **SURFACE FINISHING**—The "characterizing" of the surface obtained when prestressed is often a useful engineering property. Surface rolling frequently produces a surface so smooth that subsequent grinding or other finishing steps may not be needed. Ball burnishing and some of the techniques used on holes (bearingizing, ballizing, taper plugs, and so on) can produce quite smooth surfaces.
- 3.3.3 **CONTOUR FORMING**—An example of this is the use of rollers or racks to produce strong, accurate threads and splines. Another use of rollers is to form fillets to a desired contour.
- 3.3.4 **SIZING**—Some of the methods, under certain conditions, may perform a useful sizing function. Bearingizing and ballizing are examples of this use.
- 3.3.5 **SURFACE QUALITY CHECK**—All the methods for mechanical prestressing depend on the yield strength of the metal being exceeded, usually by a high, localized pressure. Certain types of metallurgical flaws at, or near, the surface may be rendered obvious because of local spalling when subjected to this high stress. Thus, in a limited sense, the prestressing also acts as a proof test of the surface layers.
- 3.4 Choosing a Prestressing Process**—There are many situations where either shot peening or rolling may be feasible to prestress and a choice is to be made between them. In this situation, there are several factors to be considered:
 - 3.4.1 **GEOMETRY OF AREA TO BE PRESTRESSED**—There are almost no limitations on the shape of areas that may be shot peened, with the exception of small deep holes or slots. Rolling, on the other hand, can usually be applied only to surfaces of revolution.
 - 3.4.2 **RESIDUAL STRESS DISTRIBUTION**—The depth of residual compression that can be set up by rolling is considerably greater than that set up by shot peening, although the surface compressive stress appears to be about the same for both. While there are little available data comparing fatigue strength of identical specimens prestressed by these two methods, one would expect that the potential for improvement by rolling would equal, and probably exceed, that of shot peening.
 - 3.4.3 **CHARACTER OF SURFACE FINISH**—Shot peening will produce a surface whose roughness is generally dependent on the material hardness, shot size, and peening intensity. Rolling generally produces a much smoother surface than shot peening.
 - 3.4.4 **COST**—There are very little available data to support specific statements here. On large or complex areas, shot peening will usually be cheaper, while on smaller areas of simple shape, rolling may be more favorable. A factor that enters the cost situation is the large capital investment required for an efficient shot peening machine, while rolling can be done in common machine tools with a modest tooling investment, unless highly automated equipment is desirable. Parts often require masking before peening and cleaning afterwards. Regardless of the comparison of these two methods, neither are expensive when compared to other methods of precision finishing.
- 3.5 Limitations and Precautions**—There are examples available showing that significant benefits are possible through prestressing practices. As with all potent techniques, certain ground rules must be observed and basic limitations recognized, or trouble may be encountered. In this section, some of these features will be discussed briefly.

3.6 Introduction of Prestress—Perhaps the most obvious precaution here is that all the sensitive area of the part must be covered by prestressing. The operation should cover enough area for its boundaries to be in moderately stressed zones, and all of the intended area must be properly covered.

The size of the part needs to be considered in specifying rolling conditions. The volume of metal which has not been plastically deformed by the working must be at least several times as great as that which has been plastically deformed. This is necessary to insure that appropriate surface compression stresses are introduced without unduly high internal balancing stresses of a tensile nature.

Since the introduction of prestresses depends on a nonuniform plastic action, in general, the dimensions of a part will change when prestressed. In addition to this stress effect, there may be an apparent change in size as a result of change in the geometrical character of the surface. This would be a "lowering" effect when a rough surface is smoothed by rolling, or a "raising" effect when a smooth surface is peened with large shot or a peening tool. Generally, none of these effects are large, but if fits or alignments must be precise, they should be considered.

One of the more subtle limitations on mechanical prestressing is that there is no convenient and practical method for inspecting the work produced. One must concentrate on control of the process. If this is not done diligently, there is the risk of more or less prestressing intensity than intended. If on the low side, the improvement that was counted on may not be obtained. If on the high side, some materials actually may be harmed, with or without apparent visual indication of this damage.

3.6.1 MAINTENANCE OF PRESTRESSES—Once prestresses have been properly introduced, they obviously must be kept present during service. Subsequent processing or unusual service conditions must not cancel the benefits. Machining may cut away some of, or all, the compressive layer. Sufficient exposure to elevated temperature may relax residual stresses. Straightening or stretching operations may reduce or neutralize the deliberately introduced prestresses. Analogous effects may be present in service environments which may jeopardize the effect that prestressing should have on performance.

3.6.2 FUNDAMENTAL LIMITATIONS—One must recognize that the improvements in some particular mechanical property of a part which may be obtained through prestressing may lead to a change in some other property. The compressive surface prestresses are invariably balanced by tensile stresses below the surface. This internally balanced stress system may result in a lowered elastic limit or creep resistance. Under certain conditions, the fatigue resistance may actually be reduced. Examples of this could be small diameter rolled parts tested under axial loading or a relatively thin wall tube rolled externally and tested with fluctuating internal pressure.

The excellent protection against surface abuse under fatigue loading that prestressing gives obviously is limited in the sense that abuse exceeding some depth will be just as harmful, whether the part was prestressed or not. The relationship of this depth to the intensity of working, and knowledge of whether there is any notch depth where the part's fatigue resistance is actually harmed by prior prestressing, are points on which little evidence is available, but which should be useful fields of research.

There are other properties where, in general, little or no improvement is expected. Static tensile strength is one of these. Since this is the origin of the fatigue curve, the improvements should be related in some increasing proportion with increased cycles. Part rigidity or stability are generally considered insensitive to prestressing, as is impact strength. The latter property, however, may bear investigating for sensitive materials.

3.7 Specific Characteristics of Various Materials—In the illustrations used earlier in this chapter, an attempt was made to show responses of a variety of metals. Mechanical prestressing methods (other than shot peening) have been applied to the following materials, with at least some degree of success: wrought steel, at hardness levels ranging up to Rockwell C 45; gray, malleable, and nodular cast iron; cast and wrought aluminum; and cast and wrought magnesium. This list is not intended to be exclusive of other materials.

Optimum prestressing intensities and specific peculiarities of these materials are matters on which little or no published information is available. Certain materials show that a rather well defined optimum prestressing intensity leads to maximum improvement. Others have shown the same order of improvement over widely varying intensities. Some have shown good results with surfaces which were considerably degraded by the prestressing operation, based on visual observation. Others have shown an actual loss in fatigue strength with surfaces which, under casual observation, had an excellent appearance. Since all these observations were based on specific, individual tests, it seems unwise to attempt to generalize the results. As stated earlier, the choice of a prestressing method and intensity should be based on objective tests of the part under consideration, or previous experience with similar parts under similar load conditions.

4. Theory of Surface Rolling for Fatigue Improvement (by C. W. Cable)

4.1 Introduction—Proper application of controlled surface rolling is an effective method for improvement of fatigue performance. This chapter will discuss the reasons for this improvement and note some necessary conditions associated with the typical residual stress systems obtained from surface rolling. For simplicity, the discussion of residual stress distribution is confined to a two-dimensional presentation of unidirectional stresses. The actual application of this theory to a particular part would necessarily include a stress analysis suitable and adequate for that part. It will also be shown that, while local plastic deformation must occur during rolling to obtain necessary prestressing, the combined residual and applied stresses obtained in service should be within the elastic region; any yielding will change the residual stress system.

4.2 Effects of Surface Rolling—There are three principal changes caused by surface rolling to the part:

1. The surface finish is obviously "rolled," "roller burnished," and so on.
2. Surface layers of material are strain hardened or cold worked.
3. Surface layers are plastically deformed during rolling with the result that residual stresses are produced.

Each of these effects can influence fatigue performance. A great deal of work has been done to investigate the relationship of these factors especially with shot peening. The reader is referred to the references for a more complete review of data on this subject.²

It has been commonly accepted for many years that a smoother surface finish will result in fatigue improvement due to the reduced extent of minute surface imperfections. Also commonly accepted is the fact that fatigue failures usually originate at vulnerable stressed surface areas. Accordingly, we may expect that the finer surface finish produced by rolling will contribute to fatigue improvement.

In considering the effects of cold working the surface layers on fatigue performance, it has been shown that, within limits, both tensile strength and fatigue limit are increased by increasing amounts of cold work. The fatigue limit, however, does not increase in proportion to the increase in tensile strength, i.e.: the endurance ratio is reduced. Excessive cold working can even result in a decrease in fatigue strength (5). Since surface rolling actually changes the surface layers of material by cold working, we may expect this to affect the fatigue performance of the part.

These effects are generally considered to be secondary in importance to the effects of residual compressive stresses. It has been shown that heating of shot peened surfaces will reduce fatigue performance, even though hardness and surface finish were not significantly affected (6). Sigwart has reported fatigue improvement by residual surface compressive stresses obtained by quenching (7). Horger has noted that fatigue cracks were initiated at a rolled surface, but that the cracks then progressed at a slower rate than in comparable specimens which were not rolled (11).

2. Numbers in parentheses in text and tables refer to references at end of report.

4.3 Residual Stresses—For the purposes of this discussion, only the simple case of uniaxial stress in a two-dimensional section is illustrated. The necessary extension of the principles outlined herein to more complex analysis can be carried out consistently with the stress analysis required for the particular part. The discussion also assumes that we are dealing with a piece of homogeneous material, i.e., microstresses are not considered here.

Consider a round bar section longitudinally as shown in Figure 1. It has a known or assumed residual stress distribution near the surface as indicated by the heavy line showing the stress distribution across the section. By application of two basic principles of statics requiring equilibrium of forces and of moments, for any transverse section through Figure 1, it can be stated that:

1. The sum of the axial tensile and compressive forces must be equal to zero. If Section A-A, Figure 1, were taken from a flat plate, the areas bounded by the curve and the zero stress line on the compression side would equal the area on the tension side.
2. The opposing moments must be equal so that the sum of these moments equals zero.

The stress distribution curve is shown completed by the light line in a typical shape conforming to these principles. Note that these do not define the intensity of the unknown stresses or their distribution; the exact shape of the curve is not yet determined. It does provide insight, however, into the problems and also accents a very significant point: whenever there is a given prestressed region, as at a surface, there must also be a balancing region of opposite residual stress, usually of different intensity.

Figure 2 shows the same bar as in Figure 1 except that it has been bored out. Note that the tensile stress has been increased, also the compressive stress has been reduced. Further, careful measurement will show that the bar is longer.

Figure 3 shows a narrow strip cut from the tubular section of Figure 2. The strip is bowed, similar to the familiar Almen strip used in shot peening. The compressive stress has been further reduced, but a compressive stress at the opposite surface has also been produced with this relaxation. The necessary moment and force equilibrium has been maintained.

In other words, prestressing means that the part has been mechanically processed so that it contains a desired residual stress distribution which must be balanced both as to forces and moments. The exact distribution is related to process and material.

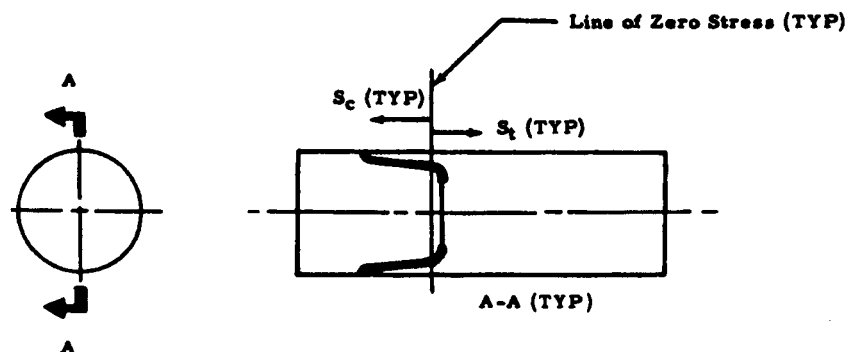


FIGURE 1—LONGITUDINALLY SECTIONED ROUND BAR

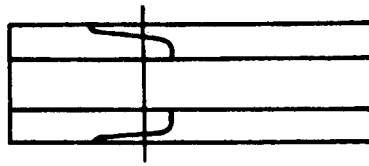


FIGURE 2—LONGITUDINALLY SECTIONED ROUND BAR, BORED OUT

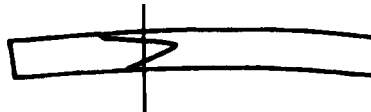


FIGURE 3—STRIP CUT FROM LONGITUDINALLY SECTIONED ROUND BAR, BORED OUT

The previous paragraphs have assumed a part with an existing desired residual stress distribution. To illustrate how the desired stress distribution was accomplished, assume there is a piece of uniform homogeneous material completely free from residual stresses. When, by definition, any loads are applied which produce only elastic stresses, the part will return to its original condition upon release of these loads. Further, if subjected to an assumed uniform plastic deformation, the shape will be altered, but no residual stresses will be produced. Therefore, to produce residual stresses by mechanical means in a part consisting of one piece of a uniform homogeneous material, nonuniform plastic deformation is necessary. This may be accomplished by locally deforming the surface by rolling, or other processes.

The most significant point is that previous local nonuniform plastic deformation has produced the present condition of static residual stress equilibrium. When known or determined, these stresses may be treated by proper application of the theory of elasticity. Local plastic deformation has been illustrated by Sigwart, using, as one example, the displacement and yielding of material under a Brinell ball (7). Essentially, high local contact stresses produce local biaxial tensile yielding at the surface of the part when the deforming load is applied. When this load is released, the yielded material will have been effectively stretched or spread out. The normal complete recovery of the adjacent unyielded material from its elastic deformation is then prevented. An equilibrium condition results where the yielded material is restrained in a biaxial residual compressive stress state by the unyielded material which is essentially in a residual tensile stress state.

In the preceding section it has been stated that a desirable residual stress distribution would improve fatigue performance. How this occurs will now be considered.

Figure 4A again shows a typical assumed residual stress distribution with surface layers in residual compression. It has been shown that mechanical prestressing is obtained by plastic deformation of a local area of initially uniform material and that the theory of elasticity must be applicable to the prestressed part. If an external load is then applied to the part to obtain a given uniform load stress as in axial tension or a nonuniform stress as in bending the applied load stresses and the residual stresses are additive algebraically. This rule holds true as long as the stresses remain below the elastic limit at all locations; when unloaded the part will elastically return to its original condition with residual stresses unchanged.

Superimposing an applied load tensile stress of less than the residual compressive stress allows the material to remain in compression; Figure 4B shows a slight increase so that an applied tensile stress greater than the residual compressive stress will cause the surface layer to be in tension, as in Figure 4C. The core material will have a final tensile stress greater than the applied tensile stress. Where applied load compressive stress is superimposed on an existing residual compressive stress layer the resultant compressive stress is increased, as in Figure 4D. The allowable applied compressive stress, therefore, may be reduced, even though the yield strength of the strain hardened surface layers will usually be significantly increased by rolling. Figure 4E shows

the effect of a residual stress distribution upon stress range when exposed to cyclic tensile and compressive applied load stresses. The vulnerable surface layers under these conditions are exposed only to cyclic compressive stress.

The effects of geometric stress concentrations such as grooves, oil holes, fillets, and so on, must be considered both in compression and in tension to arrive at the resultant stress at any location. If the material yield strength is exceeded by the resultant stress, the residual stress will be changed after release of the applied load. For example: if an applied load compressive stress equal to 0.3 of the yield strength is added to a local residual stress of 0.5 of the yield strength in the presence of a stress concentration with a factor of 2.5, the calculated local resultant stress in compression equals $0.5 + (0.3 \times 2.5)$ or 1.25 the yield strength. Obviously, local yielding must occur. Note that the actual local residual stress intensity value of 0.5 yield strength was used in this calculation and that this may be greater than the average residual stress at the surface away from the stress concentration depending upon the relative size of the stress concentration and the extent of the residual stress field.

Dugdale, in recent work, has shown some significant effects on fatigue performance obtained by prestressing machined notched bars. Compression preloading resulted in a reduction of fatigue performance (8). This may be explained as follows: it can be shown that a sufficiently large compression load applied to a notched bar would result in yielding at the notch. Upon release of the load, the root of the notch would be in residual tension. Such a residual tension stress at the notch would cause a reduction in fatigue life.

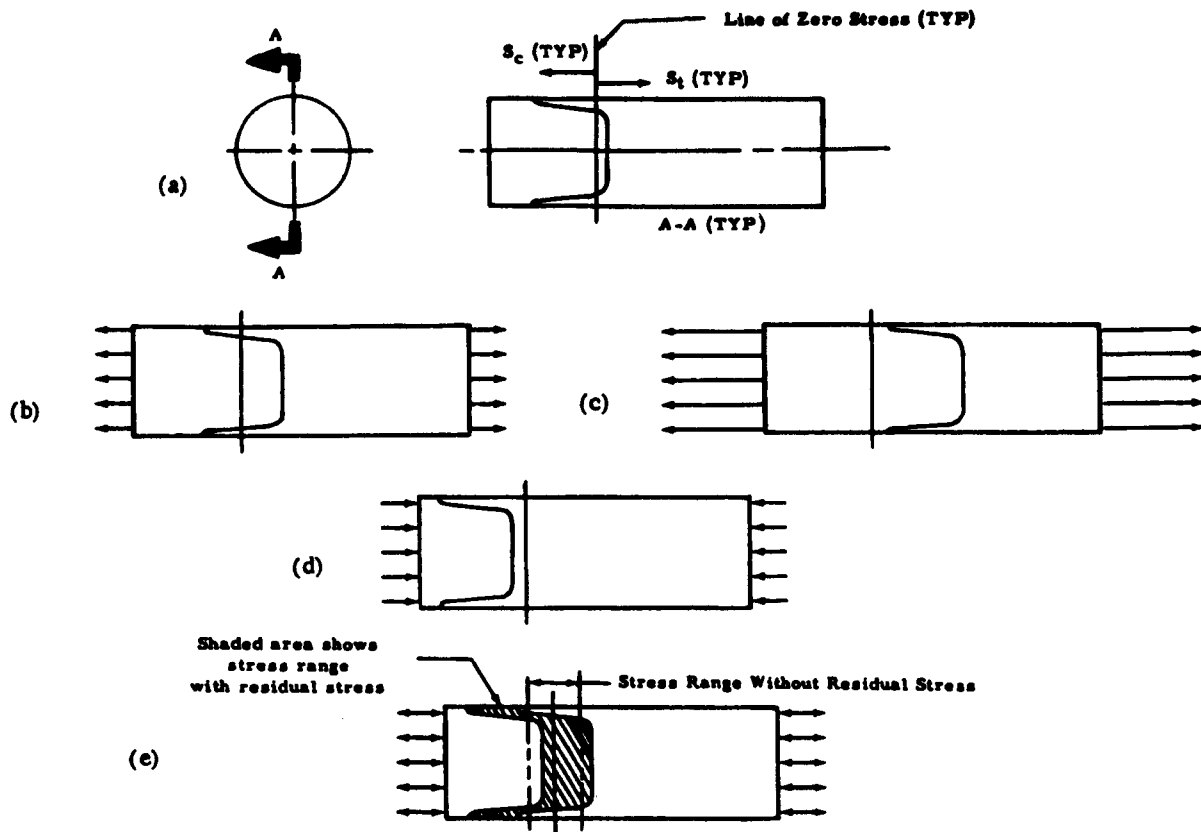


FIGURE 4—EFFECTS OF RESIDUAL STRESS DISTRIBUTION

4.4 Fatigue—In fatigue loading one is concerned with the effects of variable loads of less than the critical static loads on structural integrity, part performance, or service life. The actual loads may be uniform alternating loads or may be applied in a random manner and sequence. It is most important that any experimental or analytical techniques simulate or duplicate actual service conditions as closely as practical, if reliable design decisions are to be based on the results of using these techniques. Actual service is still the best proof of a satisfactory design. For most experimental work a uniform, essentially sinusoidal, alternating load is used. The mean stress may be zero, compression, or tension. The rotating beam test gives a zero mean stress.

A local surface residual compressive stress will affect only the resultant local mean stress; obviously it can have no effect on the amplitude of the alternating stress. Any improvement in fatigue performance due to residual stress, therefore, must come from a reduction of the mean tension stress at the surface. A Goodman diagram, Figure 5A (9), has often been used to illustrate in a general manner the relative effects of mean and alternating stresses on the fatigue limit. Note that the reduction of the mean tensile stress allows an increase in the alternating stress, and, therefore, with a given alternating stress, reduction of the mean stress will improve fatigue performance. Experimental data has indicated that this general relationship is true; however, the exact linearity indicated by the Goodman diagram is not obtained. Figure 5B (9) shows a modified Goodman diagram with a plot of typical fatigue life data. Figure 5C (9) illustrates another method used for plotting such data. It is seen that a reduction of the mean stress should increase the fatigue life. The reader is referred to the work of Grover, Dolan, and others for a more thorough review (9).

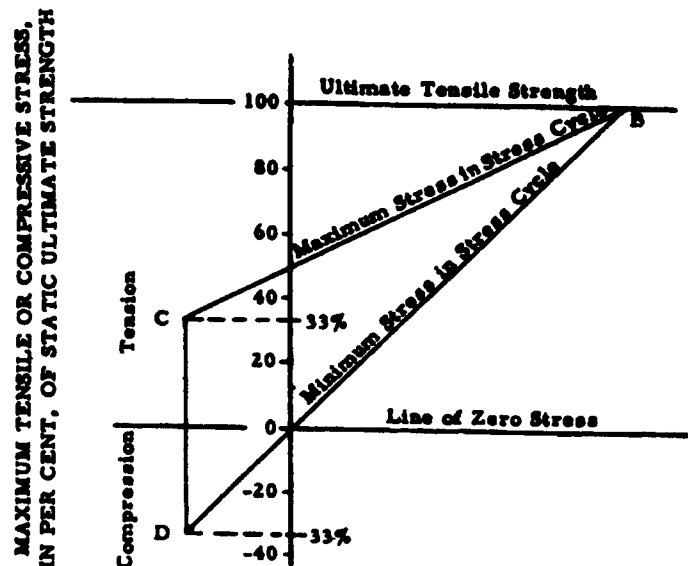


FIGURE 5A—GOODMAN DIAGRAM (9)

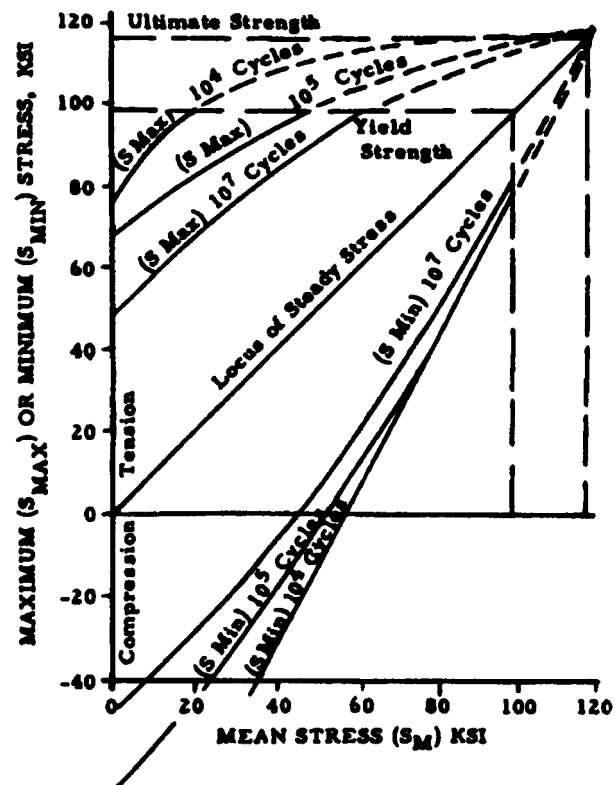


FIGURE 5B—MODIFIED GOODMAN DIAGRAM (9)

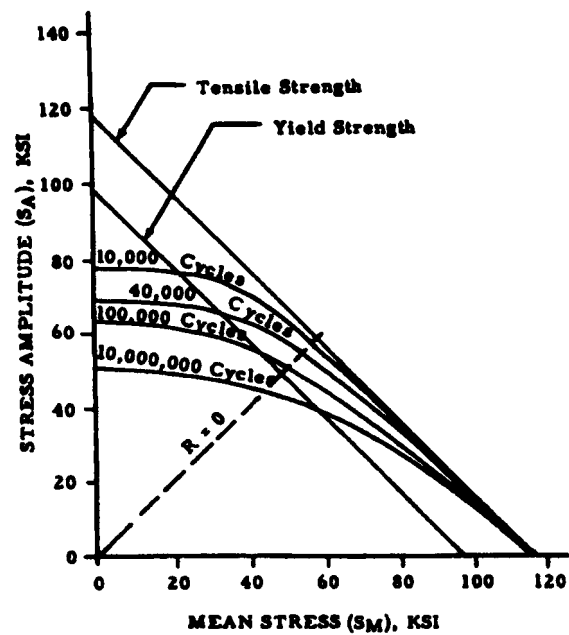


FIGURE 5C—EFFECT OF COMBINED AND STEADY STRESS ON FATIGUE STRENGTH

For the purposes of illustration in this discussion, assume a fatigue loaded specimen with a known surface defect or crack of significant depth as shown in Figure 6. It is easily seen with this idealized defect that the specimen can transmit compressive stresses across the crack without difficulty. A tensile stress, however, will cause the crack to act as an extremely effective stress concentration. Plastic deformation will occur at the tip of the crack, with the crack necessarily extending deeper into the material; repeated cyclic loading will continue this damage until a critical cracksize is reached and failure occurs. By reducing the local surface tensile stress in the vicinity of the defect, the damage per cycle will be reduced and longer fatigue life will be obtained.

4.5 Limitations of Theory—The previous sections have assumed that the material used was capable of sufficient local plastic deformation during the rolling process to produce an adequately rolled surface without deleterious effects on the material. It was also assumed that elastic behavior was obtained at stress level less than the yield strength of the material. Further assumptions have been made that the material was originally free from residual stresses and that thermal or other processes have not been introduced in the system.

If the ductile capacity of the material is questionable so that there is the possibility of surface defects being initiated, a metallurgical examination is definitely indicated. Even when this condition exists, some improvement may be possible if the depth of the deepest defect is less than the depth of the maximum compressive stress; however, the danger here lies in the possibility of defects extending beyond the compressive layer so that rapid failure could result.

Yield strength is an arbitrary definition of a measurable amount of nonelastic behavior for many materials, such as 0.2% offset on a load-strain curve. The elastic behavior and yield strength of strain hardened material will be improved over the original material. It follows that the foregoing references to yield strength should be considered in this light with due allowance for the actual elastic behavior of the original and of the strain hardened material.

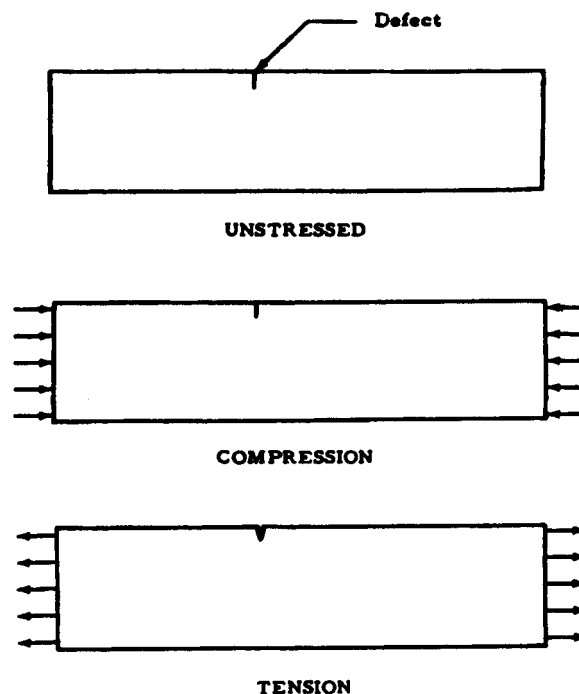


FIGURE 6—EFFECTS OF VARIOUS TYPES OF STRESS UPON KNOWN SURFACE DEFECT

The existence of residual stresses prior to surface rolling complicates the picture, particularly if these are present at a greater depth than the surface rolled layer. Surface rolling, however, can improve such parts, especially where a thin surface layer is in residual tension.

It should be noted that elevated temperature exposure may result in creep or relaxation of residual stresses or loss of residual stress by lowering of the yield strength. Similarly, severe temperature gradients and differential expansion may alter or relieve residual stresses. In other words, subsequent processing and service conditions should be examined to insure that the prestressed condition will be retained.

The actual maximum intensity of the residual compressive stress will vary with processing controls, but, for heavy rolling of ductile material, it may be expected to slightly exceed the yield strength of the original material. Residual stresses of this magnitude have been reported for shot peening by Brodrick (10), and Horger has noted residual compressive stresses of over 100,000 psi longitudinal and 46,000 psi tangential from surface rolling of normalized and tempered SAE 1050 steel (11). Far more information is available on fatigue improvement than actual residual stress data.

4.6 Conclusion—Surface rolling may be expected to improve fatigue performance when properly applied to suitable parts and materials. The process improves the surface finish, work hardens the surface layers, and imposes a residual compressive stress on these surface layers. Of these three effects, fatigue improvement is attributed principally to the super-imposition of a residual stress system upon the expected applied load stress system. Thus, the local mean tensile stress at the vulnerable surface of the part is either reduced or reversed so that the mean stress is actually in compression.

5. *Calculations for the Surface Rolling Process (by H. R. Neifert)*

5.1 Introduction—Successful application of the surface rolling process requires that the load on the roller be of sufficient magnitude to cause plastic deformation in the surface material of the work piece. Plastic deformation is obtained when the stress produced by the roller exceeds the elastic limit of the material being rolled. The depth beneath the surface to which the rolling is effective is dependent upon the geometrical shape of the roller and work piece, the materials involved, and the roller load. These factors can be related by mathematical analyses which permit a determination of required roller loading based either on the maximum compression in the contact area or on the shearing stress beneath the contact area.

The mathematical analysis assumes that the stresses produced in the contacting bodies are within the elastic range of the material. Experience, however, has indicated that the theory may be extended into the plastic stress range with reasonable accuracy for the practical application discussed herein.

LIST OF SYMBOLS

P	compressive force between the two contacting bodies, lb.
X_x, Y_y, Z_z	principal stresses in X, Y, Z directions, psi.
S_c	maximum surface pressure, psi.
S_s	maximum shearing stress (shearing stress in plane of maximum shear), psi.
S_{s1}	yield point of shaft material in shear, psi.
E	Young's modulus, psi.
μ	Poisson's ratio.
K	material factor, psi.
Z	depth below surface of contact measured along road centerline (Z axis), in.
a	major semi-axis of the ellipse of contact, in.
b	minor semi-axis of the ellipse of contact, in.
r_1, r'_1	radii of curvature at point of contact body No. 1, in.
r_2, r'_2	radii of curvature at point of contact body, No. 2, in.
δ	form factor describing geometry of the two contacting bodies, in.
α, β	constants describing the conformity of the contacting bodies.

ϕ	angle between normal planes containing radii of curvature, r_1 and r_2 .
$\cos \theta$	a parameter which always has a plus value.
P_1	roller load for a desired depth of cold working Z_1 , lb.
m	load factor = P_1/P .
e	eccentricity of contact ellipse, $\frac{b}{a}$ or $\frac{B}{\alpha}$
PMP_c	hardness, Rockwell "C" scale

5.2 Mathematical Analysis for Determination of Stress in the Contact Area—When two bodies in contact are forced together by an external force, as in Figure 7A, stresses are induced in both bodies beneath the area of contact. The three principal stresses, X_x , Y_y , Z_z (Figure 7B) are maximum at the contacting surface and decrease as Z , the depth beneath the surface, increases. The problem of evaluating the stresses in the surface of the contacting bodies was solved by H. Hertz (12, 13)³. This work was later extended (14, 15, 16) so that stresses beneath the area of contact could be calculated. The magnitude of the subsurface stresses along the load centerline for a typical contact area is shown in Figure 8. The use of the subsurface shearing stress in the computation of roller load will be discussed later in this chapter.

The maximum pressure between the two bodies, which acts at the center of the elliptical contact area, can be calculated from the equation:

$$S_c = \frac{3}{2} \frac{P}{\pi ab} \quad (\text{Eq. 1})$$

as indicated in Figure 7B.

It must be emphasized that the semi-axes of the pressure ellipse, a and b , are the projected semi-axes and are not measured along the curvature of the pressure surface.

In the general case of compression of two bodies, where the surface of contact is an ellipse, the semi-axes are given by the equations:

$$a = \alpha^3 \sqrt{P \frac{\delta}{K}}; b = \beta^3 \sqrt{P \frac{\delta}{K}} \quad (\text{Eq. 2})$$

The form factor, δ , describing the geometry of the two contacting bodies, and the material factor, K , are given by the expressions:

$$\delta = \frac{4}{\frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_{1'}} + \frac{1}{r_{2'}}} \quad (\text{Eq. 3})$$

$$K = \frac{8}{3} \frac{E_1 E_2}{E_2 \left(1 - \mu_1^2\right) + E_1 \left(1 - \mu_2^2\right)} \quad (\text{Eq. 4})$$

where E_1, μ_1 and E_2, μ_2 are elastic constants (Young's modulus and Poisson's ratio) of the materials of the two bodies. The radii $r_1, r_2, r_{1'}, r_{2'}$ are the principal radii of curvature at the point of contact of the two bodies. The radius of curvature is considered to be positive if the center of curvature lies within the body; if outside, it is negative. (Example: the radius of curvature for a fillet on a shaft is negative.)

3. Numbers in parentheses in text and tables refer to references at end of report.

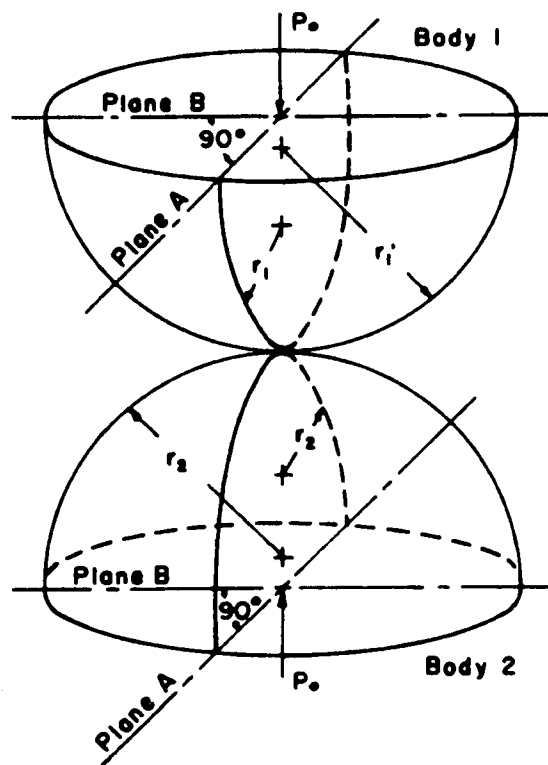


FIGURE 7A—BODIES IN CONTACT

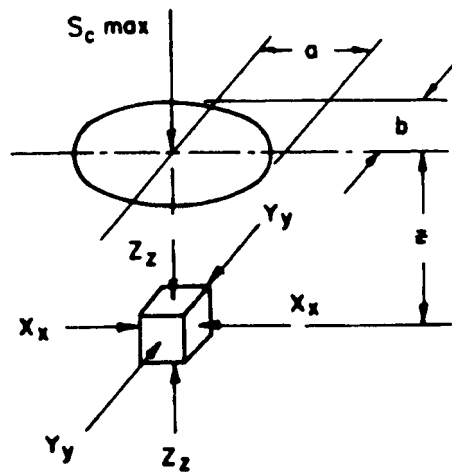


FIGURE 7B—AN ELLIPTICAL AREA OF CONTACT OF TWO BODIES AND PRINCIPAL STRESSES ACTING ON AN ELEMENT BENEATH THE CENTER OF CONTACT

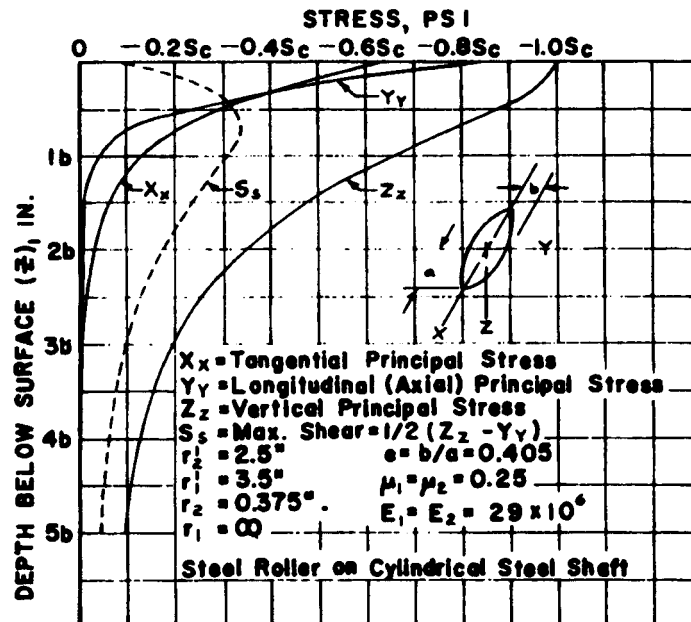


FIGURE 8—MAGNITUDE OF PRINCIPAL STRESSES AND MAXIMUM SHEARING STRESS ALONG LOAD CENTERLINE

In addition, planes A and B should be chosen so that plane A contains r_1 and r_2 and:

$$\frac{1}{r_1} + \frac{1}{r_2} > \frac{1}{r'_1} + \frac{1}{r'_2}$$

This is necessary to obtain positive values of $\cos \theta$ in Equations (5) and (6).

Plane A then determines the direction of the semi-minor axis of the pressure area and plane B the direction of the semi-major axis of the pressure area.

The values of α and β are given in Figure 9 as a function of $\cos \theta$ where

$$\cos \theta = \pm \frac{\delta}{4} \left[\left(\frac{1}{r_1} - \frac{1}{r'_1} \right)^2 + \left(\frac{1}{r_2} \pm \frac{1}{r'_2} \right)^2 + 2 \left(\frac{1}{r_1} - \frac{1}{r'_1} \right) \left(\frac{1}{r_2} - \frac{1}{r'_2} \right) \cos 2\phi \right]^{1/2} \quad (\text{Eq. 5})$$

and where θ is an angle between normal planes containing radii of curvature r_1 and r_2 . $\cos \theta$ is merely a parameter and the plus value is always used.

The angle θ will usually be 0 deg when performing a surface rolling operation, since the axes of rotation of both bodies are generally in the same plane. $\cos 2\theta$ is then equal to 1 and Equation (5) may be written in the simplified form.