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# RESIDUAL STRESSES IN METAL CUTTING

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# RESIDUAL STRESSES IN METAL CUTTING

The purpose of this paper is to make a critical review of the work that has been done on the relation of residual stresses to metal cutting processes with the further objective of evaluating progress toward the ultimate understanding and solutions to this intriguing problem. Awareness of the existence of the problem appears to have developed almost concurrently with the development of machining processes; this is indicated in early references to the warpage of castings after machining. Former practice in the automotive industry of the USA found huge inventories of motor blocks in storage yards between machining operations. A few months of aging was needed to relax both machining and casting stresses.

The advent of interchangeable manufacture with ever smaller tolerances, and higher load-carrying capacities or smaller safety factors changes the phenomena of residual stresses from a curiosity to an engineering problem thus stimulating investigation into their nature, causes, and effects. Until quite recently, however, most research in this area has been directed at the effects of residual stresses on the functional qualities of manufactured products with little attention being given to metal cutting processes as causes. The majority of publications treating residual stresses in metal cutting are concerned with grinding; there are very few devoted to what might be called "thick-chip operations".

Two major topics will be discussed in this review; experimental evidence and theory or mechanisms of creating residual stresses in metal cutting. Reference is limited to publications within the last forty years. Space and time limitations prevent discussion of all significant contributions during this time interval. Mention is made of only a few typical disclosures which characterize the development and state of knowledge of the problem.

## Experimental Evidence

Although they overlap considerably, one can recognize four distinct historical periods in the accumulation of experimental evidence. Each of these periods is dominated by a different experimental technique, all of which are still useful. In sequence of appearance they are:

1) Work-hardening by hardness determinations
2) Work hardening by X-Ray
3) Dominant stress by warpage or specimen distortion
4) Stress distribution by differential metal removal.

Early investigators were aware of the severe distortion which metal cutting causes at the machined surface. However, they were inclined to characterize the result simply as work-hardening. If they appreciated the complex stress distribution associated with this hardening it does not appear in their writings. Thus, it appears that progress in residual stress can be characterized as a gradual increase in awareness of the complexity of actual stress distribution.

### Work-Hardening by Hardness Measurements:

Hardness measurements constitute the earliest quantitative evidence of residual stress caused by machining. E. G. Herbert (1)* reported in 1926 that "metals are hardened by any process which deforms them so as to cause a permanent change of shape while they are at low or moderate temperature". He identified this effect with his Pendulum hardness tests on both the chips and the cut surface. His primary concern, however, was with the correlation

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* Numbers in parentheses designate references cited in the Bibliography.

of tool life to work-hardening capacity. His most significant conclusion with reference to cutting practice was "an obtuse-angle tool would harden the chip more"; thus, indicating greater work-hardening of the work surface as well.

In 1932, T. G. Digges (2) reported on "work-hardening near the machined surface of steel forgings". Like Herbert's work, this study involved lathe turning and hardness surveys. Digges concluded:

1) "The amount of work-hardening was not influenced by changes in cutting speed."
2) "With a given area of cut, the amount of work hardening was affected equally by changes in the feed or depth of cut."
3) "The maximum hardness developed at the surface by machining decreased rapidly with increasing carbon contents of the steels up to 0.4 percent carbon and thereafter less rapidly--".

Hardness measurements continue to be a convenient though over-simplified indication of the presence of residual stresses in machined surfaces. The recent development of the micro-hardness tester had augmented the usefulness of this technique as a means of identifying significant trends arising from changes in cutting practice. Figure 1 shows the results of a study made by Dr. W. W. Gilbert in the Production Engineering Laboratories at the University of Michigan. Micro-hardness tests were made on planes perpendicular to the axis of drilled holes. Increased hardness is seen to result from the cutting action by both sharp and dull drills with greater increases and greater penetration being associated with dull drills. The same type of result was observed for a range of titanium alloys and carbon steel as well as for the 18-8 stainless steel as portrayed in Figure 1.

Many other investigators have contributed hardness data on this subject and most are in agreement that metal cutting does indeed harden the cut surface except in grinding where the hardness has been observed either to increase or to decrease depending upon grinding conditions. The increasing mass of work-hardening evidence has produced certain anomolies which have prompted some investigators to question interpretation of hardness measurements in such cases. This situation has stimulated recent investigations in this area (3 & 4). In uniform stress situations it can be expected that residual tension parallel to a surface will decrease hardness while residual compression would increase it. On this basis one would conclude that all work-hardened surfaces represented residual compression. Such a conclusion is fundamentally unsound since a work-hardened surface in which the residual stress is dominantly tension can exhibit either an increase or a decrease in measured hardness depending upon the amount of shear strain, the rate of strain-strengthening, the depth affected and the amount of relaxation after cutting. This problem is not yet solved and merits considerable attention because of the large volume of hardness data available and the convenience of the hardness test for future studies.

## Work-Hardening by X-Ray.

X-ray techniques have also been used to study the effects of metal cutting on the resulting surfaces. Here again the earlier references mention work-hardening or cold work in characterizing these effects. Thomassen and McCutcheon (6) used X-ray on turned and milled specimens of leaded, free-machining brass and 70-30 brass respectively. They noted marked sensitivity to feed rate or thickness of chip but failed to confirm Digges (2) observation of equal sensitivity to depth of cut. One of the more important findings of this study was that a "dull" milling cutter increased the depth of cold work by 300 percent over that created by a sharp cutter.

Dr. A. O. Schmidt and his associates (7 & 8), have also made extensive use of X-ray for studying the effects of a wide range of materials and cutting conditions. These results indicate increasing amounts of work-hardening with larger cuts and decreases when either the rake angles or the cutting speeds are increased. The total results indicate sensitivity to total strain and strain rate respectively.

Only recently have X-ray techniques developed to the point where this method is dependable for resolving the distribution of residual stresses in machined surfaces. Some investigators have expressed doubts to the author as to the ability of X-ray to follow the rapidly varying stresses in ground surfaces. This fact, if it be a fact, coupled with the time required for X-ray evaluations tends to limit the usefulness of this method for all but the most exacting studies.

## The Warpage Era.

Dr. George Sachs (21) has done much to promote the use of warpage or curvature change techniques in investigating residual stresses. When coupled with etching or similar differential processes of metal removal, this approach can resolve the stress distribution quite satisfactorily. However, etching is slow, expensive and difficult to control. For this reason, the total warpage of a part or test specimen is used as a quick indication of trends in residual stress distribution resulting from changes in cutting practice.

Professor Henriksen (9) used this technique in the studies which he reported in 1934. This was an extensive investigation with single-point tools in planning cuts on low carbon steels. It was concluded that the dominant stress was tension and Henriksen suggested a plausible mechanism for this type of result. Disregarding the type of stress and considering it only as cold work, his results agree with other investigators; notably Digges (2). Henriksen was puzzled however by the existence of an optimum normal rake angle for side cutting tools whereas the stress continued to decrease with increasing normal rake with square ended tools. This difference could be attributed to changes in lateral direction of the resultant cutting force with the side cutting tool. However, this is pure speculation until more is known about the actual distribution of stresses and the mechanism of their formation.

The author has made several exploratory studies of residual stresses as secondary activities in connection with other investigations in the Production Engineering Laboratories at the University of Michigan. Since they were secondary objectives, total curvature changes were used as gross indications of the predominant stress. Mention of a couple of these will serve to emphasize the broad scope of results which can be obtained.

Figure 2 shows a representative torque-time chart obtained for reaming steel at different lubricating conditions. Upon initiating cutting, the torque increased rapidly to a value determined by the size of cut. When cutting dry and in the presence of a built-up-edge, the torque did not increase beyond this point. Curvature changes resulting from longitudinal saw cuts on the reamed bushing indicated a dominance of residual tensile stress at the reamed surface.

On the other hand, the use of carbon tetrachloride as a cutting fluid eliminated the built-up-edge and caused considerable rubbing on the margin of the reamer resulting in a smaller, more accurate hole, a smoothed burnished surface and dominant residual compressive stress. Thus despite an increase in tangential rubbing which was expected to increase tension, just the opposite occurred. It is possible that the considerable normal pressure between the reamer margin and the wall of the hole brought about this stress reversal.

Following the above result another series of tests was made on the same low carbon steel while using a chemical emulsion as a cutting fluid. The torque measurements are plotted in Figure 3. In this series the effectiveness of the fluid in reducing the built-up-edge decreased at higher feeds. Residual stress analysis showed a gradual change from dominant compression at the lowest feed to dominant tension at the highest feed. Further, the rate of change in the tensile direction was faster than was observed for increased feeds while reaming dry.

Similar studies by the author with single point tool operations on magnesium and aluminum reveal that either dominant compressive stress or dominant tensile stress will be caused by cutting. The type and magnitude of stress appears to depend primarily on tool shape and condition coupled with cutting speed, size of cut, and the degree of lubrication in effect between the flank of the tool and the cut surface. It was tentatively concluded that:

1) Negative rake, sharp tools produce compressive stress.
2) Large-positive-rake tools produce tensile stress.
3) Sharp-nosed tools produce strong compressive stress lateral to the cutting direction.
4) Light feed and well-lubricated tool flank produces compressive stress.
5) "Smear-metal" on tool flanks produces very high tensile stresses.
6) Worn or dulled tool flanks produce either compression or tension depending on the degree of lubrication, type of tool wear (polished or abraded) and the ratio of the modulus of elasticity of the tool material to that of the metal being cut.

Complete interpretation of residual stress behavior from gross curvature changes in hazardous and may lead to incorrect conclusions since differences in curvature change may be accompanied by radical changes in the type of stress distribution.

## Actual Stress Distribution.

Some of the most careful work on residual stresses produced by metal cutting has been in the area of precision grinding. Dr. H. R. Letner (13) has contributed several notable publications on this subject from the results obtained at the Mellon Insititue in Pittsburgh, Penn. The principal objective of his work was to assess the effects of practical variables but the thoroughness of his techniques has thrown considerable light on the probable mechanisms of producing residual stresses by all types of metal cutting operations.

Figure 4 is a generalized curve of residual stress distribution in grinding as obtained by Dr. Letner and by Colwell, Sinnot and Tobin (14). This qualitative curve represents all of the different effects which have been observed in surface grinding wherein the wheel traverses the work surface and portions of the wheel travel over the same area several times resulting in rubbing. Tensile stresses are plotted above the horizontal line and compressive stresses below the same line.

Four distinct causes of stress are identified. Proceeding from the right within the metal to the left toward the surface the first zone encountered is labeled TC to designate a thermal effect resulting from the cutting pass during grinding. The next section which turns abruptly toward the compressive direction is labeled MC designating mechanical effect from the cutting pass. This is followed by a steep trend toward the tensile direction which is labeled TR designating a thermal reaction to rubbing near the surface. The final source is a mechanical or compressive trend labeled MR designating a mechanical or compressive reaction to the same rubbing. This is the author's interpretation and it does not agree in every respect with Dr. Letner's interpretation of the corresponding sections.

Dr. Letner has indicated that he believes the section labeled TR is thermal but that it is the result of the original grinding or cutting pass while both of the sections labeled MC and TC, respectively, are the result of the mechanical reaction to the external forces applied to the surface. This, too, is a rational and theoretically sound interpretation; more investigation and analysis is required before this question can be resolved.

Both Dr. Letner and the author have obtained many distribution curves including only the TC and MC sections. The addition of the third section designated as TR is representative of more severe grinding conditions bordering on the condition commonly known as "burning". Halverstadt (15) and Clorite and Reed (16) have reported similar distributions for the grinding of high temperature alloys and titanium, respectively.

## Possible Mechanisms

The mechanisms which create residual stresses in machined and ground surfaces are not at all well understood. However, tentative conclusions can be drawn from the experimental evidence available in the literature. It will be well to supplement these with some speculation as to the possible but not necessarily probably mechanisms in the hope that this will stimulate some critical thought on the subject. It is suggested that the sources or causes of residual stresses be separated into two groups identified as thermal and mechanical. It will be proposed that the thermal source always creates residual tensile stresses and that mechanical sources can create either tension or compression depending upon the conditions prevailing.

### The Thermal Mechanism.

The author has carried on a number of investigations which indicate a dependency of residual stresses to the shape of the heat source in grinding. This same characteristic has been noticed in the production shop.

The basic mechanism is the same as that which occurs in the quenching of a part which is being hardened by heat treating; differential rates of cooling create residual stresses resulting in warpage of the part. Those areas which cool faster wind up with residual tensile stresses; essentially, the same thing happens in grinding. If a point source of heat is applied alternately to all portions of a surface even though at different times, it will create tensile stresses parallel to the surface and equal in all directions and this will cause a thin part of uniform section to warp into a spherical surface with the same curvature in all directions.

On the other hand, if the surface is heated up in a narrow band across the entire surface, then subsequent quenching will result in warpage or curvature in only one direction; this will be perpendicular to the band or line.

In traverse grinding the hot zone is relatively small and substantially circular in shape so that it might be characterized as a point source. In plunge grinding, on the other hand, metal is being cut all the way across the tool face resulting in substantially a line source of heat. This condition would prevail in cylindrical grinding wherein the abrasive wheel was fed in radially to the work. In this case, if the thermal conditions were sufficiently severe, the resulting cracks would be parallel to the axis of the workpiece.

Figure 5 shows the results of a recent laboratory investigation carried out by the author wherein relatively thin specimens capable of warping were surface ground in a traverse type of grinding action. The resulting curvatures in both the grinding and traverse directions are shown plotted for a range of down feeds or thicknesses of metal removal. The two curves at the left in Figure 5 were obtained for conventional grinding practices on a high temperature alloy. The two lines shown at the right in the figure are for identically similar practice except for the super-position of ultrasonic vibration on the specimen being ground. The solid lines represent average curvatures in the direction of table traverse which was the same as the direction of rotation of the grinding wheel. The dash-ed lines represent average curvature in a perpendicular direction.

At a down feed of 0.001 inch both sets of curvature curves or lines result in a behavior approximating that to be expected from a point source of heat. As the down feed or thickness of metal removal is increased, in conventional grinding the curvature in the grinding direction increases while that across the grinding direction decreases which could be the result of a gradual change in the shape in the heat source from substantially a point source to a line source at the heavier down feeds where it would appear that considerable energy is being released as heat due to rubbing across the entire face of the grinding wheel. In contrast to this the ultrasonic vibration appeared to inhibit the rubbing action resulting in little change in what might be characterized as a eliptical heat source over a broad range of down feed.

It is the author's opinion that any thermally induced residual stresses in metal cutting will be tensile. There may be exceptions to this generalization where structural or phase changes take place at exceptionally high temperatures. Another exception may be cited in the case of electro-spark machining wherein a combination of very high temperatures, shallow heated regions and high radiation losses have been observed to create residual compressive stresses in a very superficial zone.

Mechanical Mechanisms.

The mechanical sources of residual stresses would appear to be much more complex than thermal sources. The technical literature reports both tensile and compressive stresses resulting from ordinary metal cutting operations and there can be no doubt that both have been observed at relatively low temperatures which could not have been the source of tensile stresses of the magnitude which are reported. Therefore, it is necessary that we search for mechanical mechanisms which could result in either tensile or compressive residual stresses.

A rather interesting solution to this problem can be obtained by combining recent findings in the cold rolling of steel with published observations in metal cutting more than thirty-five years ago. This author has contended that all of the theory applicable to plastic working operations like rolling, wire drawing, tube sinking and extrusion are likewise applicable to cutting ductile metals since metal cutting is also a plastic working operation and extrusion and wire drawing dies are analogous to cutting tools with very large negative rake angles. The literature references cited in this instance are by W. M. Baldwin, Jr. (17), Professor Dempster Smith (18), Professor E. G. Coker (19), and Professor S. Fukui (20).

It has been demonstrated in connection with the cold rolling of strip steel that the residual surface stresses can be either compression or tension depending upon rolling conditions. Residual compression at the surface is created by what is called non-penetrating rolling as illustrated at the top in Figure 6. There will be a shallow region of residual compressive stress on both sides of the strip with moderate tensile stress more or less uniformly distributed in between. This rolling condition has been referred to as "skin-pass", "temper-pass" and "stress-relief-pass". In any case it is accomplished with relatively small diameter rolls for any given reduction in strip thickness. Larger diameter rolls or greater reductions for a given roll diameter can result in residual surface tension with a distribution substantially as illustrated at the bottom of Figure 6.

Professor Baldwin has suggested that the differences in rolling conditions represented by these different results are analogous to the known solutions for the behavior of metal between flat dies. This behavior is illustrated in Figure 7 with a flat end tool applied to the flat surface of relatively thick strip at a, b, and c and relatively thin strip at d, e, and f. The force applied to the tool is assumed to be increased from a to b to c in the first group and from d to e to f in the second group. The progress of development of plastic zones is illustrated by the spread of cross-hatched areas.

The plastic zone with the thick strip is shallow and the operation could be characterized as non-penetrating while in the case of the thin strip the plastic zone quickly spreads clear across the sheet with increasing load on the tool. The same type of differences would be observed qualitatively if the strips were both of the same thickness but the tools were rounded on the end. A small radius would produce a shallow or non-penetrating distribution of the plastic zone, whereas a large radius approaching a flat end tool as a limit can penetrate to the center. It is quite possible that these same mechanisms with some modifications will be found to be operating in metal cutting.

There is considerable experimental evidence indicating that the non-penetrating mechanism is a major contributor in causing residual compressive stresses in metal cutting. It is reasonable to assume that the somewhat rounded corners of abrasive grains would create the same type of stress distribution superficially in the surface of the metal. Thus, we would expect residual compressive stresses to be created by such abrasive operations as lapping, honing, and even grinding except where local temperatures and heat energy are great enough to completely overcome and mask this effect.

There is increasing evidence that substantially the same condition can occur with ordinary cutting tools where a built-up-edge does not exist and elastic relaxation permits rubbing between the flank of the tool the cut surface. As long ago as 1922 Dempster Smith (18) called attention to forces acting between the work surface and the flank of the tool. Since then there has been a strong tendency to ignore such forces in theoretical analyses of the mechanics of metal cutting. Recent studies at the University of Michigan have demonstrated that the feeding force in a form-turning cut can increase as much as twenty times or more during the useful life of the cutting tool. This increase must be attributed almost entirely to increased contact between the flank of the tool and the workpiece.

When the cutting tool is well lubricated in a form-turning cut as in an automatic screw machine, wear on the flank of the tool is accompanied by some plastic flow and polishing with an appreciable radius; thus, non-penetrating rolling of strip. Preliminary analysis of parts machined by form-turning indicates that increased feeding force is indeed accompanied by substantial compressive stress at the cut surface.

The mechanism for the formation of residual tensile stresses in a machined surface cannot be as simple as that set forth for penetrating rolling of strip steel. Also in 1922 Professor E. G. Coker (19) published a very interesting analysis of metal cutting behavior. He used photo-elastic techniques which indicated the presence of tensile stresses in the cut surface in back of the cutting tool during the cutting process. Similarly, Professor Fukui reported on a very thorough photo-elastic analysis in 1933, excerpts from his results are illustrated in Figure 8.

The curves in Figure 8 represent the stresses acting on the plane of the cut surface ahead of the cutting tool. It will be noted that a positive-rake tool with large contact area as shown at the left in the figure produces a tensile stress parallel to this plane and for some appreciable distance in ahead of the cutting tool. On the other hand, a zero-rake angle tool ground so as to concentrate the applied forces near the cutting edge results in high compressive stress parallel to the cut surface. These tests were made at static loading conditions and it can be expected that the friction component of cutting force would alter this distribution.

The final solution as to the mechanism of forming residual tensile stresses in the machined surface probably will require rigorous mathematical treatment of the mechanics of metal cutting as an elasto-plastic problem. This could come from an extension of the solutions obtained by theory of elasticity for a semi-infinite plate as discussed by Professor S. Timoshenko (22).

## Conclusions

1. The most significant conclusion for the present is that induced residual stresses can be either tension or compression.

2. Metal removal with both bonded and unbonded abrasives shows a strong tendency to produce residual compressive stresses at the surface. This effect is always present. When the surface temperature and rate of release of heat energy reach high enough values, tensile stresses will be super-imposed on the ever present compressive stresses. In cases of severe grinding the tensile stresses will dominate.
3. Cutting temperature does not appear to be a major factor in the creation of residual stresses by ordinary cutting tools.
4. Compressive residual stress has been observed to occur frequently in ordinary metal cutting particularly where some combination of "slippery" metals, good lubrication and low modulus of elasticity is involved.
5. "Smear" of the tool flank or work surface is invariably accompanied by high residual tension.
6. It appears that larger built-up-edges are accompanied by higher tensile stresses.
7. The relationship of residual stress to size of cut, cutting speed and tool shape is not yet clear and requires considerable investigation.

## Summary

This paper is a critical review of information regarding machining and grinding as causes of residual stresses. It is derived from publications

of the past forty years and from the opinions of people engaged in research on this subject in the United States. It is almost certain that either tensile stresses or compressive stresses will be created at the surface depending upon how the metal is cut. This appears to be true for both machining and grinding.

The mechanisms which produce residual stresses have not been described rigorously. High temperature can cause tensile stresses but this appears to be an important factor only in grinding. It has been demonstrated that "sharp" tools can produce compressive stress whereas "dull" or "smeared" tools result in dominant tension. Considerable research is needed before the mechanisms can be completely understood and related to metal cutting practices.

## BIBLIOGRAPHY

1. "Work-Hardening Properties of Metals", by Edward G. Herbert, Transactions, The American Society of Mechanical Engineers, Volume 48, 1926.

2. "Effect of Lathe Cutting Conditions on the Hardness of Carbon and Alloy Steels", by T. G. Digges, Transactions, The American Society of Mechanical Engineers, Volume 54, 1932.

3. "Influence of Residual Stresses on Hardness", by P. A. Blain, Metal Progress, Volume 71, January 1957, pp. 99-100.

4. "An Investigation of the Effect of Various Stresses on Hardness", by S. K. Setty, J. T. Lapsley, Jr., and E. G. Thomsen, Preprint No. 57-A-77; presented at the Annual Meeting of the American Society of Mechanical Engineers, December 1957.

5. "The Distribution of Hardness in Chips and Machined Surfaces", by Norman Zlatin and M. Eugene Merchant, Transactions, The American Society of Mechanical Engineers, Volume 69, 1947.

6. "Use of X-Ray on Depth of Cold Work by Machining" by L. Thomassen and D. M. McCutcheon, "Mechanical Engineering", Volume 56, 1934, pp. 155-157.

7. "X-Ray Diffraction as a Gage for Measuring Cold Work Produced in Milling" by F. Zankl, A. G. Barkow, and A. O. Schmidt, Transactions, The American Society of Mechanical Engineers, Volume 69, 1947.

8. "Strains Introduced by Sawing the Magnesium", by G. H. Found, Discussion: "Experimental Stress Analysis", Volume 2, 1944.

9. "Residual Stresses in Machined Surfaces", by E. K. Henriksen, Transactions of the Danish Academy of Technical Sciences, No. 7, 1948 (Copenhagen).

10. "Behavior of Cutting Fluids in Reaming Steels" by Henrik Branders and L. V. Colwell, Transactions, The American Society of Mechanical Engineers, Preprint No. 57-A-168, December 1957.

11. "Deformation Work Absorbed by the Work Piece During Metal Cutting", by E. G. Thomsen, J. T. Lapsley, Jr. and R. C. Grass, Transactions, The American Society of Mechanical Engineers, Volume 75, 1953.

12. "Verformung von Span und Randzone beim Drehen", "Deformation of Chip and Work Surface in Turning", by Walter Layensetter, Stahl und Eisen, Volume 72 (1952), Number 19, pp. 1139-1144.

13. "Grinding and Lapping Stresses in Manganese Oil-Hardening Tool Steel", by H. R. Letner, Transactions, The American Society of Mechanical Engineers, Volume 75, 1953.

14. "The Determination of Residual Stresses in Hardened, Ground Steel", by L. V. Colwell, M. J. Sinnott, and J. C. Tobin, Transactions, The American Society of Mechanical Engineers, Volume 77, 1955.

15. "Analysis of Residual Stress in Ground Surfaces of High-Temperature Alloys", by R. D. Halverstadt, Preprint No. 57-SA-62, The American Society of Mechanical Engineers, presented at San Francisco, June, 1957.

16. "Influence of Various Grinding Conditions Upon Residual Stresses in Titanium", by P. A. Clorite and E. C. Reed, Preprint No. 56-A-44, The American Society of Mechanical Engineers, presented at New York in December 1956.

17. "Macro-Residual Stresses In Metals Resulting From Plastic Deformation", by W. M. Baldwin, Jr., Paper presented at a seminar on Cold Working of Metals, published by The American Society for Metals, 1949, pp. 31-56.

18. "Experiments with Lathe Tools on Fine Cuts, and some Physical Properties of the Tool Steels and Metals Operated On", by Dempster Smith and Arthur Leigh, Transactions, The Institution of Mechanical Engineers, presented March 13, 1925.

19. "The Action of Cutting Tools" by E. G. Coker and K. C. Chakko, Transactions, The Institute of Mechanical Engineers, London, 1922.

20. "Researches on the Cutting Action of Planing Tool", by S. Fukui and M. Okoshi, The Institute of Physical & Chemical Research, Tokyo, Japan, Volume 22, pp. 97-166, October 1933.

21. "Control of Residual Stresses In Practice", by George Sachs, Paper No. 448, presented at the meeting of The Society of Automotive Engineers, Detroit, Michigan, January 1955.

22. "Theory of Elasticity", by S. Timoshenko, McGraw-Hill Book Company, New York, New York., 1934.

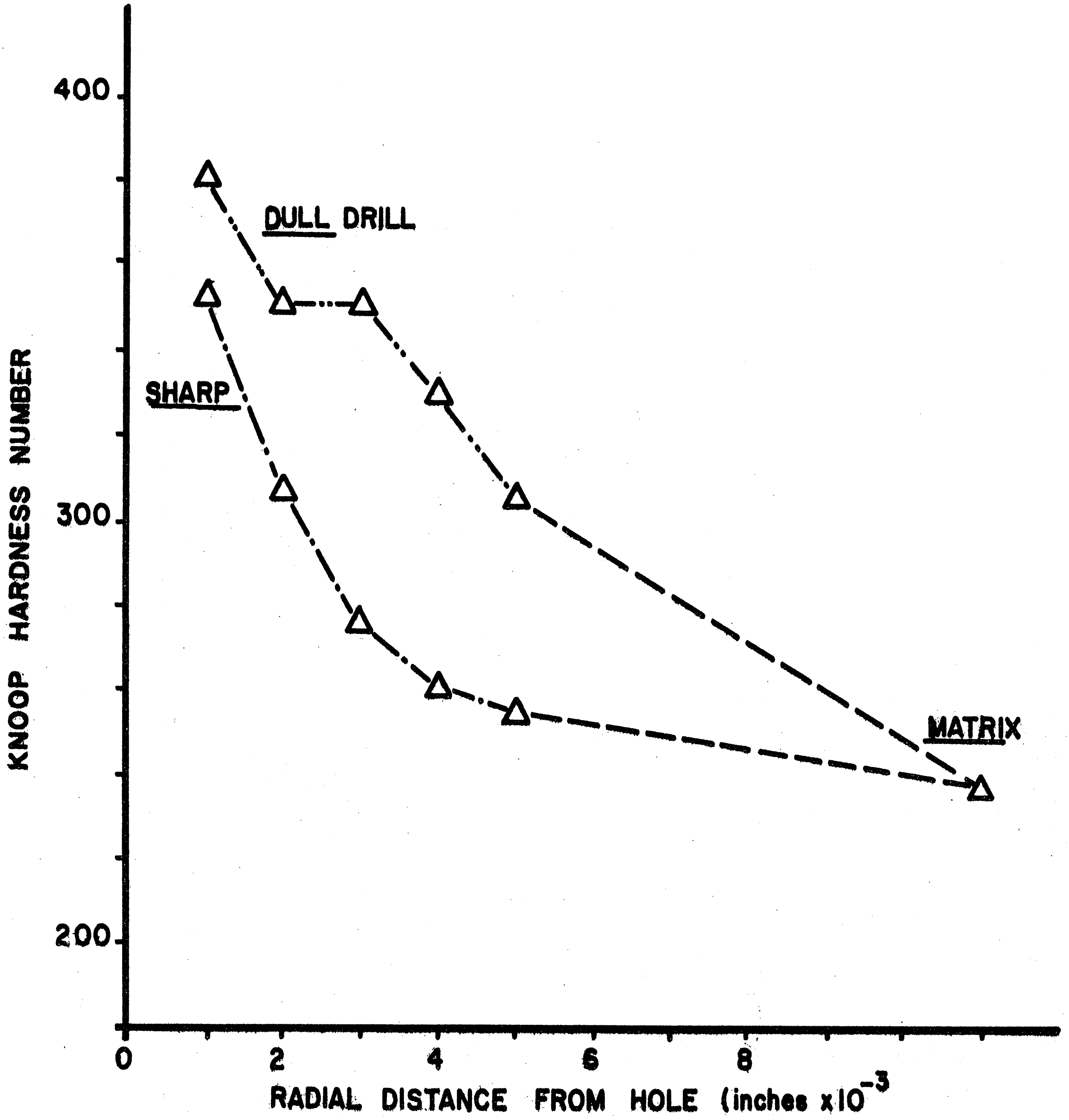


Figure 1. Micro-hardness tests were made at intervals of 0.001 inch radially outward from the wall of 3/8 inch diameter drilled holes in 18-8 stainless steel. Both "sharp" and "dulled" drills were used at a feed of 0.009 ipr. and a speed of 557 rpm. All hardness values shown are averages of at least four separate tests at intervals of 90 degrees around the hole.

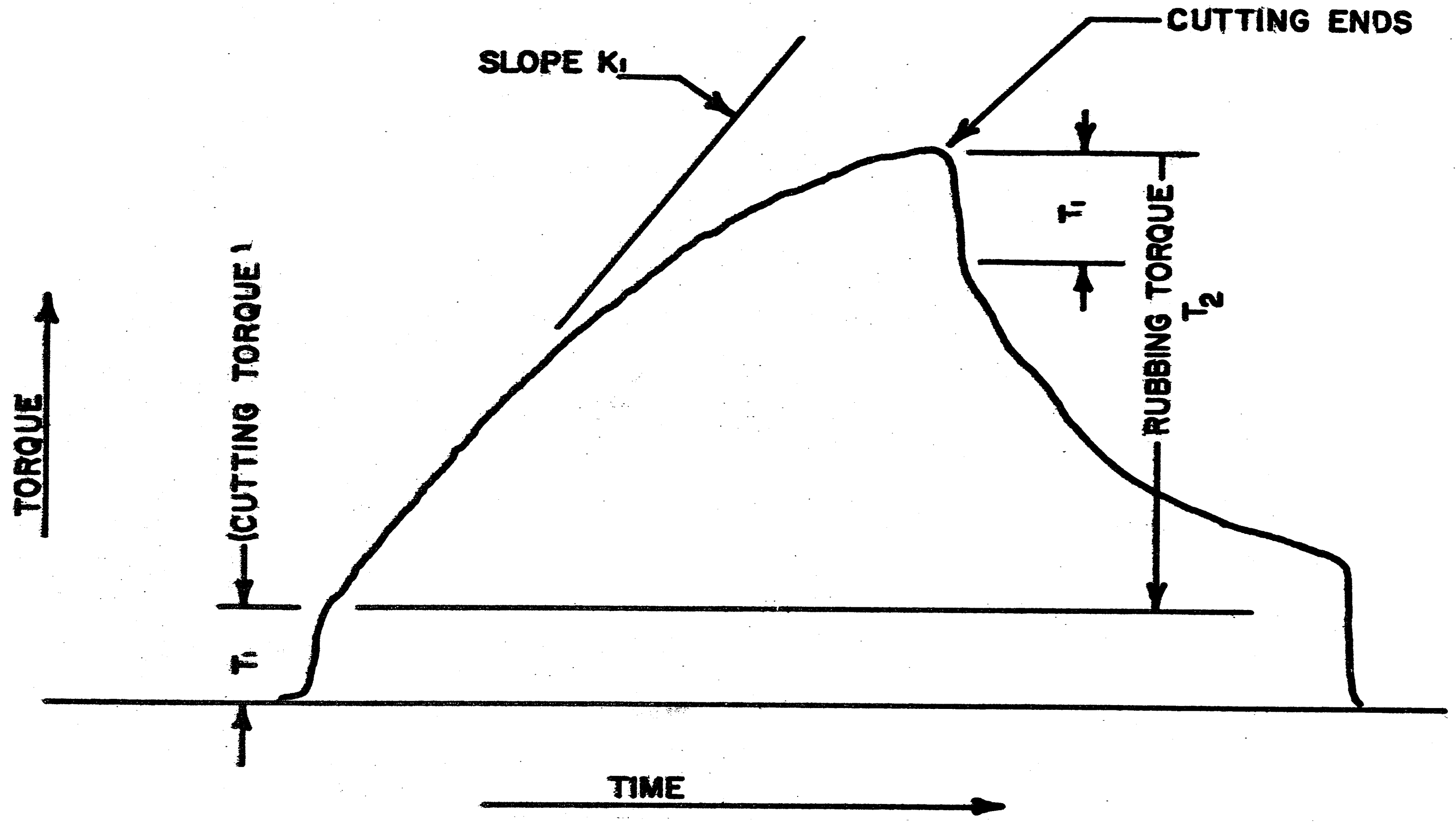


Figure 2. Typical torque-time chart for reaming when rubbing occurs. Deviation from linear trend is due to plastic flow or burnishing in the presence of an effective lubricant. Torque for dry cutting remains constant at $T_1$ level. Dry reaming creates residual tension in peripheral direction. Dominant compression accompanies the high rubbing torques observed with some lubricants.

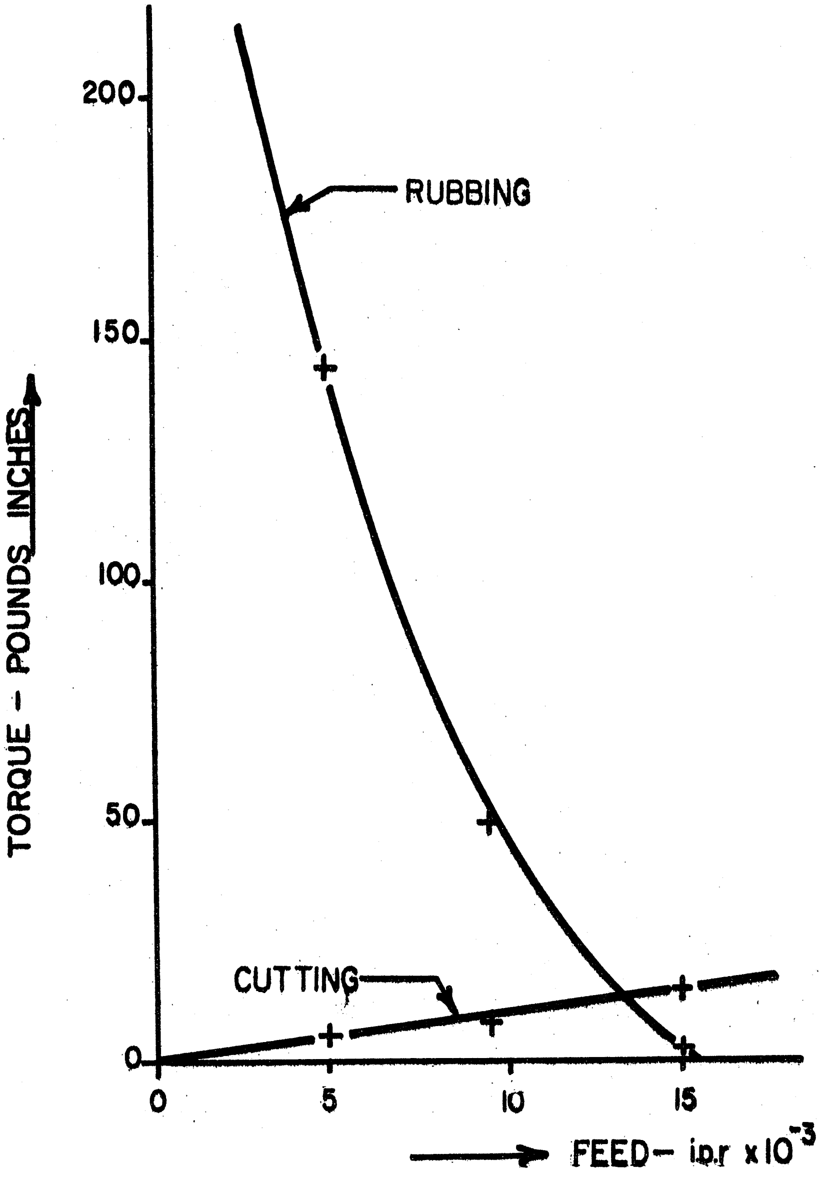


Figure 3. Increased feed with sharp reamer on C-1045 steel resulted in considerable reduction of rubbing torque as size of built-up-edge increased. Finish deteriorated with increased feed and residual peripheral stresses changed from dominant compression to dominant tension. Initial hole diameter was 0.745 inches; reamer diameter was 0.7504 inches.

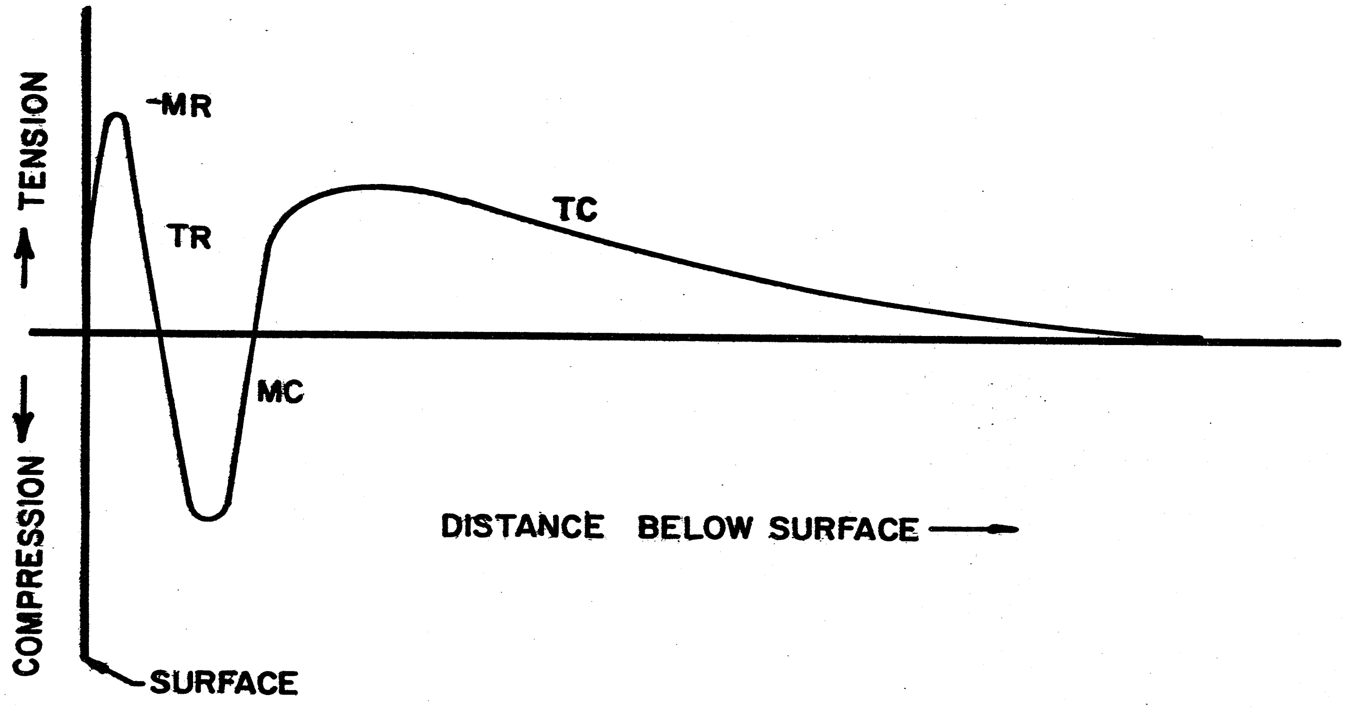


Figure 4. A generalized stress distribution curve typical of surface grinding. Stresses arising from four distinct sources are identified as TC (Thermal from cutting), MC (Mechanical from cutting), TR (Thermal from rubbing) and MR (Mechanical from rubbing). The section designated as TR usually is absent in carefully ground surfaces. Sections TC and MC may be related and both arise from mechanical sources.

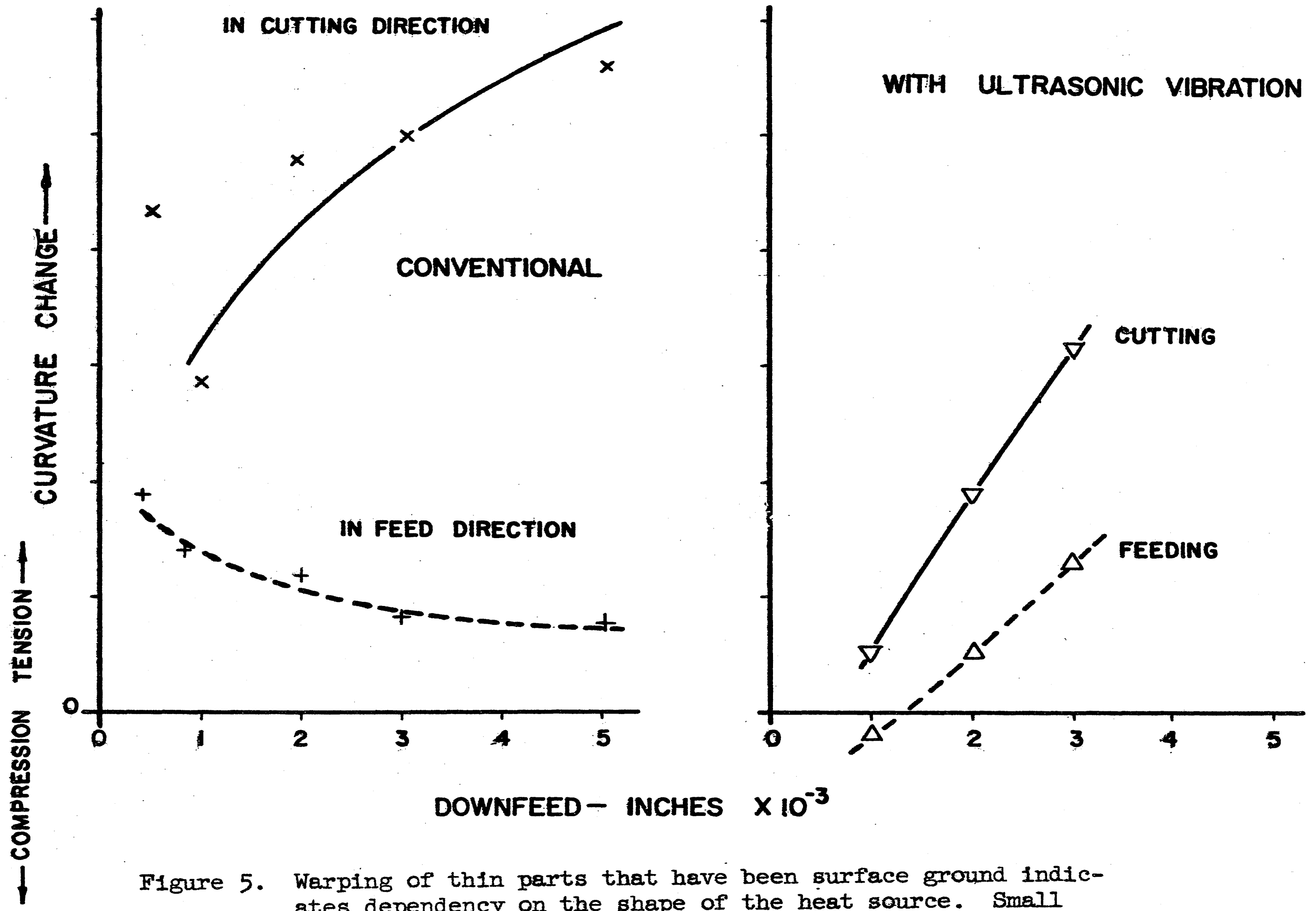


Figure 5. Warping of thin parts that have been surface ground indicates dependency on the shape of the heat source. Small downfeed creats substantially a circular source while large downfeed and rubbing across the wheel face causes shape of the source to approach a line. This property is demonstrated for conventional grinding by curves at left. Superimposing ultrasonic vibration prevents formation of line source.

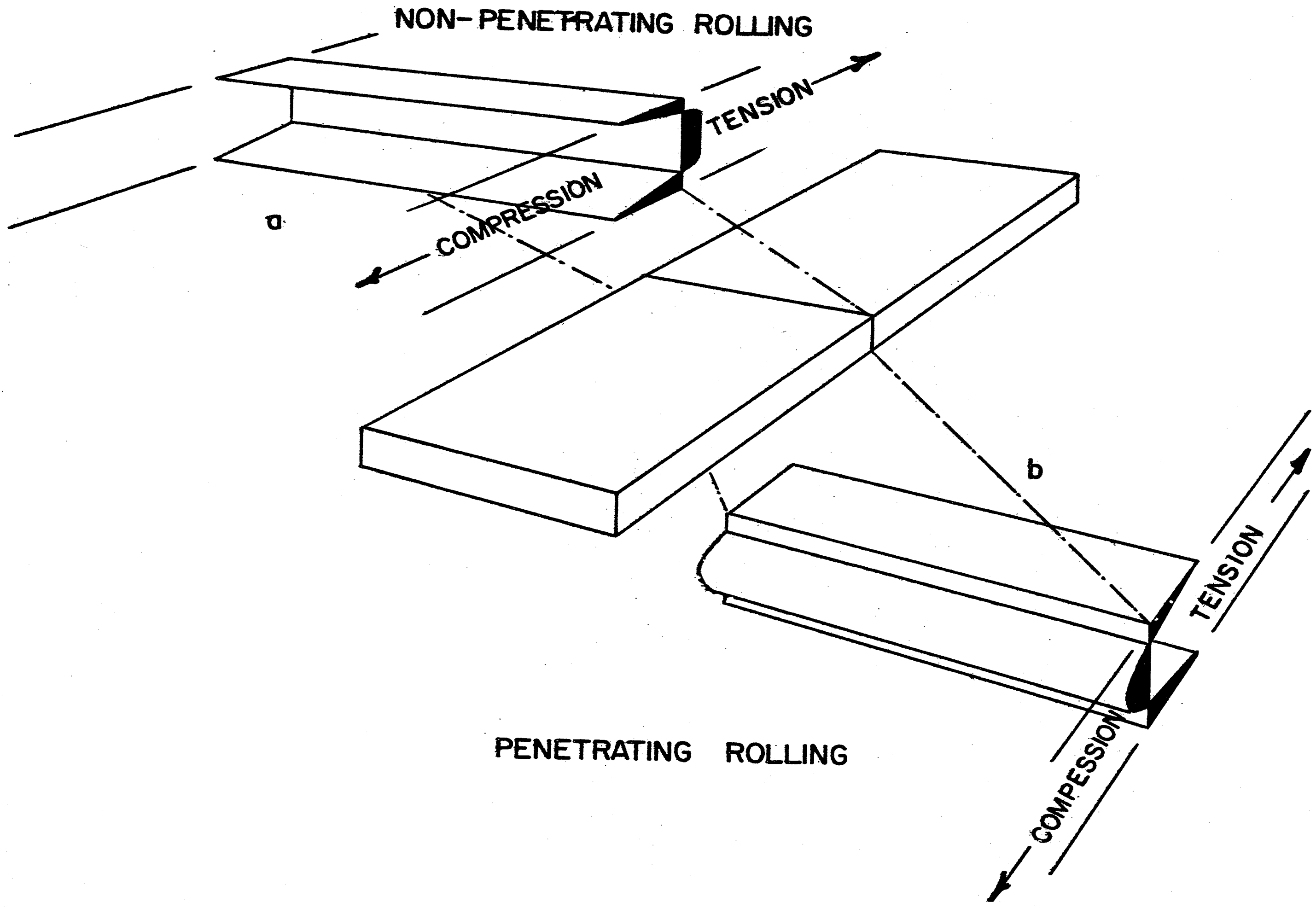


Figure 6. Residual stress distribution produced in rolled strip. (a) For non-penetrating rolling. (b) For penetrating rolling. (From "Cold Working of Metals", pg. 41, The American Society for Metals", Cleveland, Ohio 1949).

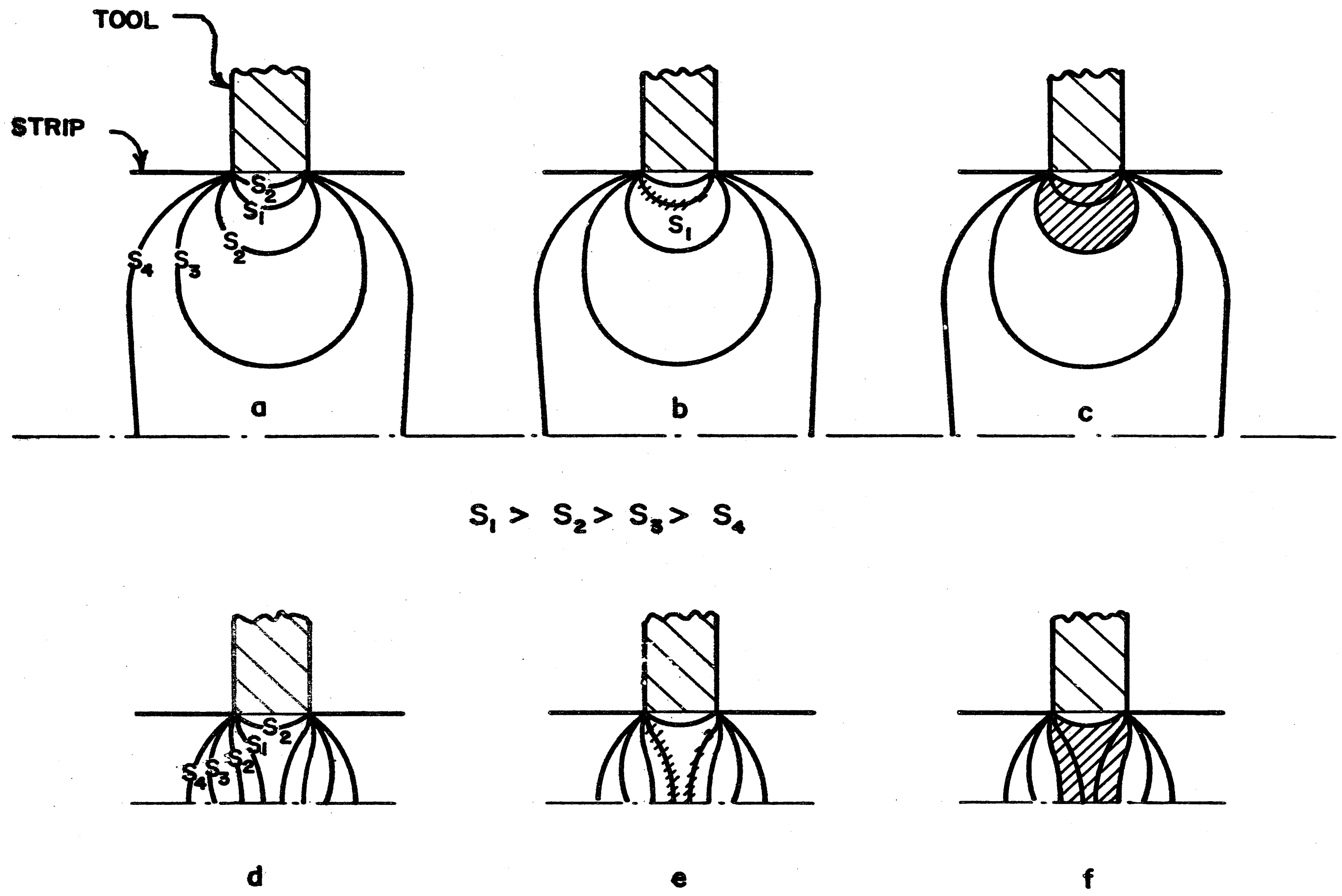
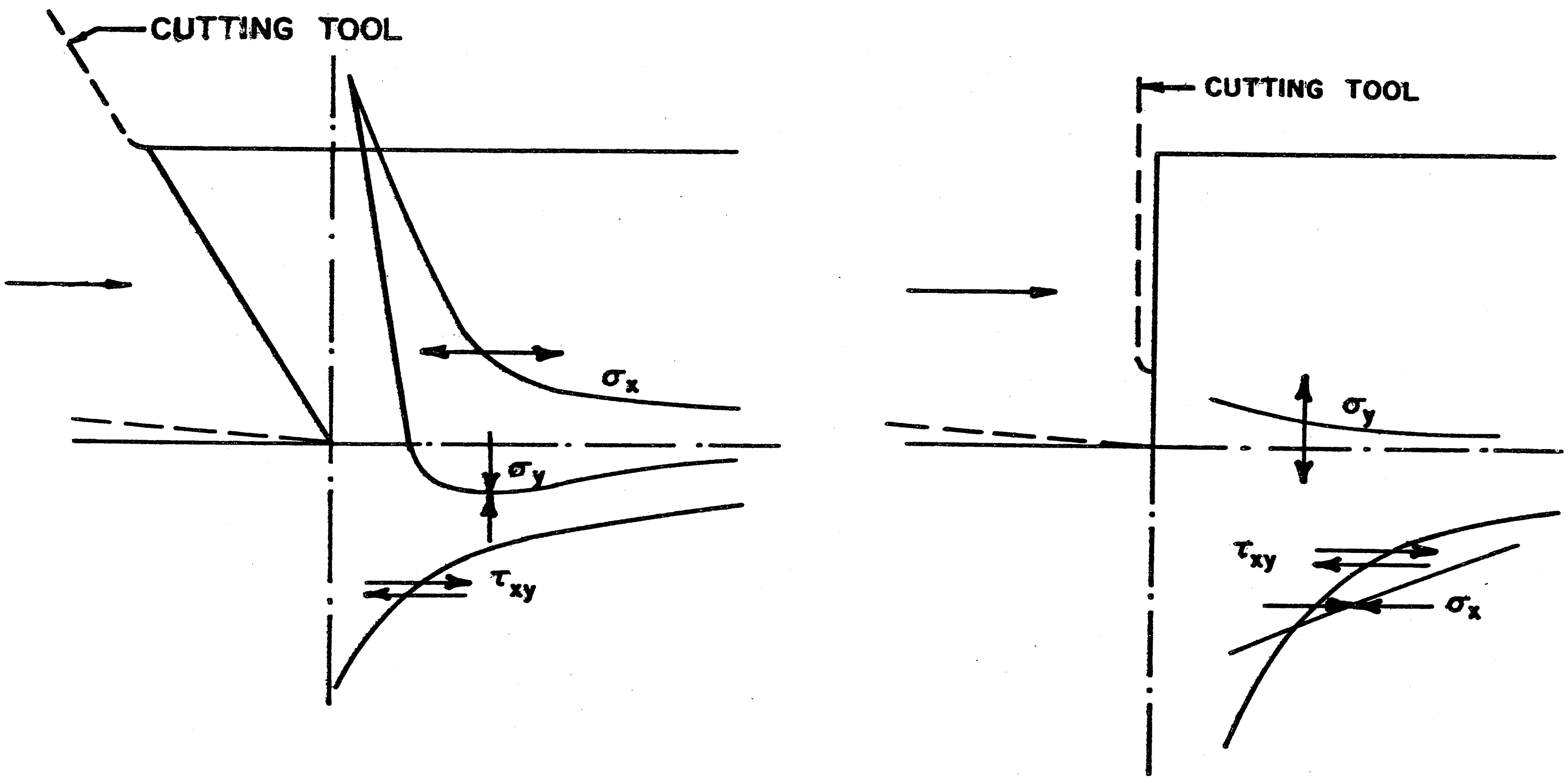


Figure 7. Manner in which plasticity is developed in strip compressed between flat-faced tools. Only upper half of full arrangement is shown. Upper set of conditions produces residual compression in surface; lower produces tension. Upper set could be analogous to contact between flank of cutting tool and machined surface. (From "Cold Working of Metals", pg. 43, The American Society for Metals, Cleveland, Ohio 1949).



POSITIVE RAKE ANGLE

ZERO RAKE ANGLE

Figure 8. Stresses acting on plane of cut surface in ahead of cutting tools; determined by static photo-elastic analysis. Note change of normal stress in cutting direction from tension at left to compression at right in figure. (From "Scientific Papers of The Institute of Physical and Chemical Research, Volume 22, pp. 139 and 147, Tokyo, Japan, October 1933).