THE GRINDING OF LEATHER AND OTHER NON-METALLIC MATERIALS

by

Robert B. Burditt

SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIRES FOR THE DEGREE OF
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(1952)

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May 16, 1952

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Dear Sir:

In partial fulfillment of the requirements for the degree of Bachelor of Science, I submit herewith a thesis entitles THE GRINDING OF LEATHER AND OTHER NON-METALLIC MATERIALS.

Respectfully,

Signature redacted

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ABSTRACT

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Submitted for the degree of Bachelor of Science in the Department of Mechanical Engineering on May 16, 1952.

This thesis reviews the basic principles thus far established on grinding and relates them to the problem of belt grinding, with special emphasis on the problem of belt grinding of non-metallic materials.

The belt grinding process is recommended as that most likely to produce a satisfactory surface finish for non-metallic materials. Recommendations are made for the further study of the belt grinding process.

LEGEND

b	width of the specimen, inches
d	wheel depth of cut, inches
D	diameter of wheel, inches
e	ejection function
F	force in pounds
f	coefficient of friction
n	number of blades cutting
N	wheel speed, RPM
S	grinding shear function
t_c	chip thickness, inches
u	energy per unit volume, inch pounds per cubic inch
v	table speed, feet per minute
V	Surface velocity of wheel
w'	grinding rewelding function
ϕ	rebound angle
γ	clearance angle

Subscripts H, V, etc., represent directions of vectors

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ACKNOWLEDGEMENTS

The author wishes to express his appreciation to Professor M. C. Shaw for his constructive advice, assistance, and guidance during this study.

He also would like to thank the United Shoe Machinery Corporation which provided the grant through which this entire investigation of the machining of non-crystalline materials is being carried out.

The author is also indebted to Mr. Nate Cook of the Metal Cutting Laboratory for guidance, as well as to Mr. Andrew Ling, with whom he worked on some of the material included.

The assistance of Mr. J. Leach of the Machine Tool Laboratory and Mr. H. C. Uriot of M. I. T. Building and Power in setting up the belt grinding apparatus discussed is also acknowledged.

Thanks are also due to the many other members of the Metal Cutting Laboratory and Machine Tool Laboratory at the Massachusetts Institute of Technology for their advice and aid.

INTRODUCTION

This work is part of a program of study initiated by the United Shoe Machinery Corporation several years ago. Its main purpose was the study of the machining characteristics of non-crystalline materials, primarily leather and related materials, aimed at extending the knowledge of the properties of these materials and making improvements in the present methods of working them.

This is also the beginning of a long term study of the belt grinding process, particularly in relation to these substances. The present slowness of machine deliveries, as well as the period of transition through which the M. I. T. Metal Cutting Laboratory is now passing, have prevented the gathering of any data in regard to the actual problem. However, an analysis of the problem will be presented, along with notes on the results of work on single-blade rotary cutting of the materials in question done by Mr. Andrew Ling of the Metal Cutting Laboratory and the author.

The analysis will be divided into four main sections:

1. The basic theory of grinding

2. The process of belt grinding and the characteristics which distinguish it from the ordinary grinding process.

3. The cutting properties of fibrous materials.

4. A correlation of the three points, with deductions and recommendations for future work. This will also include a brief description of the equipment which the author has set up for the program.

In order to avoid the recapitulation of already familiar work, the discussion of grinding theory will be kept as brief as possible, and for a complete development the reader is referred to the work of Marshall,[1] Outwater,[2] and Shaw.[3,4]

THE BASIC THEORY OF GRINDING

Because the grinding process is carried out by the small cuts of innumerable grits rather than by the cutting action of a single tool, a scientific analysis of the grinding process must of necessity be carried out in terms of the energy involved in the process rather than of the forces themselves.

The energy per unit volume involved in the grinding process is given by the equation

$$u = \frac{\pi D N F_H}{12vbd}$$

where the quantities involved are as defined in the preceding legend. The factor πDNF_H represents the power input in the process, while the factor vbd represents the volume rate of feed. Care must be taken to keep the units consistent in this term, and the variables are at present in the units in which they are generally used in engineering practice.

Marshall[1] devised a grinding dynamometer with which he obtained relations for the variables F_V, F_H, V, v, b, and d. His results indicated that the forces involved in the grinding process were independent of the direction of feed with respect to the direction of rotation of the wheel (the "up" and "climb" grinding processes) and whether the work is annealed or hardened. Marshall and Shaw[3] go on to propose that for small depths of cut the specific energy, u, is constant for a given table speed, since their results indicated that for small depths of cut F_H is proportional to b, d, and 1/N. For depths of cut greater than .001 inches the specific energy decreases with increased depths of cut. This may be explained by the size effect[5] and the dislocation theory on which it is based.

Although the measured depth of cut as mentioned previously is of the order of .001 inches in the grinding process, the actual depth of cut for a given grit is much smaller than this. From figure 2 may be seen that the arc of contact for any given grit is, to a very close approximation, $(Dd)^{\frac{1}{2}}$.

Considering two grits a distance m' apart passing through the same tangential plane in the work material, it may be seen that x', the distance between their successive arcs of contact, is m'v/V, where V is πDN/12. Since m' is of the same order of magnitude as the contact arc length and v/V is of the order of .001, the maximum actual depth of cut will be of the order of magnitude of one ten-thousandth to one one-hundred-thousandth of an inch. At these small depths of cut the atomic properties of the material become significant for crystalline materials.

The power absorbed in the grinding process, i.e. the specific energy u, must be dissipated in three ways, as heat through heating of the work and the wheel and through radiation to the surroundings and heat and kinetic energy to the sparks, as energy used in the generation of the new surface, and as residual energy remaining in the crystalline lattice.

Outwater and Shaw[4], working from the theory of Jaeger[6] on heating of a surface in a sliding contact arrive at an approximate mean temperature on the path of contact of about 2200 F and an approximate maximum temperature of 3200 F. These values check fairly well with approximate values obtained using a thermocouple.

Outwater concluded from his temperature studies that the rewelding of the gouge which is formed by the individual grit was a key factor in the magnitude of the forces and the specific energy in grinding of a metal. He set up a relation for u in terms of a shear term S, which was a function of the coarseness of the wheel or N, w', which was a rewelding term depending on the atmosphere in which tests are run, and e, an ejection term which he estimated should depend on the lubricant used. It also would seem reasonable to assume that e should be dependent on the relative velocity between the wheel and the work, since the chip will instantaneously pick up the velocity of the wheel over a certain contact area.

Working from these factors which he considered to be significant, i.e., S, w' and e, Outwater set up an equation for u as

$$u = sw'e$$

The significance of the shear term is obvious, since in the cutting of metals the process of chip removal is one of shear, and this holds even for the small chips removed by the individual grits in grinding.

That the rewelding term is significant was indicated by his results using helium and nitrogen, which when related to a similar depth of cut as tests run in air showed a twenty-five fold increase in both the horizontal and vertical forces. He attributed the drop in forces found in cutting with air to the fact that an oxide layer is formed instantaneously on the freshly cut surface when grinding with air and that this layer prevented most of the rewelding which resulted during the inert-atmosphere grinding. This premise is supported by work on welding processes in which the basic aim is to prevent the instantaneous oxide layer from forming. This rewelding action also produced a much coarser surface than results in normal atmosphere grinding.

Outwater also suggested that liquids used in the grinding process had almost no effect on the temperature involved so that a cutting fluid was of little use as a coolant. The liquid did, according to his shear-ejection-rewelding premise, serve to effect the ejection term by acting as a lubricant. It might also be suggested that in the case of some oxygen-forming compounds the fluids might effect the oxide layer and thus the rewelding factor.

Mention should be made in closing of the grinding coefficient F_V/F_H which is defined by Shaw and Marshall.[3]

This is usually found to be greater than the coefficient of friction for the materials and to be fairly constant as long as the wheel is cutting properly.

THE BELT GRINDING PROCESS

The process of abrasive-belt grinding is a relatively old one, and consists of rotating a belt coated with an abrasive material at very high speeds, supported by a pair of wheels in such a way as to maintain tension in the belt. In early work no coolant could be used due to the resultant weakening of the bond between the belt and the abrasive, with the net effect being an excessive heating and rapid loading of the belt. However, with the development of a plastic bonded cloth belt with the abrasive applied by electrostatic means, the use of a coolant became permissible and the usefulness of the belt grinding process was extended tremendously.

There are many advantages involved in the belt grinding process. The high velocity of the belt relative to the work, coupled with much lower temperatures found in belt grinding, makes possible a much faster rate of removal of stock than is found possible in the conventional wheel grinding method. The belt is also able to follow somewhat the contour of the work piece in some cases, so that belt grinding may be used in the production finishing of many curved contours with a substantial increase in production rate.

On the other hand, the wear of belts represents an extremely serious problem, in that the thinly coated belt is not nearly so durable as the solid grinding wheel, nor does it supply as much abrasive as the wheel on a dollar-for-dollar basis. This added expenditure is nevertheless often justified.

Belt grinding may be conducted in one of three ways, free-belt grinding, contact-wheel belt grinding, and platen grinding. The free belt grinding is well represented by its title, since an unsupported section of the belt is used for the actual grinding, with the force being supplied by the tension in the belt. In contact-wheel grinding the work is fed into the belt in the section supported by the contact wheel. In platen grinding the work is ground horizontally on the flat surface of the belt, supported by a metal plate. This method is used to produce extremely accurate finishes on metal parts. (see figure 4)

Walker[7] noted in work on both wheel grinding and belt grinding that there was actually far less tendency to burn the work when cutting dry with a belt than with a grinding wheel, and that the tendency to burn was decreased with increased depth of cut for the abrasive-belt grinding process, whereas the wheel grinding showed an increase in burning tendency with increased depth of cut. He used the contact-wheel method of abrasive-belt grinding and the analagous "snagging" method of wheel grinding.

Walker found that the tangential, or cutting force, increased linearly with the normal force and cutting rate for a 36 grit belt, concluding that a plot of normal force against cutting rate would also be linear. This result is not unexpected, considering the results of similar plots with wheel grinding. He found the chips produced in abrasive-belt grinding to be large enough so that there was no noticable size effect.

Working from the Shaw-Outwater temperature equation, he concluded that, due to the high belt speeds and high depths of cut involved, almost all the heat generated during the operation was carried off by the chip. He also proposed that the energy consumed in cutting was low and thus the heat generated was also low. It is also to be noted that at the velocities obtaining from the belt-grinding process the rate of removal of the work approaches the rate of heat transfer from the cutting surface into the work piece.

To summarize these observations, the chief distinguishing factors in the belt grinding process are the increase in velocity of the tool and feed of the work and the far lower temperatures which occur in the belt grinding process.

If we accept Outwater's conclusions on the actual mechanism of the grinding process and his premise that the energy, u, may be represented as a function of the shear term, S, a rewelding term, w', and an ejection term, e, we may come to a few conclusions about the reasons for the increased feed rate which is possible in belt grinding. First of all, the temperature in abrasive-belt grinding work is probably below the solidus maximum temperature which Outwater found in wheel grinding by a very large margin. Furthermore, the higher velocity of the belt is probably responsible for a far greater degree of succes in ejections, following my previous reasoning, so that the necessity for recutting chips which have rewelded to an already cut surface is reduced to a minimum and perhaps eliminated.

THE CUTTING PROPERTIES OF FIBROUS MATERIALS

It now becomes necessary to consider the mechanism involved in the cutting of fibrous materials and compare it to that involved in metal cutting. First of all, the process of cutting a fibrous material appears to be one of severing the individual fibers of the material, or tearing them completely from the body of the material. On the other hand, it has become accepted that the process of metal cutting is one of shear, that is the chip is removed from the work by a shearing action on the part of the tool.

Tests run by Cook and Howitt[8] with a single blade cutting tool using a planer type of cutting operation showed the leather cutting mechanism to be a combination of vertical tension directly below the cutting edge, horizontal compression in front of the cutting edge, and shear strain above the blade, with the tensile deformation being the most important. These conclusions were reached on the basis of the effect of the cutting operation on a grid superimposed on the leather following a recommendation by Loewen.[9] Plastic cutting was found to be similar to leather cutting in that large tensile deformations were produced beneath the cutting edge. During the growth of these stresses, however, a "bubble" was formed at the cutting edge. The authors suggested that when the tensile strain reached a certain critical level the material split from the cutting edge toward the plastic surface along a path of maximum stress. This discontinuous chip formation began at a very low depth of cut, only .004 inches in the case of lucite.

Using a rotary edge trimmer furnished by the United Shoe Machinery Corporation, Cook and Howitt then began experimenting with rotary cutting on leather specimens. They found that the observed forces decreased assymptotically with increasing cutter speed and increased with increasing table speed. The horizontal force increased much more rapidly with increasing depth of cut than did the vertical force, although this also showed an increase. Defining chip thickness as

$$t_c = \frac{V}{2Nn} \sin \theta$$

where n is the number of blades on the cutter used on the angle θ is defined by $\cos \theta = \frac{R - d}{R}$, a curve was found relating specific energy to t_c as $u = 3.39 \times 10^6 \times t_c^{-.428}$ $\frac{\text{in. oz.}}{\text{in.}^3}$.

At high speeds the temperatures reached were found to be high enough so as to drive some of the collagen out of the leather. The chip thickness for these speeds also reached low values, such that the mechanical strength no longer seemed sufficient to maintain a continuous chip.

It was suggested that the surface finish of the leather was dependent on the relative velocity between the work and the cutter and also dependent on chip thickness. Within the previously mentioned limits increased cutter speed gave improved surfaces; beyond these limits increased speed led to burnishing. Decreasing chip thickness led to better surface finish.

In order to get more significant results, Cook[10] continued the study of rotary cutting using a single bladed cutter. Two of the blades of a three bladed shaper head were ground back so that they contributed nothing to the cutting process but merely served to balance the wheel. He theorized that actually only one of the blades on a multibladed cutter was working during the cutting, while the other blades contributed nothing to the process. This he based on the fact that there is usually a variation of at least 10^{-4} and sometimes well over 10^{-3} inches in the cutter blades, depending on whether or not the blades were sharpened by hand.

If, however, we consider the rebound characteristics of leather it seems quite likely to this author that this assumption is inaccurate. This would depend on the time lapse involved in the rebound process, which might lead to cutting on the part of even the shortest blades despite the small chips which are generated. On the other hand, the time lag might be such as to only give a rubbing effect which would make it appear that all the blades were cutting although the burden would be borne by only one, as proposed by Cook. Considering that the rebound process must be continuous and the order of damping required to justify the Cook assumption this would not appear to be consistent with the physical picture.

Using the method of slopes[10], we may reduce the rotary cutting process to a series of infinitesimal planing type cuts. In any cutting of material withhigh elasticity, we have forces acting on the back face of the tool as well as on the front face, and it becomes necessary to separate the forces into components on each face if we are to analyze them. The force on the back face of the blade should be proportional to the volume under the rebound curve which intersects the back of the blade and thus produces the force. (see figure 5) For a given set of parameters, varying only the clearance angle γ , the force would then, by the Cook analysis, be proportional to the cotangent of the clearance angle.

Actually the force is roughly proportional to the angle $\phi - \gamma$, but if we hold all the variables which effect the rebound curve constant except the clearance angle, it may then be seen that the proportionality proposed by Cook holds.

Working on the basis of this assumption, coupled with many approximations such as neglecting shear forces, side flow, and the effect of the force on the back or clearance face on the force on the front face, Cook proceeded to solve for the forces on the faces of the tool. This solution Should be reconsidered in the light of work now being done on thrust at the point of the tool if the thrust picture of cutting proves valid.

The wave picture of the neolite cutting process should also be reconsidered, since studies by Mr. Ling with the aid of the author inicated that the rebound curve continued to build up and follow the tool in leather and avonite, rather than following the wave form pictured. These tests were run at a wide variety of speeds with consistent results. (No tests were run on neolite, on which Mr. Cook bases most of his study.)

Cook arrives at the conclusion that the poor surface finish which we seek to eliminate is inherent in the rotary cutting process and cannot be avoided by altering the geometry, i.e. the angles, of the operation. Tests we have since run with a single blade cutter using various rake angles and clearance angle and an inclination angle appear to justify this conclusion.

FRICTION

It should be fairly obvious that there exist many similarities between the grinding process and the friction and wear processes. For instance, Outwater's relation for specific energy in terms of a shear term, a rewelding term and an ejection term is very similar to the analysis of the friction process by Bowden[11], who pictures friction as a combination of plowing and shearing. Whereas Bowden's analysis results in a term which is a function of a hardnesses of the metals involved, however, it appears from experimental data that the specific energy in grinding is independent of the hardness of the metal. The grinding coefficient obtained by Marshall and Shaw is also substantially greater than the coefficient of friction for the same combination of materials.

Although the grinding process is also similar to that of wear, the experimental knowledge which is available on the wear process is insufficient to provide the basis for any conclusions or comparisons between the two. In fact, it is generally agreed that even the friction and wear processes are not the directly related processes which they were once assumed to be.[12]

Furthermore, knowledge of the real mechanism of the friction process in the case of fibrous materials is extremely limited. It has been fairly well established that Amonton's Law (friction force is proportional to normal force) holds to a good approximation. It has also been found that in at least a few cases there is a profound decrease in the frictional coefficient due to the use of lubricants.[13] It should also be noted in conclusion that wear failure quite frequently takes place below the surface of the material, with the surface section then breaking off.

CONCLUSIONS AND RECOMMENDATIONS

We are now in a position to draw some very few conclusions about the belt grinding process. First of all, the extreme rebound effect which occurs in rotary cutting of leather will not take place in the grinding process and especially in the abrasive-belt grinding process, since the verticle deformations are too small to produce sufficient elastic force to alter the grinding forces. These forces will be in the order of magnitude of a few ounces and will actually be insignificant in any considerations of the practicality of the abrasive-belt grinding process but will be of considerable value in a theoetical analysis of the process.

The primary problem in the working of leather is the production of an acceptable surface finish. The finish in the two-dimensional rotary cutting process has already been mentioned as being inacceptable and the results of work by Mr. Ling and the author indicate that the assumption that surface finish would not be improved by altering the angles involved is correct. The surface finish should be improved considerably by the belt grinding process. The primary cause of poor surface finish appears to be the rebound effect, with its resultant varying depths of cut and rubbing effect. This as we have just mentioned, should not occur in the belt grinding process; thus we may assume, perhaps optimistically, that the surface finish resulting from the belt grinding process should be far superior in quality to those produced by other mechanical cutting means. Although the surface may also be improved by the use of wheel grinding, the surface burning which would be produced would probably be too great to meet the standards required.

RECOMMENDATIONS

A sketch of the layout which has been constructed by the author for use in the study of belt grinding is included as figure 6 in this report.

1. A study should be made of the various surface finishes produced by altering the feed rate and the grit of the belt, as well as the belt velocity. Some definite criterian for surface finish, perhaps along the lines of that now being used on metals, should be worked out on the basis of photomicrographs of the surface resulting from the various operations which have been tried. The present arbitrary system of classification of a surface as good or poor is completely unsatisfactory.

2. The forces involved in the process should be measured, but only in order to better understand the mechanics of the process.

3. Examination should be made of the effects of the back-up wheel on the forces and the surface finish produced in leather cutting. Some study might be advisable on the use of platen-grinding. The freebelt process would probably reintroduce elastic effects which we have been seeking to eliminate. Since the platen method has the most stable belt support, it should produce the best surface finish.

4. In the study of the abrasive-belt grinding of metals a study should be made of whether there is a grinding coeficient in the belt grinding process which is analagous to that found in the case of wheel grinding and experiments should be run to determine whether this is related to the coeficient of friction between the two surfaces. It should be remembered that the coefficient of friction may vary according to velocity and temperature, so that these factors should be considered in any attempt at correlation.

5. Since, as has already been noted, the use of fluids has greatly enhanced the belt-grinding process, a study should be made of the effect of fluids on the surfaces and forces involved in metal grinding and the increase in feed rate made possible by the use of a fluid. It is unlikely that any improvement would be found in leather grinding, rather the effect might be damaging, although it should be investigated.

6. Since the wear of the belts used is the primary

factor in the use of belt grinding a careful check should be made on the relation between belt wear and the amount and rate of production. The effect of fluids on belt wear should also be studied.

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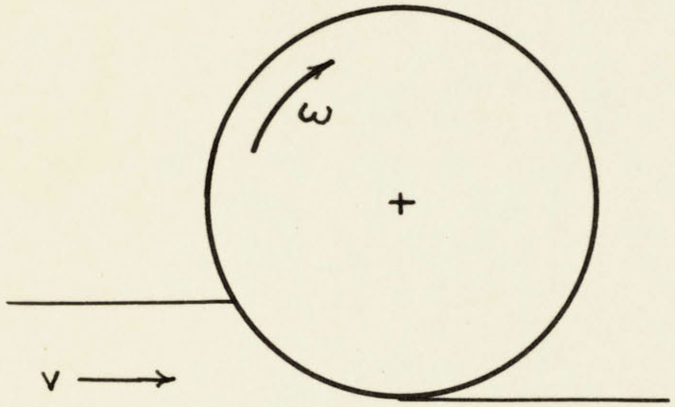
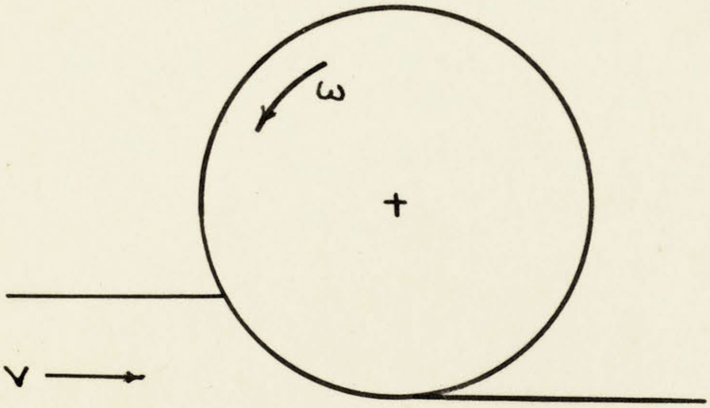


UP GRINDING



DOWN (CLIMB) GRINDING

Figure 1 - UP vs DOWN GRINDING

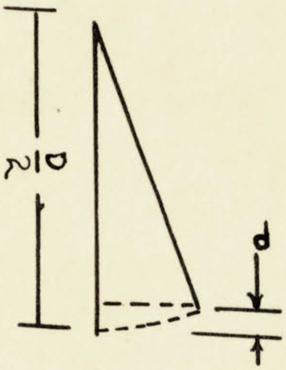


Figure 2 - CONTACT ARC LENGTH

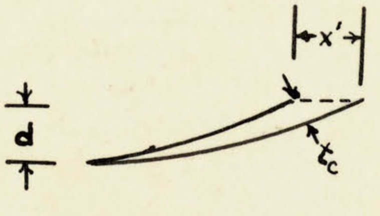
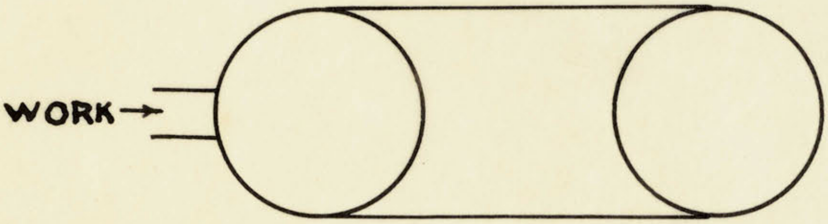
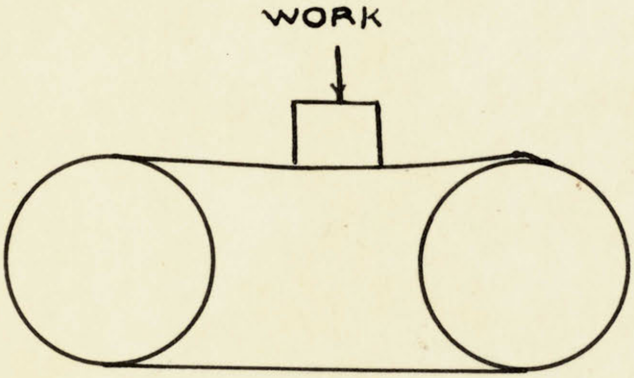


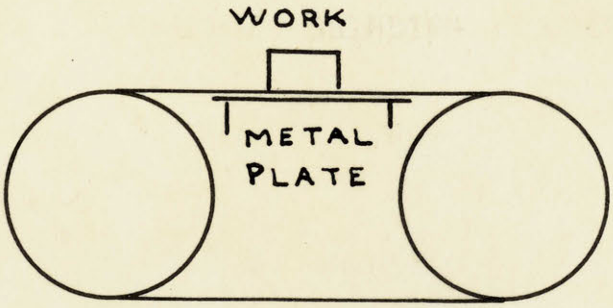
Figure 3 - ACTUAL GRINDING DEPTH OF CUT



CONTACT-WHEEL GRINDING



FREE-BELT GRINDING



PLATEN GRINDING

Figure 4 - TYPES OF BELT GRINDING

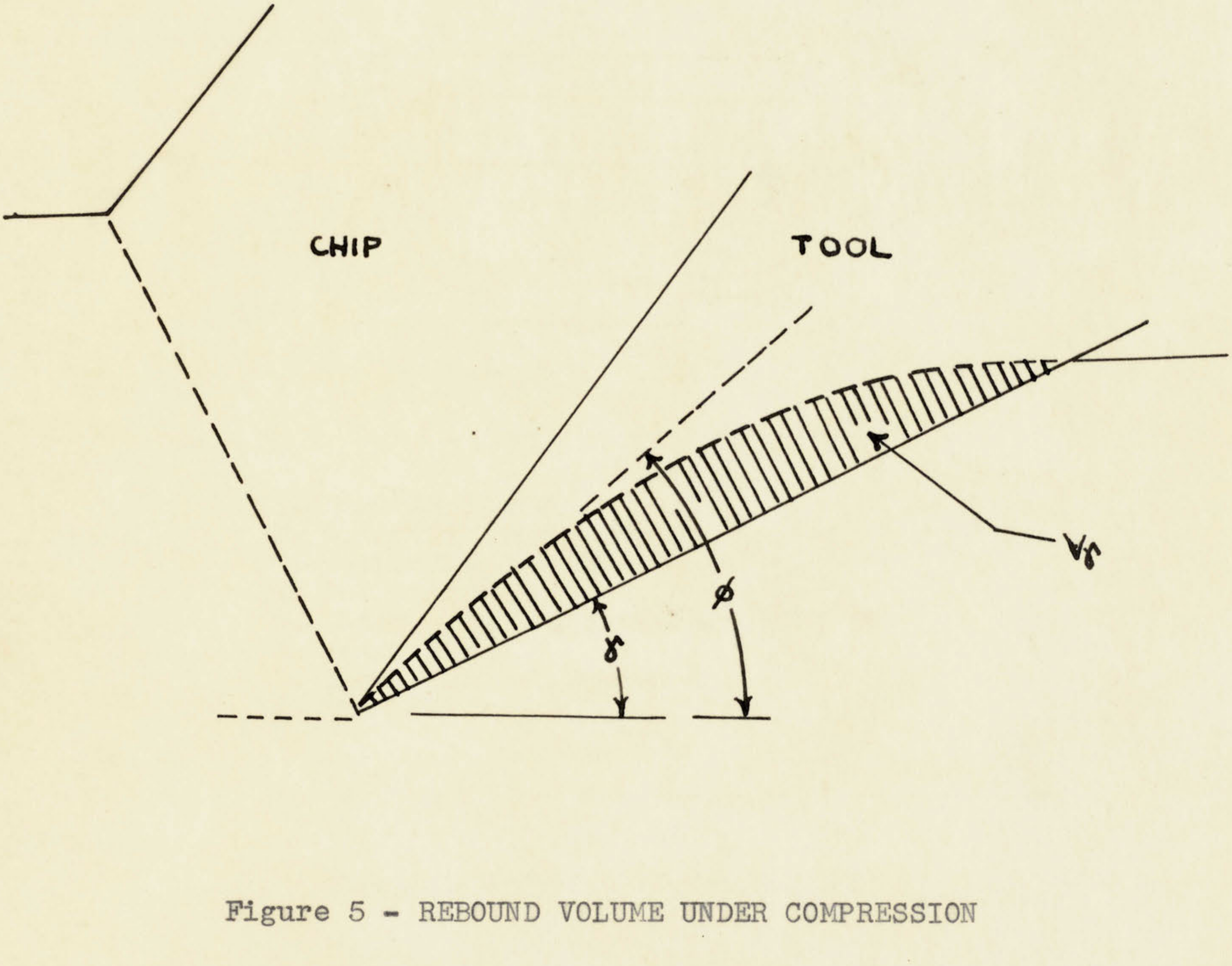
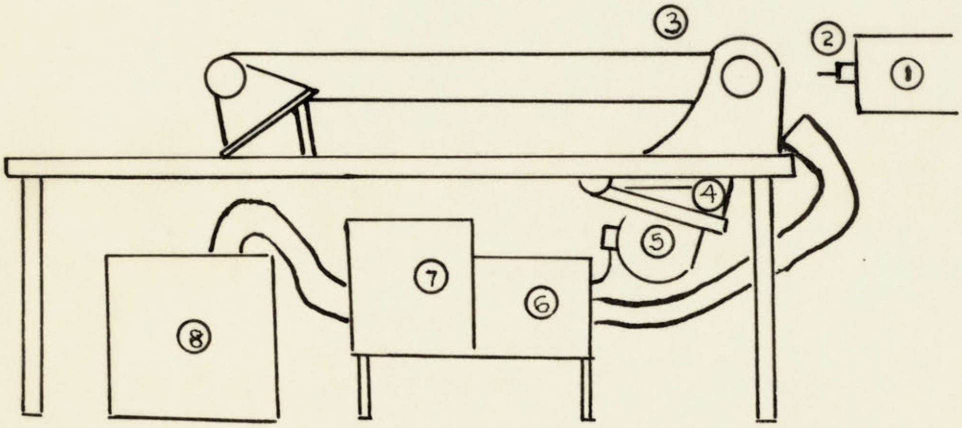


Figure 5 - REBOUND VOLUME UNDER COMPRESSION



1. Milling Table
2. Grinding Dynamometer
3. Backstand Grinder
4. Motor Mount
5. Motor - 3/4HP, 1150-3450 RPM, DC
6. Motor Reset
7. Speed Control Rheostat
8. Dust Collector

Figure 6 - BELT GRINDING LAYOUT