TEMPERATURE RISE OF THE WORKPIECE IN METAL CUTTING

by

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ABSTRACT

Temperatures near the surface of a lathe workpiece were measured by placing a thermocouple wire at some distance ahead of the tool and cutting toward the junction until the wire was cut off. Measurements were taken at cutting speeds of 100 to 500 fpm. The effect of changing the diameter of the workpiece at the same cutting speed was investigated and temperatures found to be higher for smaller work diameters. The action of cutting fluids at higher cutting speeds is discussed and data presented showing the degree of reduction of workpiece temperatures obtained with water as a coolant. The possible effect of the above findings on tool wear is discussed.

Several early and two recent Russian works in the metal cutting field are reviewed to give a picture of the extent of metal cutting research in Russia.

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Part II: Review of Three Russian Metal Cutting Works

FOREWORD

This thesis consists essentially of two separate parts: (1) An investigation of the workpiece temperatures in turning; (2) A review of a few Russian works in the Metal Cutting field.

The review of some Russian metal cutting literature was undertaken because of the author's rather accidental familiarity with the Russian language. Russian metal cutting literature is extensive but generally little known in the West since only works of earth-shaking significance are translated and made available by various agencies in the United States. Thus, it was a longfelt desire to review some of the Russian works in the metal cutting field for the members of the Metals Processing Laboratory at M.I.T.

Whenever applicable, the references to Russian sources are included in the text; but when a direct connection was not present, the works are discussed in a separate section.

This review will provide the reader with some opportunity to see to what background can Russian workers look back in the case of metal cutting research and what is the quality of some of their current work.

It should be pointed out that only the best of the Russian literature which was available to us is reviewed here.

It is my private opinion that the work of the younger generation of Russian sectores metallorum is in general more impressive because of its quantity rather than quality.

In the following text the numbers in parentheses at the end of sentences refer to the list of references on page 95 .

INTRODUCTION

The main purpose of this investigation was to determine experimentally the temperature distribution in a lathe workpiece in turning at higher cutting speeds.

There are several reasons why the workpiece temperature should be of interest, such as its effect on dimensional accuracy and perhaps surface finish, but our main problem was to investigate the possible effect of workpiece temperatures on tool life, particularly when cutting fluids are used in machining.

It is well known that the tool life depends to a very high degree on cutting speed and as a result on cutting temperatures -- i.e., temperatures existing at the contacting surfaces of the chip and tool (1). In the tool life - cutting speed relationship $T = Const/V^m$ the exponent m is often reported to be approximately equal to 5 for cutting steel with carbide tools (2). The dependence of the cutting temperature on cutting speed can be expressed as $\theta = Const.V^n$ where n is reported to be approximately equal to 0.25 again for carbide tools cutting steel (3). This indicates that the tool life is inversely proportional to the cutting temperature raised to about 20th power.

Since the tool life depends to such a degree on the cutting temperature, the decrease of that temperature by as much as 50°F due to the application of the cutting fluid or the increase by the same amount due to a small volume of the machined part should have a considerable effect on the tool life. It is seen that the changes mentioned are in the order of magnitude of 5% or less of the cutting temperature and therefore are rather difficult to establish by direct measurements.

The measurements of the workpiece temperatures undertaken in this investigation are not expected to give a complete account of the effects stated especially concerning the cutting fluids; but they will be helpful in determining at what temperature does the metal arrive into the cutting zone and in investigating the possible effect of the variation of the workpiece diameter on the cutting temperature at the same cutting speed. They may serve as a step toward analyzing the basic mechanism of the cutting fluid action at high speeds when heat transfer (cooling) rather than lubrication (in whatever form) becomes important. They may be used, finally, to check the theoretical calculations of the amount of heat going into the workpiece.

EXPERIMENTAL METHOD
FOR MEASURING WORKPIECE TEMPERATURES

The experimental method consisted simply of inserting a thermocouple wire into the workpiece a certain distance away from the beginning of the cut and then cutting toward the junction until the metal with the wire was cut off. This method was used by G. S. Reichenbach (4) for obtaining the temperature distribution in the work material ahead of the shear plane and in the chip. His measurements were performed on a shaper with orthogonal cutting. By using depth of cut of 0.050" and 0.005" diameter wire and placing the wire at different distances from the work surface, he was able to obtain the temperature history at the junction as the wire passed from the workpiece into the chip.

Originally it was planned to obtain the same type of measurements in this investigation for a lathe workpiece and at higher cutting speeds. But unfortunately all attempts to keep the wire from breaking as it passed through the shear plane were not successful, and so the measurements were limited to determination of the temperature distribution only in the workpiece.

The experiments were performed using an AISI 1020 steel billet (3¼ diameter, 20" long) on a Monarch (12") lathe. The holes for the thermocouple wire were made by a small drill press mounted directly on the lathe; they were 0.0051" in diameter, about 0.020" deep and drilled in the radial direction. One end of constantan thermocouple wire of 0.005" in diameter and about one foot long was inserted into the hole and held firm by peening with a small center punch; the other end was soldered to a lead wire which was taken out through the headstock of the lathe and connected to the measuring instrument by means of a mercury pool. To establish a good electrical connection between the workpiece which is one of the thermocouple materials and the measuring instrument a rod was attached to the headstock end of the workpiece in the usual manner of chip-tool thermocouple measurements and the contact provided again by a mercury pool. The constantan and the lead wires were, of course, insulated from the workpiece and the lathe. The set-up is schematically shown on Fig. 1. With this arrangement it is not necessary to insulate the workpiece or the tool since the e.m.f. generated at the chip-tool interface is short circuited.

To record the e.m.f. from the constantan wire-workpiece thermocouple the D.C. side of a Du Mont (Type 324) oscilloscope was used. The potentiometer recorder type instrument does not have a fast enough response to follow the rapid changes of temperature when the wire junction passes near the tool. The trace obtained on the oscilloscope screen

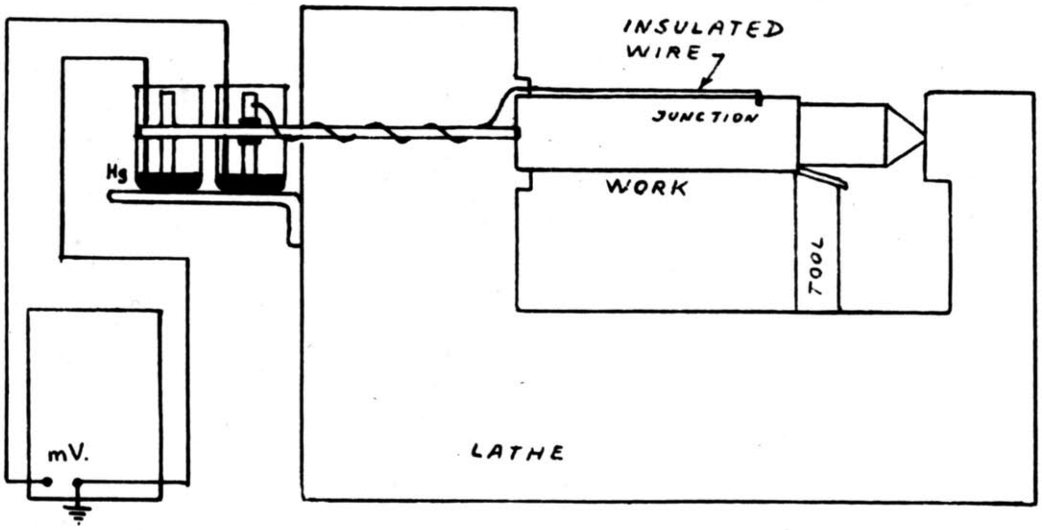


Fig. 1 - Schematic Sketch of the Experimental Set-Up

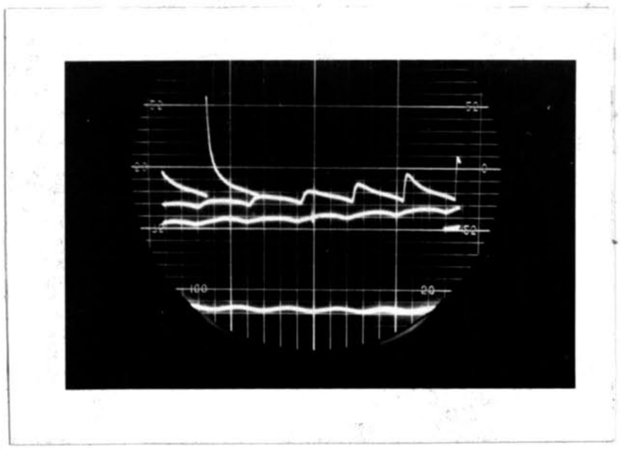


Fig. 2 - Example of an Oscilloscope Trace

represents the temperature history of a single spot near the surface of the workpiece with respect to time. But since any other spot on the workpiece surface undergoes completely similar temperature changes, one can obtain in this way the temperature distribution in the material ahead of the tool. An example of such a trace recorded with a Polaroid Land camera is shown on Fig. 2. The waviness at the beginning of the trace is due to the rotation of the workpiece alone -- i.e., it will be present when the workpiece is only turning, without cutting. This effect accounts for approximately ± 1/8 mv from the center line which corresponds to about 4°F.

The cutting conditions used were mainly 0.100 in. depth and 0.010 ipr feed; the tool was carbide with a rake angle of 10°; clearance angles of 6°; zero side cutting edge and 15° end cutting edge angles and no nose radius. The choice of cutting conditions and the tool geometry was dictated by several considerations and also by some difficulties encountered when performing the tests such as, for example, the relation between the thermocouple wire diameter and the feed or the fact that the wire would break off due to the deformation under the cutting edge from the previous cut when a tool with minus seven degree rake angle was used.

There are some other uncertainties associated with these measurements. It is rather difficult to locate the hole for the constantan wire with respect to the tool with desired accuracy. In most cases the holes were drilled using a magnifying glass between feed marks left from the previous cut and the thread cutting screw of the lathe was used to follow the same cutting path (except when 0.005 ipr feed was used). Even with that precaution, at times the end of the wire which was inserted into the hole could be seen to have been cut through by the tool leaving a semicircular cross section at the tip. At other times with the same conditions the end of the wire, which was usually bent over after insertion into the hole, would be simply broken off leaving a very short stub at the tip. In the latter case the peak temperature obtained was considerably lower.

An attempt was made also to measure the temperature on the surface of the workpiece and the top surface of the chip by simply holding a constantan wire against the surface forming a so-called dynamic thermocouple between them. Although this method indicated temperatures in the correct order of magnitude, measurements of any reasonable accuracy could not be made because the values obtained in this manner depend very much on the pressure applied, and secondly the motion of the chip was not steady enough and the surface too rough for getting continuous readings.

Fig. 3 shows the qualitative temperature distribution in a lathe workpiece obtained by the first method. $\Delta \theta_b$ is the last temperature value recorded on the

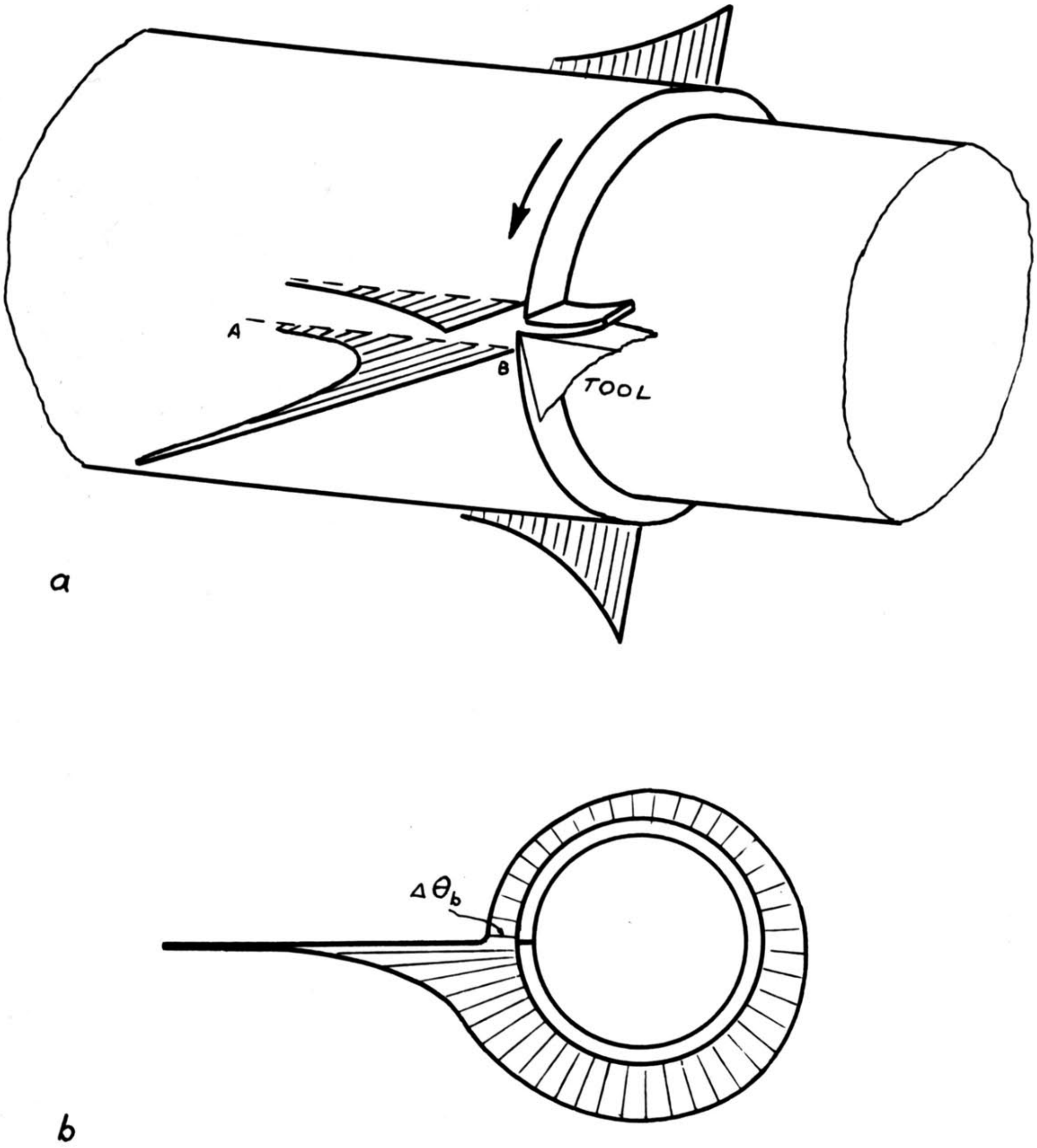


Fig. 3 - Temperature distribution in a lathe workpiece at higher cutting speeds (qualitative).
a - in the axial direction; distances are exaggerated relative to the chip thickness
b - around the circumference

oscilloscope trace just before the constantan wire is broken. The temperatures on the surface parallel to the cutting edge cannot be obtained directly. Extrapolation to the surface can be made easily where the gradients are small, but the peak temperature just below the tool opposite the clearance face ($\theta_{c,\ max.}$) is difficult to obtain because: (1) the temperature gradient in the direction EA is very steep and (2) the distance of the wire to the cutting edge is not known accurately, the uncertainty at worst being about ± 0.25 of one feed distance. Table 1 gives a comparison of the values obtained under the same cutting conditions.

Table 1 - Showing the Amount of Scatter in the Experimental Data

$\Delta \theta_b$	1st Peak $\Delta \theta_c$	2nd Peak	3rd Peak	Number of Runs
50°F	240°F	100°F	75°F	11A
50	280	115	75	13A
50	250	100	72	15A
50		165(?)	82(?)	16A
45	230	90	66	17A

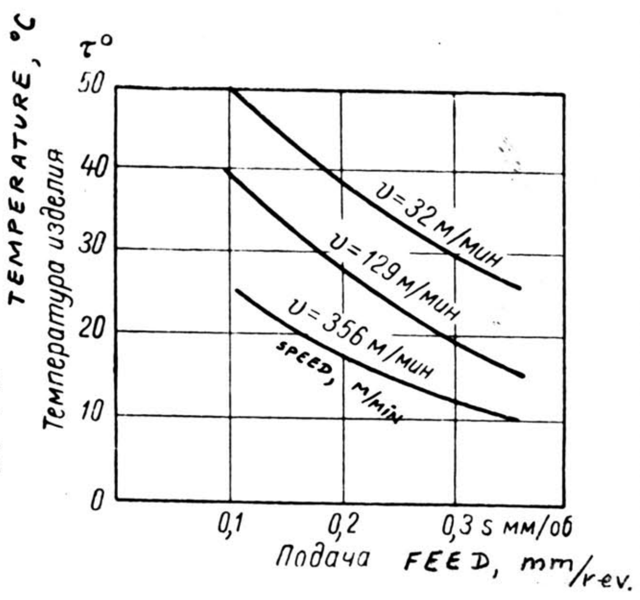
Speed - 390 fpm; diameter - 2.75 in.

TEMPERATURE DISTRIBUTION IN THE WORKPIECE

It is well known that the portion of heat flowing into the workpiece from the shear zone decreases with increasing cutting speed. This fact is clearly shown by several authors who have investigated the partition of heat energy and the temperatures in the cutting zone. (5, 6, 7) Since the total energy per unit volume of the metal removed is essentially constant or decreases slightly with increasing speeds, it is evident that the amount of heat going into the workpiece for the same amount of machining done decreases with higher speeds. This can be shown by experiment as given by an example in Fig. 4. With dull tools or very small relief angles more heat will flow into the workpiece because of additional friction on the clearance face of the tool. For dull tools the friction on the clearance side may account for 10% of the total energy and most of it goes into the work since temperature gradients are favorable in that direction (7). Fig. 5 illustrates this effect obtained in thread milling (2). It is interesting to note that higher feeds give less temperature rise in the workpiece because of shorter cutting time for the same amount of machining.

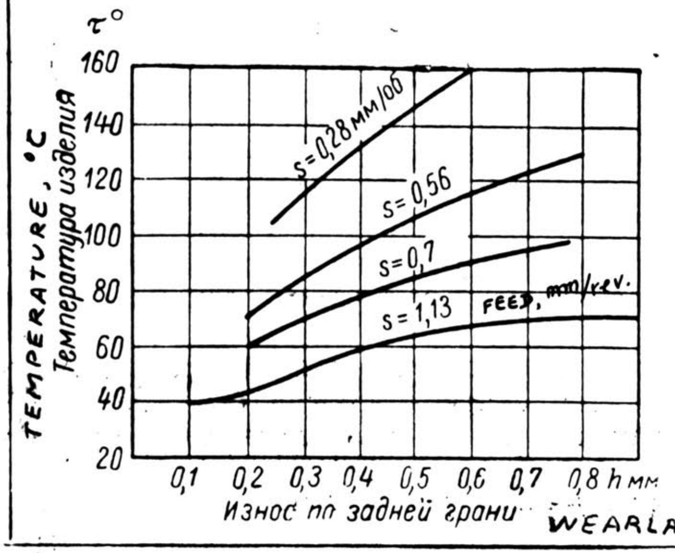
The amount of heat conducted into the workpiece has been discussed in literature, but the temperature distribution in the workpiece has not been given much attention.

Fig. 4 - Temperature of the Workpiece with Different Feeds and Speeds



Фиг. 134. Температура на поверхности изделия.

Обрабатываемый материал — сталь $\sigma_в = 75$ *кг/мм²*; глубина резания $t = 3{,}2$ *мм*.



Фиг. 135. Температура изделия в зависимости от износа резца.

Fig. 5 - Dependence of the Workpiece Temperature on the Sharpness of the Tool

At low speeds metal approaches the cutting zone essentially at the ambient temperature of the workpiece but is preheated before it comes to the shear plane by heat flowing back into work. At higher cutting speeds there is less preheating but more retained heat from the preceding cutting. When temperatures in the cutting zone are analyzed theoretically, the effect of preheating from previous cutting is usually neglected (5, 7, 8). This may be justified by noticing that the chip-tool thermocouple measurements indicate that the temperature reaches equilibrium in a few seconds after cutting begins. Besides it is rather a simple matter to calculate the rise of the ambient temperature of the workpiece by knowing its thermal properties, the time of cutting and the fraction of the total energy going into the workpiece. This rise can then simply be added to the calculated values provided that the workpiece temperature does not have any other effect on the cutting process.

In this discussion the effects associated with hot machining are not considered since they can hardly take place below about 300°F. In this connection it is interesting to note that some writers do not seem to differentiate between the effect on the mechanical properties of metals of the relatively long time heating and very short time heating which take place when the chip is formed (9, 10). Whatever the physical nature of the changes in mechanical properties they can hardly occur in a time of one or two thousandths of a second. (11) If such were not the case, it is difficult to see how a cutting fluid could be effective in reducing tool wear, since it would be always desirable to heat the workpiece rather than cool it. Besides the hot machining results reported by different investigators are conflicting. For example, Krabacher and Merchant's (1) data indicate improvement of tool life with increasing workpiece temperatures in the vicinity of room temperature while Vieregge (9) reports data showing decrease of tool life in general but little change from room temperature to about 300°F.

It will be assumed then that an increase of 50 or 100°F in the workpiece temperature will increase the cutting temperature accordingly and have corresponding adverse effect on tool life. Some evidence in the support of this opinion may be obtained from chip-tool thermocouple measurements. Such measurements often show decrease of temperature as the cutting progresses, but if carefully executed, they should show a slow rise of temperature since in metal cutting a complete steady state is practically never achieved. The experiments reported by Danielian (3) which are described below will illustrate this.

A. M. Danielian, being an ardent supporter of the chip-tool thermocouple method of measuring cutting temperatures, made considerable amount of tests to prove that this method, if carefully employed, gives the most reasonable results of all other experimental methods. One series of his tests is of interest to us since it shows a small but steady increase of the cutting temperature with the length of cut indicating most likely that the rise of the ambient temperature of the workpiece raises the cutting temperature accordingly. The effect of the tool wear is not certain. First, a carbide tool cutting steel at about 200 fpm for only a few minutes does not wear much. Secondly, some investigators (4) have shown that dull tools do not produce higher cutting temperatures. But the reason for this may be due to the fact that the chip-tool thermocouple measures average temperature of the contacting surfaces and the additional area of contact between the tool and the work produced by wear is generally a considerably lower temperature than the contacting surfaces of the rake face. Thus one may arrive at a paradoxical case when temperatures in the tool will rise all around but the emf measured by the thermocouple may become lower.

Danielian used seven different variations of the chip-tool thermocouple method, namely:

(1) Using a solid carbide tool bit 20 x 20 x 120 mm.

(2) Clamped-on carbide plate with a carbide rod attached to it; both being insulated by mica sheets from the tool holder; lead wire attached to the carbide rod.

(3) Same as (2) but without insulation.

(4) Using a clamped-on carbide plate. The copper wire for the electrical connection attached to the tool holder.

(5) Brazed carbide plate. Wire attached to the holder.

(6) Same as (2) but brazed-on, contacting carbide rod insulated frrom the tool holder.

(7) Carbide plate with a specially made small tail to which the wire is attached. The plate is insulated from the tool holder and the junction is cooled by water circulated by a special pump.

Care was taken to select tools with similar thermo-electric properties and same geometry and the same tool holder was used for all cases. Fig. 6 is one of the plots showing the results of these tests. Other plots are given for different cutting speeds and display the same behavious, the temperature rise being somewhat more intensive at the higher speeds.

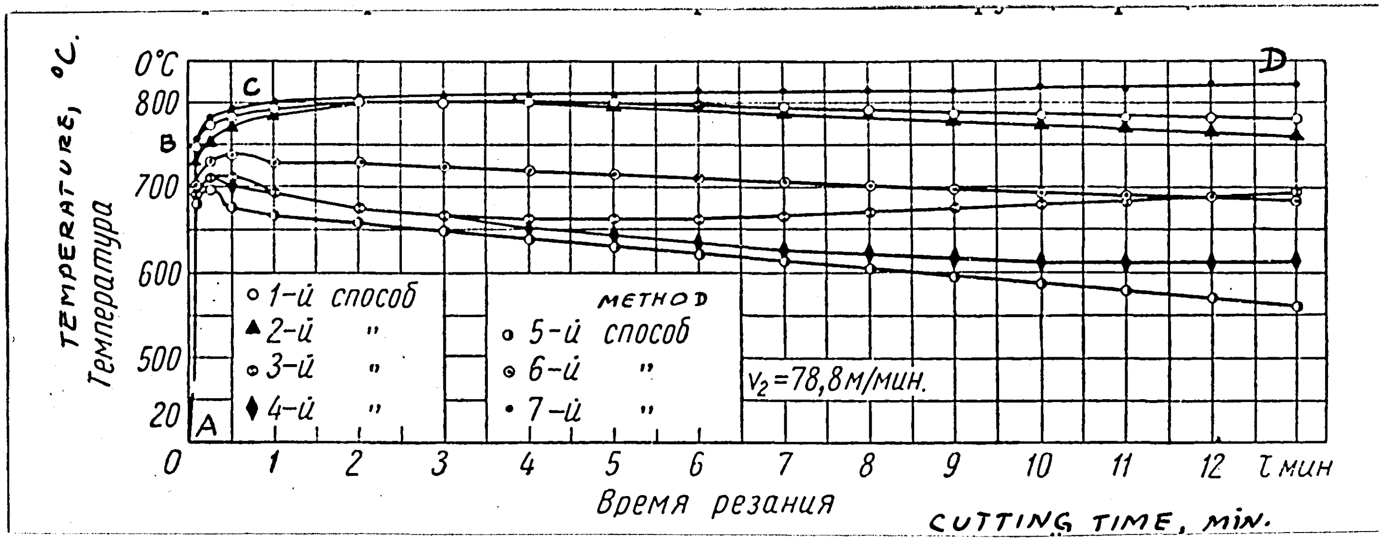


Fig. 6 Chip-Tool Thermocouple Measurements with Various Methods of Holding the Carbide Plate in the Tool Holder

The cutting was done on a billet of steel (H_B = 190), depth of cut 2 mm, feed 0.2 mm/rev. It may be observed that the seventh method with cooled cold junction gives steadily rising temperature with time.

The shape of the temperature-time curve is in good agreement with various transient effects discussed by Reichenbach. The point B (Fig. 6) at the initial quick rise is reached in fractions of a second, then as the tool and the section of the workpiece near cutting zone heat up, point C is reached; this may take about one minute. The rise in the region CD must be due to the rise of the ambient workpiece temperature. Reichenbach noticed that the cutting temperature increased with successive cuts on a shaper, but the work was not large enough to determine the number of cuts necessary to obtain equilibrium. It would be interesting to know also how much the temperature does rise before equilibrium is reached. On Fig. 6 it is seen to be about 50°C.

One of the questions to which the author attemped to find an answer was how the above temperature rise is affected by various cutting conditions. For example, it was reasoned smalled diameters of the workpiece for the same cutting speeds should produce more heating of the material ahead of the tool since there is less time for the heat to escape during one revolution. That is, the heating of the material ahead of the tool rather than the ambient temperature of the work proper was of primary interest.

To our knowledge the mentioned problem was not discussed in detail in literature except by K. Nakayama whose paper (12) was received at the Laboratory when work on this project had already begun, and it was gratifying to see his similar interest. Nakayama's analysis for orthogonal cutting (for a workpiece in the form of a tube) is reviewed below since it illustrated the question raised and should be applicable qualitatively to an ordinary cylindrical workpiece as well and since a more or less accurate theoretical analysis for the latter case could hardly be made without turning this work into a major mathematical project.

For orthogonal cutting the workpiece is considered to be a semi-infinite solid (extending in the axial direction) which is heated on the cross-sectional surface by a number of line heat sources succeeding one another at πD distances or once each revolution. The temperature rise $\Delta\theta$ at any point inside of the solid when a moving heat source reaches the origin of the coordinate system is discussed by Jaeger (13). For a line source

$$\Delta\theta = \frac{q_w V}{\pi \rho c k} \exp\left(\frac{Vx}{2k}\right) K_0\left\{\frac{V}{2k}(x^2+z^2)^{1/2}\right\} \qquad (1)$$

where q_w - heat conducted into the workpiece per unit contact area

V - sliding velocity or the cutting speed

ρ - the density

c - the specific heat

k - the thermal diffusivity of work material

K_0 - the modified Bessel function of the second kind of order zero

x - the direction of motion of the source (the tangential direction of the tube)

z - direction perpendicular to the surface (axial direction of the tube)

When several heat sources pass over the surface, the temperature rise at a point is taken as the sum of rises due to each source. The coordinates of a point P which appears at the surface after n turns and which is $\omega \pi$ D distance away from the "last" tool will be $(-\omega\pi D, 0)$ with respect to tool #1 (Fig. 7); $(-(1+\omega)\pi D, t)$ with respect to tool #2 and, in general, $(-(n-1+\omega)\pi D, (n-1)t)$ with respect to tool # n. ω is the fraction of the circumference beginning from the clearance side of the tool and t is the depth of cut.

The resulting temperature rise at point P(-X,Z) becomes

$$\Delta\theta = \frac{q_w V}{\pi \rho c k} \sum_{n=1}^{n} \exp\left\{\frac{(n-1+\omega)\pi D V}{2k}\right\} K_0\left[\frac{V}{2k}\left\{(n-1+\omega)^2(\pi D)^2 + (n-1)^2 t^2\right\}^{1/2}\right] \qquad (2)$$

The effect of the chip removal is neglected here which will exaggerate the temperatures, but it was estimated to be small for small t^2N/k , where N is rotating speed in rpm. For usual cutting conditions $V\pi D \gg 1$ and $\pi D \gg t$ and from the theory of Bessel functions $K_0(u) = \sqrt{\pi/2u}\, e^{-u}$ for large u . With the above considerations the expression for $\Delta\theta$ is simplified to:

$$\Delta\theta = \frac{q_w \sqrt{N}}{\rho c \sqrt{\pi k}} \sum_{n=1}^{n} \frac{1}{\sqrt{n-1+\omega}} \exp\left\{-\frac{Nt^2}{4k} \frac{(n-1)^2}{(n-1+\omega)}\right\} \qquad (3)$$

For ordinary feeds $Nt^2/4k \ll 1$ and the equation can finally be reduced to:

$$\Delta\theta = \frac{q_w}{\pi \rho c} \sqrt{\frac{V}{kD}} \sum_{n=1}^{n} \frac{1}{\sqrt{n-1+\omega}} \qquad (4)$$

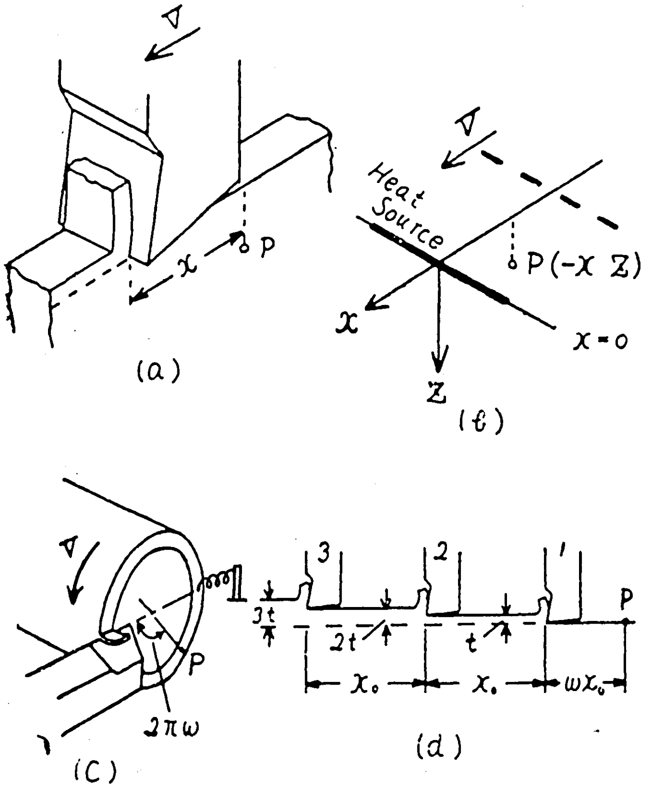


Fig. 7 - Showing the Tubular Workpiece and the Coordinate System Used by Nakayama

where n is the number of turns of the workpiece from the start of cutting.

The last equation gives, of course, exaggerated temperatures not only because of the approximations made but mainly because the heat losses are neglected. The series on the righthand side is not converging and so the equation does not represent practical cases. Nevertheless it indicates the tendency for greater heating of the workpiece in the vicinity of cutting for smaller work diameters when cutting speed is held constant.

It should be noted that $\Delta\theta$ in the above equation becomes infinite when ω equals zero and n equals 1. This is theoretically correct because a line heat source rather than band source was assumed.

Nakayama measured the work surface temperature by rubbing against it a brush made of several coiled constantan wires and the smallest ω used was 0.25 (see Fig. 7). In other words, his analysis does not apply for the region of relatively high temperatures existing on the workpiece surface just after the tool has passed. Neither can his measuring technique be employed to obtain these temperatures since it is hardly possible to reach with a brush into the narrow wedge between the tool and the work.

There is some uncertainty associated with temperature measurements by a sliding contact (dynamic) thermocouple (14) and the calibration should be perhaps made in motion.

Some results of Nakayama's measurements are shown in Fig. 8 . Fig. 8 a indicates that the surface of the workpiece is heated considerably due to the preceding cutting. Unfortunately the measurements are not continued after 60 seconds; it would be most interesting to know if and when an equilibrium is reached. The temperatures shown seem rather high even considering that the data given are for a small diameter tube (about 1-3/4 in.). The rise of 250°C - and at that point the rate of increase does not seem to slow down much - corresponds to actual surface temperatures of over 500°F which is certainly reaching into the hot machining regions. It should be remarked, though, that this is only the surface temperature, and it has been shown by Jaeger that the temperatures decrease rapidly toward the interior of the workpiece. (Fig. 9)

Fig. 8 b demonstrates the effect of changing the work diameter while keeping the cutting speed constant. It may be observed that the temperature rise is higher for smaller work diameters even though the total cutting path is less (number of turns constant).

To estimate the temperature rise right behind the tool (small $\underline{\omega}$) a band heat source extending from $-\underline{1}$ to $\underline{1}$ must be used. This temperature is thought to be

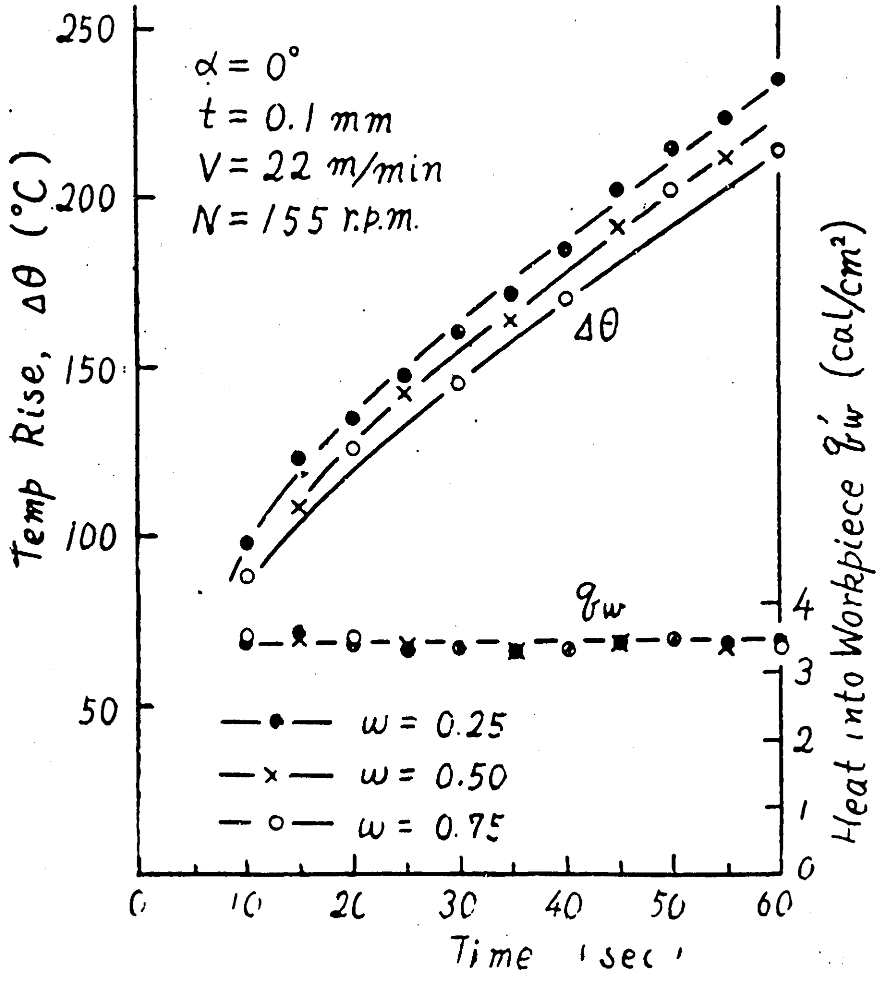


Fig. 8a - Variation of Workpiece Temperature Rise with Cutting Time (After Nakayama)

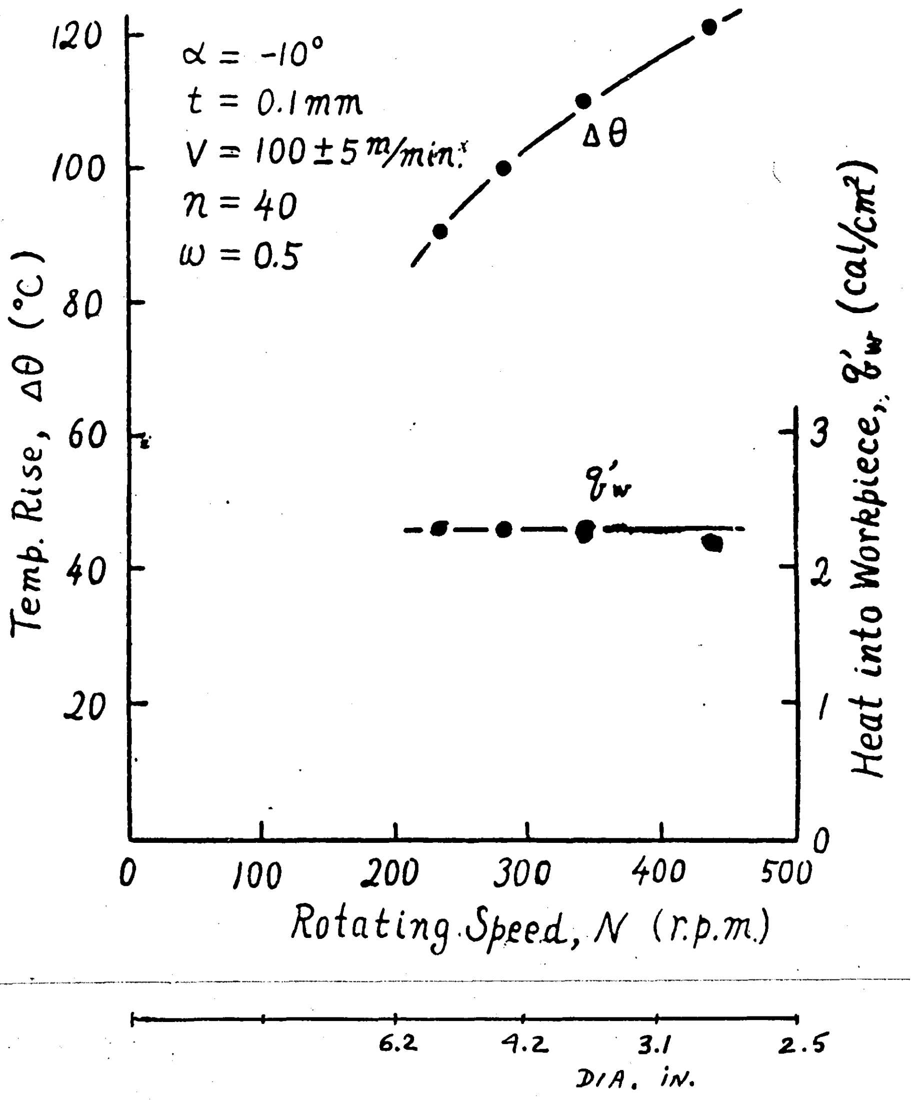


Fig. 8b - Dependence of Workpiece Temperature on the Diameter (After Nakayama)

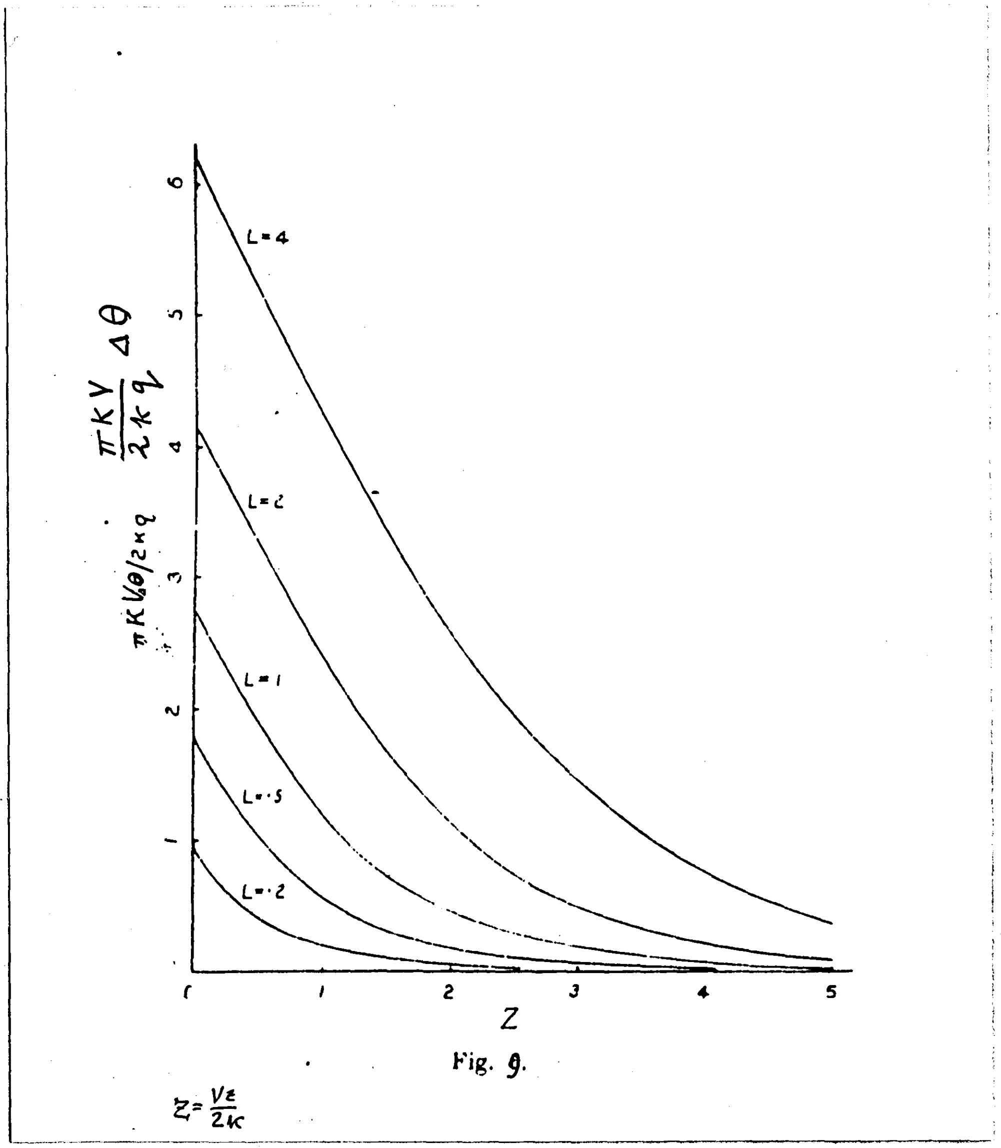


Fig. 9 - Temperature Distribution under the Surface with a Moving Heat Source (After Jaeger)

of importance for the evaluation of coolant action as far as workpiece cooling is concerned and is discussed in the next chapter. Jaeger gives and approximate solution for the temperature on the surface below and behind a single heat source moving in X direction as follows: (Fig. 10)

$$\frac{\pi K V}{q_w k}\Delta\theta = \left[2\pi(L-X)\right]^{1/2} \qquad \text{for } -L < X < L \qquad (5)$$

$$\frac{\pi K V}{q_w k}\Delta\theta = (2\pi)^{1/2}\left[(L-X)^{1/2} - \left(|X+L|\right)^{1/2}\right], \qquad X < -L$$

where X and L are dimensionless parameters

$X = \frac{Vx}{2k}$ $\qquad$ $L = \frac{Vl}{2k}$ $\qquad$ and

K is the thermal conductivity of work material.

To obtain the accumulation of the temperature from a number of heat sources following each other for a point inside of the material which then finally comes to the surface after n turns from the start of cutting the second of equations 5 can be added to equation 4 and the summation made from $n = 2$ ($\omega = 1$). This gives a maximum at the rear end of the source or at the tip of the tool.

The above may give an approximation for continuous orthogonal cutting of short duration, say $n \approx 200$. As mentioned before, due to the neglect of heat losses equation 4 predicts exaggerated values for long time

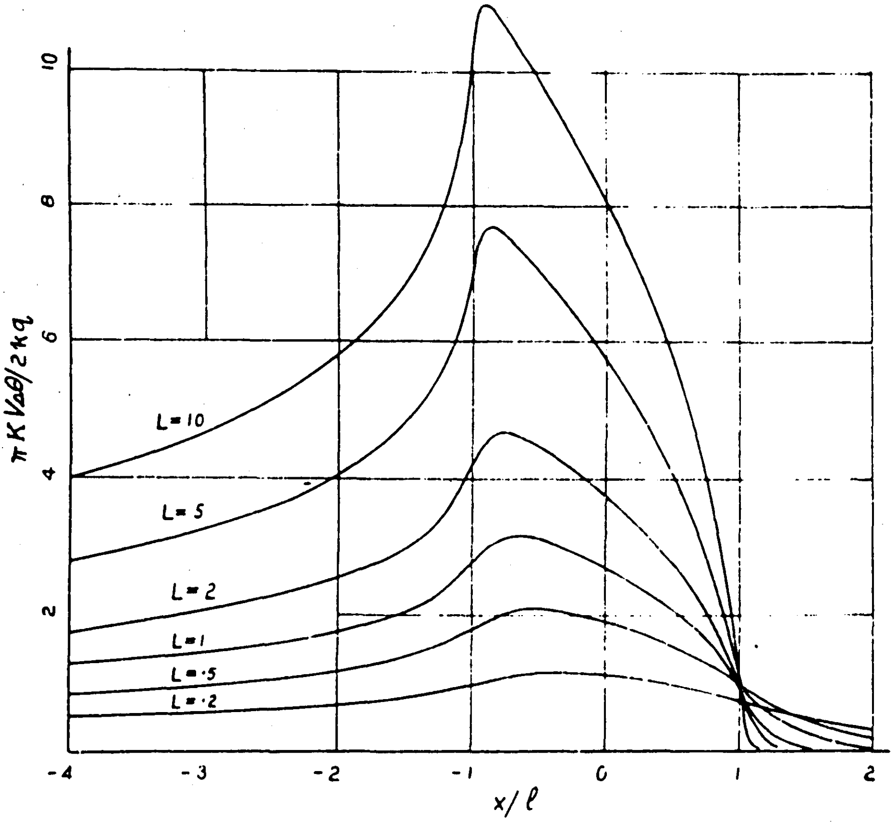


Fig. 10.

Fig. 10 - Temperature Distribution on the Surface below and behind a Moving Heat Source (After Jaeger)

cutting. Even though the temperature may increase continuously due to the ambient temperature rise, it cannot be expected to be proportional to the $\sqrt{n}$ as believed by Nakayama.

The analysis cannot be applied to an ordinary workpiece because there is the additional complication of the heat flow in the radial direction. Moreover, the effect of the side cutting edge angle becomes important. For tools with zero side cutting edge angle and when the ratio of width of cut to feed is large (say $b/t = 10$) the heat flow near the outer surface of the cylinder will be predominantly in the axial direction at least for small $\underline{n}$. If the width of cut and the feed are interchanged, the heat flow in the radial direction will predominate.

For usual cutting conditions in turning the analysis should indicate correct tendencies. It is interesting to note that for a single moving heat source the temperature rise on the surface is lower for high velocity of motion if all other quantities are kept constant -- it is approximately proportional to $V^{-0.5}$ according to Jaeger. But q_w decreases with increasing speeds (5) and the effect of the cutting speed in equation 4 becomes uncertain.

Table 2 shows the results obtained from our workpiece temperature measurements at different cutting speeds. In this table θ_b, henceforth called base temperature, is the temperature of the workpiece just ahead of the tool -- i.e., the temperature at which the material arrives at the shear plane or shear zone, and $\Delta\theta_b$ is θ_b minus room temperature (or bulk workpiece temperature). First and second peak refer to temperature rises at approximately 1/2 and 1 1/2 feed distances away from the cutting edge.

Table 2 - Temperature Rise of the Workpiece at Various Speeds

Cutting Speed	Work Diameter	Base Temp. Rise $\Delta\theta_b$	1st Peak $\Delta\theta_c$	2nd Peak	Number of Turns, n
320 fpm	2.25 in.	50°F	-	125°F	25
"	"	45	330	110	"
240	"	42	255	100	"
"	"	35	-	110	"
120	"	40	-	155	"
"	"	40	350	110	"

Other cutting conditions: feed - 92 threads per inch (0.0109 ipr); depth of cut - 0.1 inch; rake angle - 10°; material - 1020 steel.

As can be seen, the most repeatable values are obtained for $\Delta\theta_b$ because of small variation with the horizontal distance away from the tool. The peak temperatures are uncertain because of the difficulty to locate the thermocouple hole accurately as mentioned in the preceding chapter.

The effect of changing the diameter while keeping the cutting speed constant is shown in Table 3 and Fig. 11. It is seen that smaller diameters produce more heating even though the total cutting path is only half as much (same number of turns).

Table 3 - Temperature Rise of the Workpiece at Various Diameters

Cutting Speed	Work Diameter	Base Temp. Rise $\Delta\theta_b$	1st Peak $\Delta\theta_c$	2nd Peak	Number of Turns, n
390 fpm	1.65 in.	80°	-°F	115°F	25
"	2.75	50	2.25	115	"
340	1.45	120	(350)	(200)	50
"	3.15	50	(170)	90	"

Other cutting conditions: feed - 0.0095 ipr; depth - 0.1 in.; rake angle - 5°; material - 1020 steel.
The numbers in parentheses indicate extrapolation because the peaks were not included in the photograph. The sensitive scale was used to give $\Delta\theta_b$ more accurately.

The difference of 70°F in the base temperature (second case in Table 3) should have some effect on the cutting temperature according to our assumption that no hot machining effects take place in the range which is involved here. It should be recalled, perhaps, that

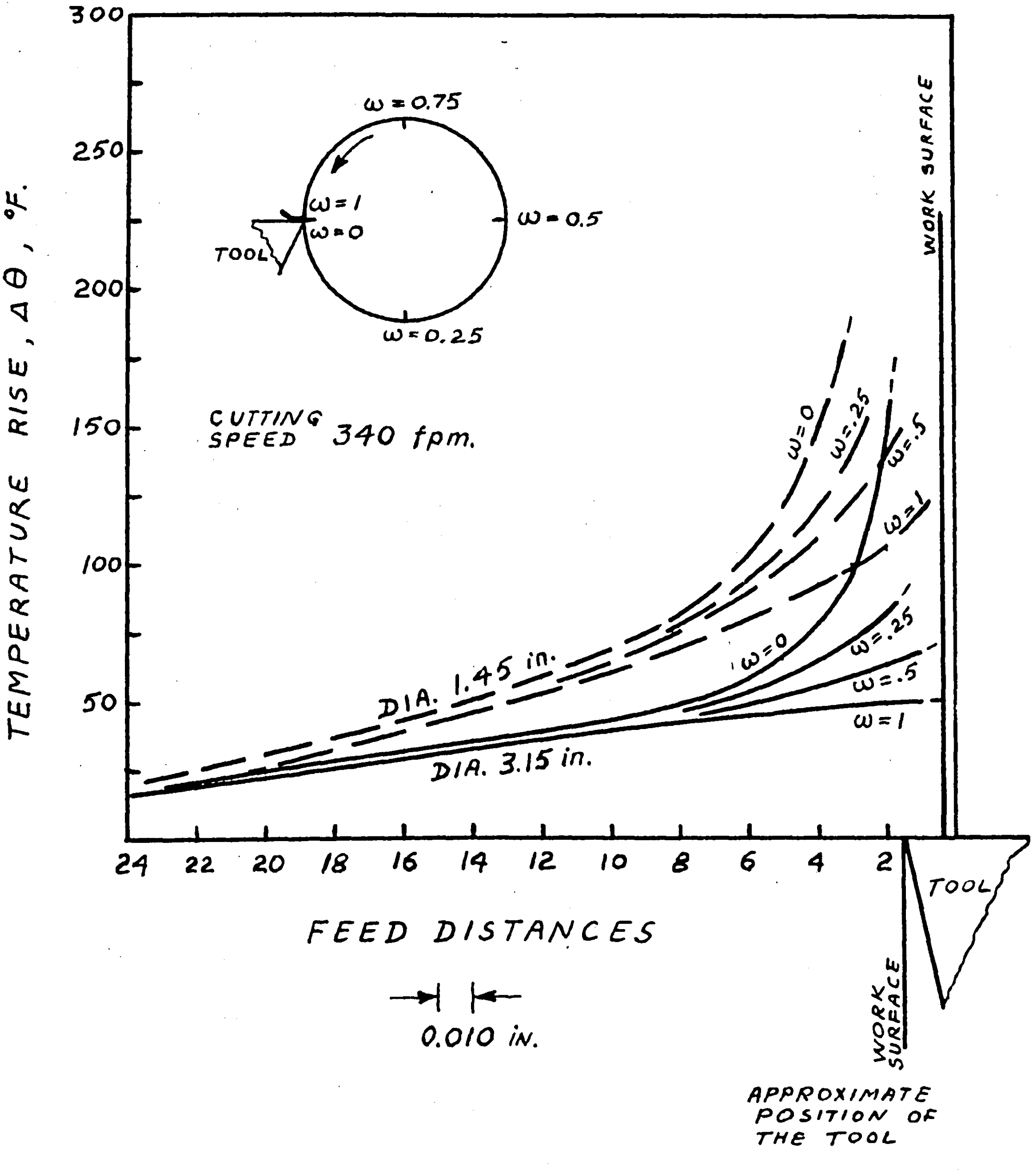


Fig. 11 - Temperature Distribution in the Workpiece ahead of the Tool for Two Different Workpiece Diameters

ordinary steels usually are somewhat stronger and tougher at about 200 to 300°F as compared to room temperature. The time available for heating of the workpiece material before it is cut is in the order of magnitude of one second.

The ultimate test for the above diameter effect must be established by wear studies. To make a tentative check the data obtained in the Metal Cutting Laboratory at M. I. T. (by R. J. Bowley) were examined. The data from wear studies were plotted in the usual form of wearland versus cutting path. They were obtained in cutting large steel billets beginning with 6 to 7 in. diameter and ending at about 2.3 to 2.5 in. diameter. It was noticed that when billets were changed during one run (i.e., continuing to cut with the same tool), a change of slope or wear rate often occurred. In the 28 such plots examined the wear rate distinctly decreased on 16 occasions when cutting was transferred from 2.5 in. to 6.1 in. diameter, in 5 instances the slope was distinctly higher; and in 7 instances there was practically no change. These changes occur at random wearland values so the effect is not due to the size of the wearland as such. Considering that the metallurgical differences between billets of nominally same material are rather important for tool life (15) and that the hardness is usually somewhat higher at the outer portions of the billet, the above can be explained by the effect of the diameter on workpiece temperatures.

ACTION OF COOLANTS AT HIGHER CUTTING SPEEDS

Two different aspects of the cutting fluid action are generally recognized. At low cutting speeds boundary lubrication is thought to reduce the friction between the chip and tool (16); at high cutting speeds direct cooling action can have an effect on the cutting temperature and on tool life. The boundary between low and high speeds is about 400 fpm according to M. C. Shaw and P. A. Smith, at least in the case of water-based cutting fluids. A brief review of literature of the use of cutting fluids is given by the same authors (15).

It is well known that active cutting fluids, such as carbon tetrachloride, can produce spectacular effects on the cutting process at low speeds (below 100fpm) when there is enough time for the penetration of the cutting fluid and for the chemical reactions to take place. Such effects are usually attributed to boundary lubrication, but other possibilities have been suggested. An example of how diffusion phenomena can have an effect on the cutting process is given by Epifanov, whose article is summarized below (18).

In the case of ductile metals, action of active media causing decrease of cutting energy consists in decreasing the degree of plastic deformation of the chip and surface layer of the workpiece. It is *not* due, according to Epifanov, to the decrease of friction forces (lubrication). This "cutting" effect consists in the intensification of the strain hardening process in the cutting zone so limiting states are reached sooner. It is analogous to free cutting conditions but takes place only in the narrow shearing zone. This fact, that under influence of active media, strain hardening is more intensive and exhaustion of plastic deformation and transformation into "brittle" state comes about sooner (at less degree of deformation) is evident from tests of deformation of mono- and polycrystaline metals in the presence of the active media. Physically this can take place, according to Epifanov, only as a result of penetration of foreign atoms into the metal lattice. Such diffusion phenomena are not new. Metal can absorb oxygen, nitrogen and other gases under certain conditions. In other words, catalytic decomposition of active media produces new atoms which can penetrate into the metal undergoing deformation. Under extreme conditions of pressure, plastic deformation, new surface, etc. diffusion processes can increase up to 10^6 times (at temperature of $500^{\circ}K$). Calculation shows that for such products of decomposition as hydrogen speed of diffusion into deforming metal is sufficient for ordinary cutting speeds. Strength of the metal may remain as is or decrease considerably as % reduction and % elongation decrease. (Reported 20 times for steel in the hydrogen atmosphere). The "brittleness" caused in this manner is quickly lost afterwards since hydrogen diffuses out again. The same behaviour is expected for oxygen; CO_2 and N dissolve only in metals which are capable of forming stable carbides and nitrides -- causing the metal to get less plastic but stronger. So in this case cutting may become more difficult. This may be taking place in cutting iron in non-polar hydrocarbons and amines.

The above-mentioned phenomena cannot take place at high speeds since water, which is the best coolant, appears to be the best cutting fluid at about 500 fpm (17) and thus the heat transfer aspects of the cutting fluids become important.

The application of cutting fluids when using carbide tools is usually not recommended because of the danger of cracking due to the possibility of sudden temperature changes. Besides, the high temperatures developed during high speed cutting were often thought to be beneficial in reducing the strength and impact toughness of the material being cut and also increasing the toughness of the carbide tool (19). Also, the opinion has been expressed that the cutting temperatures reach an asymptotic value as the cutting speed is increased. Data contrary to this are reported by Danielian (3) as shown in

Fig. 12. The temperatures were obtained by chip-tool thermocouple measurements.

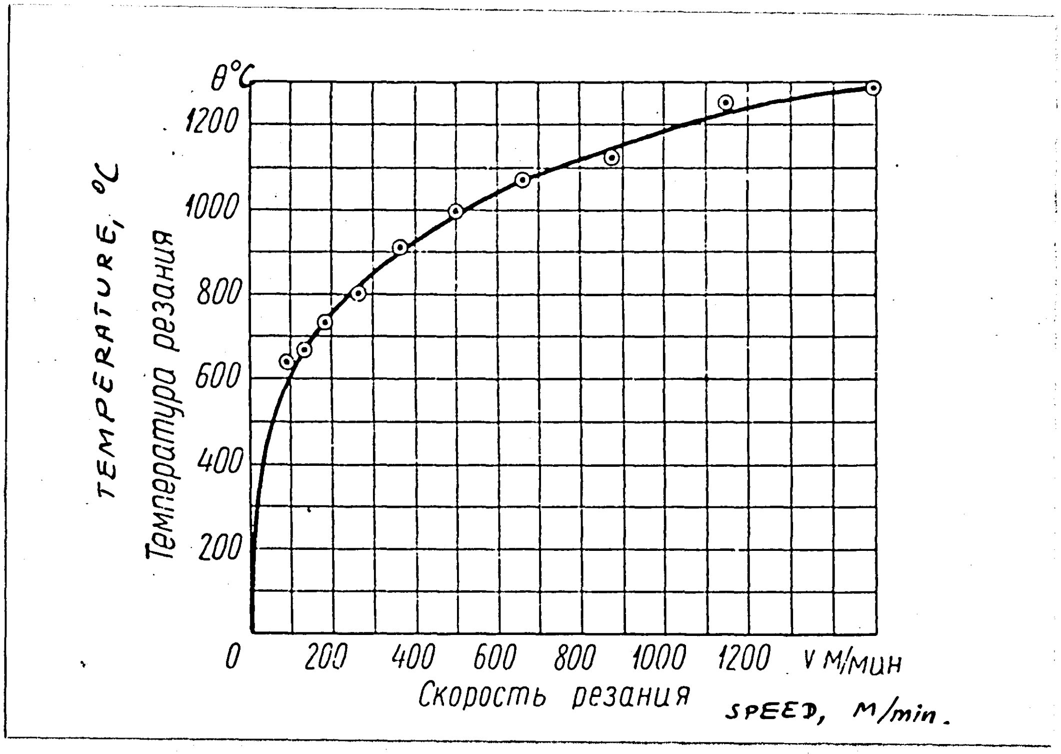


Fig. 12 - Variation of Cutting Temperature with Cutting Speed. Conditions: carbide tool - $\alpha = 10^{\circ}$ (T60K6); work material - steel (55 kg/mm^2). After Danielian (3)

Recently more interest has been shown in using cutting fluids with carbide tools. Feldstein (11) concerning the use of coolants for cutting at high speeds says that it is unquestionably useful and should be applied provided that the fluid is supplied without interruptions to avoid cracking of the tool. An example of turning tests with and without coolant is shown on Fig. 13 from which it is seen that the tool life increases about twice when fluid is used. Unfortunately the tests shown have a very short time range, and the nature of the coolant is not disclosed.

Artamonov (20) reports tool life tests with and without cutting fluid for cast iron. He points out that with malleable cast irons there is hardly any soiling of the cooling system. Fig. 14 shows about 60% increase of tool life when cutting fluid is used; also, a sharp improvement of the surface finish is reported. A decrease of wear on the rake surface of the tool was noticed, and it is stated that this is apparently due to the decrease of the cutting temperature.

The possibility of the reduction of the cutting temperature at higher speeds using water as cutting fluid was checked by the author with the help of Mr. F. H. Anderson of the Metal Cutting Laboratory, revealing values given in Table 4 for 640 fpm.

Table 4 - Chip-Tool Thermocouple Measurements

(0.050 depth	Dry	13.4 mv	-1220°F
(0.005 feed	Water	12.7 mv	1160°F
(0.100 depth	Dry	13.5 mv	1230°F
(0.005 feed	Water	13.1 mv	1190°F
(0.100 depth	Dry	13.9 mv	1270°F
(0.010 feed	Water	13.55 mv	1235°F

Cutting speed - 640 fpm; tool - K2S carbide; material - 1018 steel.

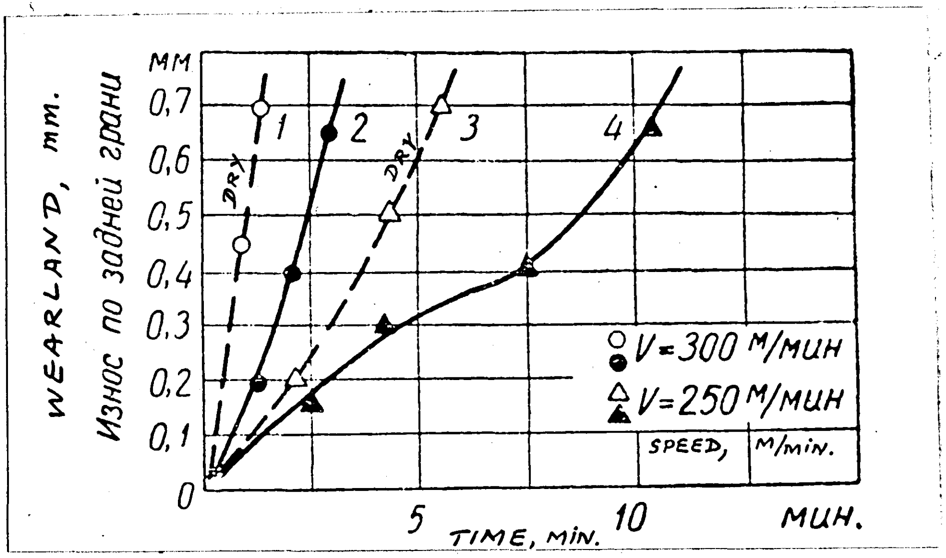


Fig. 13 - Wearland Versus Cutting Time with and without Coolant (After Feldstein)

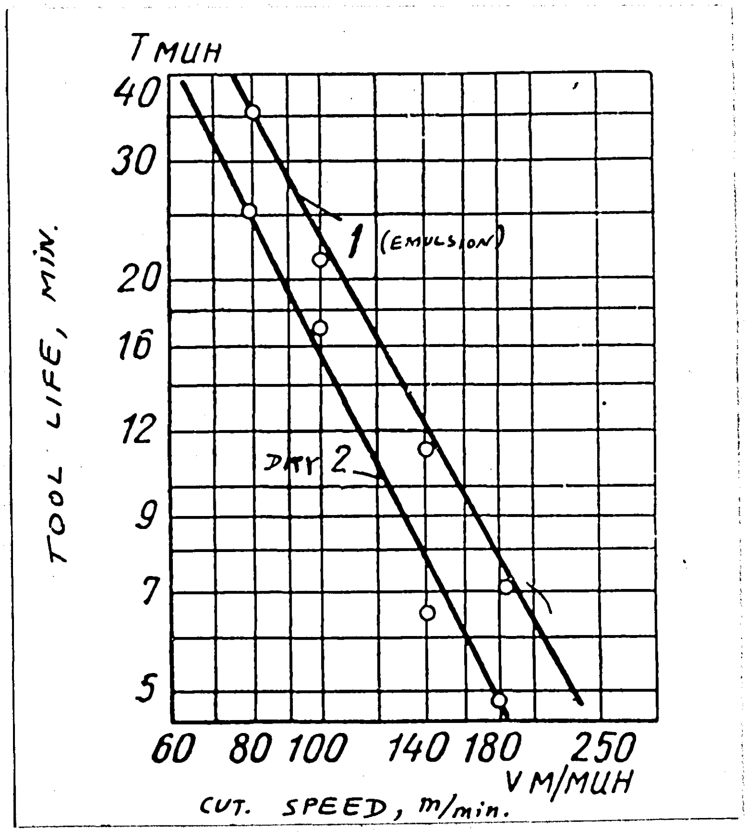


Fig. 14 - Tool Life Curves for Cast Iron with and without Coolant (After Artamonov)

There are three distinct bodies which can be cooled by the cutting fluid: the tool, the chip and the workpiece. Returning to Fig. 6, it may be observed: (1) that the cutting temperature rise in the region CD can be easily reduced if it is due to the ambient workpiece temperature rise; (2) the rise in the region BC can be reduced, at least partially, by cooling either chip, tool or workpiece; (3) the temperature established in the region AB cannot be reduced with an ordinary cutting fluid by cooling the tool or the workpiece because it is established in fractions of a second before the tool or the workpiece have an opportunity to heat up.

The small possibility of reducing the cutting temperature by cooling the tool is discussed by Loewen (6). Shaw and Smith discuss the cooling of the workpiece and the chip emphasizing the effect of the latter (15, 17). Vieregge (9), discussing the cooling effect of cutting fluids, concludes that the simplest is to cool all three - so all temperatures become lower - and says that the demand is best achieved by evaporative cooling.

The evaporative cooling which is thought to take place when cutting fluids are applied in the form of small droplets in an air stream, called mist, is also discussed by Shaw and Smith (15). The mist applied at the rate of 2 lb/hr. was found to have in general the same effect on tool life as the fluid applied in the conventional manner at the rate of 1.5 gal/min. Cutting 4340 steel at 400 fpm for example with water mist the tool life was better than with the stream of water.

To indicate the relative importance of cooling the chip, the tool or the workpiece the following estimate can be made.

The specific energy for the above conditions was given as 385,000 in.lb./cu.in. = 41 BTU/cu.in.

The volume of material removed with cross section of the chip of 0.1 x 0.01 in. and a cutting speed of 400 fpm is 4.8 cu.in./min., which gives about 200 BTU/min. of energy released in cutting.

Fig. 15 shows approximately the areas covered by the cone of the mist issuing from a nozzle placed above the tool.

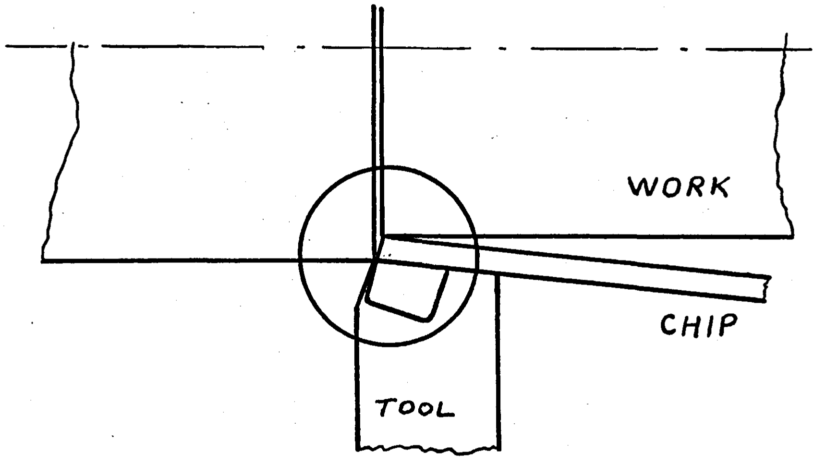


Fig. 15 - Areas Cooled by the Mist

If the limiting assumption is made that all of the droplets contained in the mist evaporate upon striking a surface, the total heat absorbed by the mist will be:

$$\frac{2\ \text{lb}}{\text{hr}} \cdot \frac{970\ \text{BTU}}{\text{lb}} + \frac{2\ \text{BTU}.\ \text{lb}.\ 140\ ^\circ\text{F}}{\text{lb}\ .\ ^\circ\text{F}\ .\ \text{hr}} = 2200\ \frac{\text{BTU}}{\text{hr}} = 37\ \frac{\text{BTU}}{\text{min.}}$$

Less than 1/10 of the droplets strike the chip, and at the given cutting conditions it will contain about 80% of total energy released (3, 6). Besides the cooling of the chip after the point of separation from the tool isuseless and the above 1/10 should be again divided by about five. The final result for the amount of heat removed from the chip before separation is:

$$\left(\frac{37\ \text{BTU}}{\text{min}}\right)\left(\frac{1}{50}\right)\left(\frac{\text{min}}{200 \times 0.8\ \text{BTU}}\right)100 \approx 0.5\ \%$$

If the same estimate is made for conventional stream of water by assuming a high heat transfer coefficient of 9000 BTU/hr.,(sq.ft.),°F for boiling water according to McAdams (22) and taking the average temperature of the outer side of the chip as 500°F, the result for the amount of heat removed from the chip is again in the order of 0.5%.

It should be noted that high heat transfer coefficients associated with boiling of liquids are not due to the utilization of the latent heat of vaporization but are caused by the disturbances in the boundary layer as a result of bubble formation (22). Heat transfer coefficients for a mist type flow are not listed in the literature, but Sibbitt (23) reports tests with heat transfer from a heated platinum plate to a spray of water and indicates coefficients below 1000 BTU/hr. (sq. ft.)^{o}F for a comparable flow rate.

The flow rate was found by Sibbitt to be the most important variable controlling the heat transfer. This was also indicated by the tests performed in the Metal Cutting Laboratory with a heated steel plate which was sprayed with mist while the surface temperature was recorded by a thermocouple wire. Contrary to that the above wear test did not reveal any difference when the flow rate was increased from 2 lb/hr. to 16 lb/hr. This fact, together with the estimate of the amount of heat removed from the chip, seems to indicate that the reduction of the cutting temperature is not due to the cooling of the outer surfaces of the chip.

There is little doubt that the bulk temperatures of the tool and the workpiece can be reduced by the coolant. As mentioned above, the possibility of reducing the cutting temperatures by cooling the tool are discussed by Loewen.

Our interest is to estimate the effect of cooling the workpiece in the vicinity of cutting. Using the results of the preceding chapter and tests reported in Table 5 and Fig. 16, an estimate of the amount of heat removed from the workpiece can be made. Using heat transfer coefficients of 400 to 500 BTU/hr., ft.^{2}, °F according to Sibbitt (24), dividing the surface of the workpiece into several areas with average temperatures and taking the amount of heat conducted into the workpiece as 5% of the total energy released in cutting, it can be shown that approximately 1/4 to 1/2 of the heat can be removed from the workpiece by the coolant.

As Table 5 shows, reductions in temperature of the metal approaching the shear zone of 10 to 60°F are possible by application of the cutting fluid in the vicinity of 400 fpm cutting speed.

Table 5 - Results of the Temperature Measurements in the Workpiece Using Water as Cutting Fluid

Fluid	Cutting Speed fpm	Work Dia. In.	Base Temp. Rise $\Delta\theta_b$ °F	1st Peak $\Delta\theta_c$ °F	2nd Peak °F	No. of Turns n	Tool Rake Angle
Dry	400	2.95	70	480	300	15	-7°
Dry	390	2.75	70	510	330	"	"
Water	400	2.95	50	(300)	-	"	"
Water	400	2.95	50	250	140	"	"
Dry	390	2.75	50	240	100	15	10°
Dry	"	"	50	280	115	"	"
Water	"	"	40	380	100	"	"
Water	"	"	40	-	-	"	"
Dry	350	2.5	60	160	105	50	10°
Dry	"	"	55	230	115	"	"
Water	"	"	50	200	105	"	"
Water	"	"	45	155	100	"	"
Dry	340	1.45	120	(350)	(200)	50	5°
Water	"	"	55	(250)	110	"	"

Depth of cut - 0.100 in.; feed - 0.010 ipr.

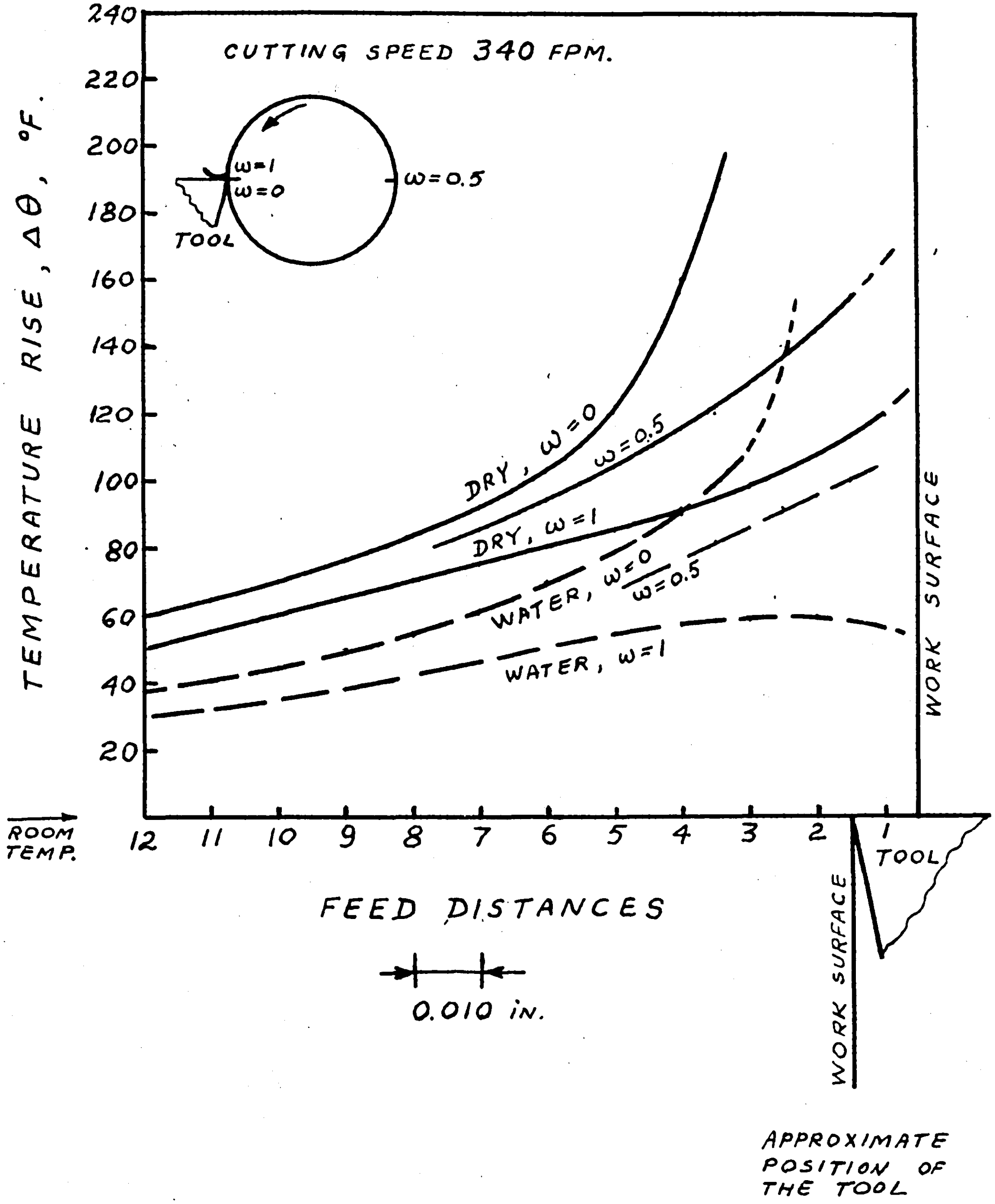


Fig. 16 - Temperature Distribution in the Workpiece ahead of the Tool with and without Coolant

CONCLUSIONS

From the data and the discussion presented the following general conclusions can be made. These conclusions should be regarded as tentative because the work performed in the course of this investigation was of exploratory nature and the time did not allow collection of a sufficient amount of data.

1. The differences in the degree of heating of the workpiece due to preceding cutting cannot be always neglected.
2. The diameter of the workpiece may have an effect on tool wear, the wear being greater at lower diameters for the same cutting speed.
3. The cutting fluid should be more efficient at smaller work diameters, and the differences between various cutting fluids should become more apparent at lower work diameters.
4. The cutting fluid should be applied in such a manner that a good portion of the flow is directed on the workpiece itself. The flow of the fluid should be opposite to the direction of

rotation which can be achieved, for example, by dividing the stream at the very top of the workpiece. Otherwise, the relative velocity between the fluid stream and the work surface becomes very low (and may even coincide with it), resulting in poor heat transfer conditions.

5. The fact that tool life is often found to be better when the fluid is applied from below - between the clearance face of the tool and the workpiece - may be explained by noticing that the temperature on the surface of the workpiece is much higher in that region. Also, the relative speed between the fluid stream and the workpiece surface is probably higher in this case.

Finally, the wide discrepancies in experiments with cutting fluids reported by various workers (15) become at least partially explainable in the light of the above conclusions.

PART II

REVIEW OF THREE RUSSIAN METAL CUTTING WORKS

In a review of past work in metal cutting research prior to 1930, I. Finnie (25) mentions the work of Thime (Timay?) and says that Thime's work was continued by Zvorykin and Briks, but these works are not available.

In 1952 K. P. Panchenko (26) published a book in Moscow entitled Russian Scientists - Founders of Metal Cutting Science. The book includes reprints of works of Russian investigations as follows:

I. A. Timay (1838-1920) - Resistance of Metals and Wood to Cutting and Memoirs on Metal Cutting

K. A. Zvorykin (1861-1928) - Work and Forces Necessary for Separation of Metal Chips

Y. G. Usachev (1873-1941) - Phenomena Occurring in the Cutting of Metals

A. N. Chelustkin - Influence of Chip Dimensions on Forces in Metal Cutting

Panchenko supplied and introduction, summaries and biographical notes. The introduction contains a brief history of the development of early machine tools in Russia and a listing of important books and papers on metal cutting beginning with Timay and up to 1950.

Brief reviews of the above-mentioned publications as representative of early Russian work follow.

The reader who is interested in details should procure the originals and follow the discussion with the figures and graphs which are not reproduced here. The originals, if not available at the Metal Cutting Laboratory at M. I. T., can be located by referring to the "Monthly List of Russian Accessions" published by the Library of Congress.

I. A. Timay (Thime)

The first paper by Timay, published in 1870 in St. Petersburg entitled Resistance of Metals and Wood to Cutting, occupies over 100 pages of Panchenko's book and the Memoirs on Planing (Cutting) of Metals (Reference 10 by Finnie) only 18 pages. Almost all observations were already stated in the first paper. Actually the second paper is a condensed and streamlined version of the first. And since the second paper was published in French and then in German, further discussion of Timay's work is omitted here. Incidentally the title pages of Timay's 1870 papers are reproduced in the book.

K. A. Zvorykin

It should be mentioned that there were at least two papers published in Russia discussing force relationships in metal cutting after Timay's work and before Zvorykin published his. Afanasiev (1884) and Gadolin (1888) have improved the force analysis by taking the friction process into consideration, which was entirely omitted by Timay.

Zvorykin in his paper (1893) developed a theoretical solution for the shear angle by minimizing an expression he obtained for the cutting force.

He apparently assumed the resultant force to be in the direction of cutting and resolved the forces acting between the chip and the tool and between the workpiece and the tool into their normal and tangential (friction) components (Fig. 5, page 266). By balancing the forces acting on the tool he obtains for the cutting force:

$$F = Q\left[\sin\alpha(1-f^2) + 2f\cos\alpha\right] \qquad (2)$$

where Q - is the normal component of the force between the chip and the tool

f - the friction coefficient

α - the cutting angle (90° - rake angle)

Since the force between the tool and the workpiece does not take part in the chip formation, the shear force acting on the shear plane is composed of the sum of the projections of the forces Q and fQ on the shear plane, giving

$$F_s = Q[\sin(\alpha+\beta) + f\cos(\alpha+\beta) \tag{3}$$

where β - is the shear angle.

Projections of Q and fQ perpendicular to the shear plane will apply normal pressures on the shear zone. This normal pressure is thought to increase the shear force necessary to slide the segment of the chip relative to undeformed metal. It is stated in a footnote that this proposition seems plausible to the author but is not investigated. It should be noted that early Russian investigators almost invariably discuss segmented, discontinuous chips considering the analysis of continuous chips too difficult. Also, they point out, the latter occur rarely in practice.

The algebraic sum of the forces normal to the shear plane is written:

$$N_1 - N = fQ\sin(\alpha+\beta) - Q\cos(\alpha+\beta)$$

and the increase of the shear force due to the normal pressure can be expressed by multiplying the above expression by a certain coefficient f_1.

Now if S is the resistance of the material to shear, b the width and e the depth of cut, two expressions for the shear force can be equated as follows:

$$\frac{Sbe}{\sin\beta} + f_1 Q\left[f\sin(\alpha+\beta) - \cos(\alpha+\beta)\right] = Q\left[\sin(\alpha+\beta) + f\cos(\alpha+\beta)\right] \tag{4}$$

Solving for Q and substituting the result into (2) gives for the cutting force:

$$F = \frac{Sbe\left[\sin\alpha\,(1-f^2) + 2f\cos\alpha\right]}{\sin\beta\left[\sin(\alpha+\beta)(1-ff_1) + (f+f_1)\cos(\alpha+\beta)\right]} \tag{6}$$

All quantities in (6) are considered fixed by the cutting conditions except β - the shear angle, and it is presumed that β will be such as to make the force F a minimum. F is minimum when the denominator in (6) is a maximum, which gives:

$$\tan(\alpha + 2\beta) = -\frac{f+f_1}{1-ff_1} \tag{7}$$

Replacing f through the tangent of the friction angle φ and f_1 similarly through $\tan\varphi_1$, Zvorykin finally obtains for the shear angle:

$$\beta = 90 - \frac{\varphi + \varphi_1 + \alpha}{2} \tag{8}$$

By taking $f = 0.44$ based on some reported data and $f_1 = 0.34$ arbitrarily, Zvorykin obtains good agreement between equation (8) and Timay's and his own cutting data.

The solution for the shear angle (8) can be shown to be in out notation (except the last term):

$$\phi = 45 - \frac{\beta}{2} + \frac{\alpha}{2} - \frac{\varphi_1}{2}$$

which almost coincides with that derived by Merchant for the same problem. (24)

Further, Zvorykin attempts to prove by theoretical considerations that the specific energy is greater for smaller depths of cut. This section is not very clearly written and is rather difficult to follow. It is based on geometrical considerations concerning the relative amount of sliding of the previous segment of the chip upon the segment being formed. (Fig. 8, 9)

The conclusion is that this amount is relatively greater for larger chip segments or greater depths of cut. Next the speculations are made concerning the shape of the force versus displacement curve during the formation of one chip element. (Fig. 10) The above together with force balance equations lead to an expression for the cutting pressure which includes the depth of cut in a complex inverse relationship (equation 10).

Zvorykin also constructed a hydraulic dynamometer to measure the forces and obtained plots of what he calls "mean pressure" or "mean resistance" versus depth of cut or chip thickness (Fig. 16 - 22) for various rake angles and several metals. The plots clearly show the increase of the specific energy at low depths of cut, which he attempted to express by expression of the type $P_o = C/\sqrt[3]{e}$; $P_o = C/\sqrt{e}$; $P_o = C/\sqrt[4]{e}$ for different metals. He also stated that the width of cut has no effect on the cutting pressure in orthogonal cutting.

Y. G. Usachev

Usachev's work is interesting historically because of a rather thorough discussion of the built-up edge phenomena. His paper was published in 1915 reporting on work performed in 1912.

The main problem of his investigations was to obtain the temperature of the cutting edges in the tool; but he felt, as he points out, that he had to learn more about the process of cutting before making actual measurements. Usachev, incidentally, is credited by Panchenko to be the first in using thermocouple measurements and also microphotography in metal cutting research, but it appears that the editor is somewhat over-optimistic at least in the case of microscopic observations (see Finnie, Reference 25).

Usachev discussed the fact that the segmented chip, when broken, does not fracture along the visible line which separates the segments, concluding that deformations must be taking place inside of each segment. (Fig. 1, 2, 5) His photomicrographs show that there are no cracks ahead of the tool except when a segment of a discontinuous chip is formed, one segment being formed at a time. He criticizes Taylor's picture of cutting, pointing out that no deformation in the chip can occur above the line of maximum crystal elongation. The picture of several cracks forming several chip semgnets simultaneously is attributed to the fact that these were obtained after the tool was slowed down to a stop on a lathe. To avoid this Usachev used a shaper and reversed the tool in the middle of a cut. From the wording of the discussion it is difficult to say whether he committed an obvious fallacy by not realizing that the tool has to come to a stop before reversing or whether he simply considered the shaper stopping quicker.

In this connection it is interesting to mention that recently in Russia a special device is used to drop the tool suddenly during cutting on the lathe to obtain photomicrographs of partially formed chips. It appears though that in order to be more or less successful, such a device must bring the relative motion between the chip and the tool to a stop in a time of order of magnitude of 0.0001 sec.

Next Usachev discusses strain hardening during cutting and, to show its effect, cuts together two specimens of the same metal - one cold worked and the other annealed. The photomicrographs for the annealed specimen show large deformation zone in front of the tool (Fig. 10, 12) while the cold worked specimens show sharply defined shear plane (Fig. 11, 13). Usachev concludes that it should take less energy to cut the worked metal and obtains some experimental evidence to this effect.

To measure cutting temperatures Usachev used thermocouple wires inside a hole in the tool. After trying various arrangements (Fig. 14-16) he came to the conclusion that the best results are obtained by drilling a hole (1 mm dia.) to a distance of 0.3 mm from the rake face which ends in a smaller hole (0.4 mm) drilled from the clearance face. One constantan wire is inserted into the small channel and is insulated along the larger hole. He obtained plots of temperatures versus cutting speed and feed and concluded that for high speed steel tools the temperature should not be allowed to rise much above 560°C.

Some calorimetric measurements by collecting chips during cutting were done to show that from 60 to 86% of heat developed in the cutting remain in the chip, the amount being higher at higher speeds.

To investigate the distribution of temperatures on the tool face Usachev inserted two thermocouple wires into the tool, one toward the clearance face as described above, the other inward, away from the cutting edge. He observed that mostly the temperature near the cutting edge was lower, but at times it was about 50°C higher in the course of the same cut. Thus he became interested in the built-up edge and obtained excellent photomicrographs showing its formation.

Usachev regarded the built-up edge as an occurrence of adaptability of nature to the conditions of minimum energy expenditure. He discussed very intelligently the effective decrease of the rake angle due to built-up edge, forces that act on the built-up edge, its effect on the surface finish, its effect on the cratering type of tool wear, the conditions at which the built-up edge is not formed such as high temperatures at higher speeds and cutting of brittle metals; he explained, also, such puzzles as the periodic change of the chip color, the periodic change of chip thickness and the change of the chip curvature during the same cut.

A. N. Chelustkin

The major contribution of Chelustkin (1925) was graphical analysis of available force data together with his own numerous experiments on measurements of forces at various widths and depths of cut, speeds and rake angles.

His conclusions can be expressed in a single formula for the cutting force:

$$P = C \delta b \, (a)^{0.75} W$$

where C - is a constant depending on work material

δ - is the cutting angle (90° - rake angle) in the range of 60 - 90°

b - width of cut

a - thickness (depth of cut)

W - is a coefficient depending on the cutting fluid used and is equal approximately to one for water

The exponent 0.75 actually ranged from 0.7 to 0.8, being higher for the ductile metals.

The general decrease of forces at higher speeds was considered negligible for the range used (2 to 30 m/min).

E. I. Feldshtein (11) reports results of ten years of experimentation on machinability of steels in a monographical work published in 1953. Three basic factors characterizing the complex term "machinability" are studied in this work with eight different steels for various heat treatments and microstructure. They are: (1) intensity of tool wear; (2) surface roughness; and (3) forces required for cutting.

Intensity of Tool Wear

Cutting speed for 60 minutes tool life, V_{60}, is taken as a quantitative parameter to indicate the relative intensity of tool wear for various steels at certain cutting conditions. To determine V_{60} Feldstein uses a method of facing instead of the conventional turning. He justifies the use of the method, which is described below, by the following arguments.

The conventional method is too costly because of expenditure of large amounts of metal and time. Large billets are usually used for the tests, and they do not generally have the same properties as small parts, particularly when effects of heat treatment are under study. The values one obtains for V_{60} by this method do not differ from conventional ones by more than 10%, and the average error is below 4%. Half a dozen leading metal cutting laboratories in Russia have used this method successfully. Saving of time with this method is about 20 times and material about 100 times.

The method of facing consists of cutting from a hole in the center of the workpiece toward the outside surface with a high enough rotational speed so that tool failure occurs at the first pass. The radius at which the failure occurs, R_n, is recorded. This is done for several values of $\underline{n}$ so that with greater $\underline{n}$ failure will occur at lower radius.

If values of $\underline{n}$ are plotted against R_n on logarithmic coordinates, the slope of the line obtained (Fig. 3, p. 15) can be expressed as:

$$\tan \alpha = \frac{m+1}{m-1} \qquad (2)$$

where $\underline{m}$ is supposed to be the same as in the expression

$$V = \frac{\text{Constant}}{T^{1/m}} \qquad (1)$$

$\underline{V}$ being the cutting speed and $\underline{T}$ the tool life. The justification of this is given more fully at the end of this section.

To obtain an accurate value for $\underline{m}$ a large variation of workpiece diameters is necessary; and if it is not available, one can use known values of $\underline{m}$ such as $m = 10$ for carbon steels, $m = 9.1$ for chrome steels, $m = 8.3$ for chrome-nickel steels.

The tests then were performed as follows. On a lathe equipped with continuous speed variation 5 to 8 tests were made are various rpm. The values of n and R_n were plotted on log-log paper and a line drawn through the points having the slope m. A set of values n and R_n of an arbitrary point on that line was substituted into the equation:

$$C = V_n \sqrt[m]{\frac{R_n}{sn\,(m+1)}} \qquad (3)$$

where R_n - is the radius at which the tool failed

Vn - cutting speed corresponding to R_n

S - feed (mm/rev)

Finally if m and C are known, V_{60} can be obtained from (1).

To facilitate calculations tables can be prepared with an agreed value of R_n (say 30 mm), corresponding n, C and V_{60} for a given feed (Table 2, page 17).

Feldstein claims that data with very short tool lives do not given great scatter, as might be suspected, and that the progress of tool wear (cratering) is principally the same as in conventional tests, only much more intensive.

The tools used in all tests (except high speed cutting discussed below) were high speed steel with clearance angles 12°, side and end cutting edge angles 45 and 10°, nose radius 1.5 mm. For each material (or heat treatment) an optimum rake angle was previously determined and that rake angle was used for obtaining V_{60}. Depth of cut was kept at 2 mm and feed at 0.5 mm/rev. Total destruction of cutting edge was considered as failure. The compositions of the steels used are given in Table 3.

The results of the above tests are given in the form of plots of V_{60} versus temperature of annealing or tempering (after quenching in oil or water). Fig. 17 gives this information for steel 40X; Fig. 27 shows the same results for steel 40; Fig. 36 for steel 35X C; Table 4, page 39 for steel 15; Table 5 for steel Y12. The recommended heat treatments as most economical are as follows:

Steel 40X - Annealing at 900°C
40 - Normalization at 900 - 950°
35X C - Spheroidizing annealing, subcritical (780°C, cooling at 5-10° per hour) or isothermic (heating at 900°C for one hour, quick cooling to 700°C and holding for 8 - 12 hours)
15 - Normalization at 950°C
Y15 - Annealing which produces granular pearlite structure, for example at 750° for 5 hours
High speed steels P18, P9, P4 - Isothermic annealing - heating at 870°C for 4 hours, quick cooling to 740°C and holding for 2 hours

Best results are obtained when cementite has the form of spherical grains uniformly distributed in the ferrite. The least tool wear is obtained when cutting ferrite, then follow with increasing intensity granular pearlite, lamellar pearlite and sorbite.

Next, Feldstein attempts to establish correlation (or the lack of it) of chip-tool contact temperature and cutting speed V_{60}. Temperatures were measured by the two-tool thermocouple method. For comparison a speed at which the cutting temperature was 450°C, called V_θ , is chosen. The general lack of correlation between V_{60} and V_θ is emphasized (Figs. 54 to 61). This leads to consideration of the so-called "wearing ability" of work material, which can be perhaps best translated by the "degree of abrasiveness."

Rejecting the data available from friction and wear experiments as not applicable for metal cutting conditions Feldstein uses a special set-up (shown on Fig. 62 and 63) which has a small high speed steel cylindrical rod riding on a freshly cut surface of the workpiece on the lathe. The difference between initial and final length of the rider is measured and this quantity, K_{uc}, is used as a relative indication of wearing ability of the work material at given conditions. To increase the amount of wear on the HSS rider its hardness was reduced from $Rc = 63$ to $Rc = 45$ by additional tempering and the relative wear of the original rider and the one with decreased hardness was found to be the same.

Conditions for these tests were: Diameter of the rider 1.5 mm, pressure at the contact 8.5 kg/mm^2, speed 6 m/min, feed 0.065 mm/rev, total friction path 7 meters, (1.2 min time); 4 or 5 tests were done for each specimen.

Fig. 65 shows some but not very satisfactory correlation between V_{60} and the experimentally obtained coefficient K_{uc}. Now the attempt is made to correlate the data of cutting temperatures and the factor K_{uc} in the form $V_{60} = f(V_\theta, K_{uc})$.

For workpiece materials which have the same K_{uc} but different V_{60} if it is assumed that variation of V_{60} is due to cutting temperature, the following relation can be written

$$V_{60} = E\, V_\theta^{\alpha}$$

and α can be obtained from experimental data (as shown on Fig. 67, $\alpha = 0{,}6$ approximately, for various steels). For workpiece materials which have the same V_θ, similarly, if $V_{60} = \frac{D}{K_{uc}^{\beta}}$ the coefficient β can be obtained from data shown on Fig. 66. ($\beta = 0.3$ approximately)

The general relationship is then written:

$$V_{60} = C\,\frac{V_\theta^{0.6}}{K_{uc}^{0.3}}$$

and Fig. 68 shows the log-log plot of V_{60} versus $W = \frac{V_\theta^{0.6}}{K_{uc}^{0.3}}$, where the points for all steels are sent to fall on a 45° line. Considering that K_{uc} is by no means a precise factor but depends for example on the contact pressure, that tools of optimum rake angle were used for obtaining V_{60} for each material, whereas the tools for all temperature tests were the same and that built-up edge effects were neglected, the scatter in Fig. 68 is remarkably small. This is taken as an experimental proof of the fact that the machinability from the point of view of cutting speeds is determined by the action of two basic factors: the wearing ability of the work material and the influence of the work material characteristics on the chip-tool contact temperature.

Next Feldstein discusses the mechanism of tool wear and proposes what is called "the abrasive-molecular hypothesis of tool wear." Essentially he postulates that at high temperatures in very thin layers of the tool the hardness of high speed steel can decrease to 610-700 H_B, whereas the cementite in the work material has $H_B = 800$. The chip with hard particles acts somewhat like a grinding wheel and "cuts" the tool material on a microscopic scale. The shape of the tiny "cutting tools" will explain the different intensity of wear, the scratching being more efficient with sharp lamellar structures rather than spherical ones. It is interesting to note that the friction force between the chip and the tool should be less for the former despite the fact that they produce more wear on the tool. In fact the friction force on the rake face of the tool was measured by a special instrument (reference 133) and found to be higher for steels with lower wearing ability.

Feldstein also investigated the effect of mechanical properties of the work material on cutting. It is seen that the plots of V_{60} against the ultimate strength and the Brinnel hardness have the least, but still considerable scatter compared to % elongation, % reduction and the strain hardening coefficient (λ) obtained by making a Rockwell test impression inside and outside of a Brinnel impression.

Attempts to improve the correlation of the cutting data with the mechanical properties by using two of these properties were not successful. Here Feldstein criticizes the work of some American investigators (Yanitsky, Sorenson and Peters, Merchant and Zlatin, references 96-101). Incidentally Merchant is almost accused by Feldstein (and also by Panchenko) for repeating in several instances Zvorykin's and Bricks' work from 1893 and 1896. Examples of lack of correspondence between V_{60} and parameters based on mechanical properties alone are given (Fig. 84, 85). Plotting the mechanical properties of various work materials against their "abrasiveness" K_{uc} and cutting temperature θ reveals much more correlation with the former (Fig. 88 and 89). The importance of thermal conductivity (low for H.S.S.) is mentioned in a footnote, but the effect is not explored further. The conclusion is that increase of hardness and strength gives lower values of V_{60} because they increase the wearing ability of the metal and the cutting temperature, the increase of ductility gives higher V_{60} because it lowers the wearing ability. Since the peculiarities of microstructure in their effect on the above variables cannot be treated in an abstract manner, the experimental measurements of the wearing ability (K_{uc}) and the cutting temperature provide the two basic factors for the understanding of the mechanism of tool wear.

Surface Roughness Studies

Since the major interest was in the quality of surface finish from the point of view of work material properties rather than tool geometry, the cutting was done by an orthogonal tool between grooves previously made on the specimen. (Fig. 1 and Fig. 9) H.S.S. tools were used having a rake angle of 15° and a clearance angle of 8°. A feed of 0.05 mm/rev was used for all tests; emulsion was used as a coolant. Mean height of asperities H_{cp} was measured by means of a double microscope.

Numerous plots of H_{cp} is microns versus cutting speeds are given for various steels and heat treatments (Fig. 92 - 115, accompanied with photographs of the machined surfaces). Some general conclusions are drawn from the given data as follows: (Fig. 119, 120)

1. For all steels independent of their content the curves of H_{cp} vs V are shifted toward the region of lower cutting speeds and the range of cutting speeds with poor surface qualities is narrower for granular pearlite and sorbitic structures as compared to lamellar pearlite. Therefore, the form of cementite has a decisive influence on the relative position of these curves.
2. The greatest height of asperities occurs with greater amounts of free ferrite which depends more on the content than on the heat treatment.
3. Lamellar pearlite and ferrite structures obtained by normalization or full annealing have good surface finish even at low speeds. For medium carbon steels best results are obtained with normalization at 900°C which gives also best tool life.
4. Large non-uniform concentrations of ferrite worsen the quality of surface finish.
5. Surface becomes better with the increase of pearlite grain size.
6. Best machinability from the point of view of surface roughness obtained with sorbites of high hardness.

The roughness of surface at the low speeds is associated with the built-up edge phenomena except the lateral tears which are thought to form as a result of ruptures behind the cutting edge. The photomicrograph of the profile of such lateral (perpendicular to the direction of cutting) grooves shows no difference between the structure of the asperity and the parent metal (Fig. 132) unlike the asperities which are associated with the built-up edge (Fig. 125).

The differences of built-up edge formations for various steels are associated with temperatures in the cutting zone. The size of built-up edge depends on the friction force between the chip and tool and the "internal friction" (shear) of the metal. The greater is the first force compared to the latter, the greater will be the built-up edge. The temperature of the cutting zone influences the above forces. The friction coefficient between chip and tool has a maximum at certain temperatures (References 57, 148, 149), and this fact is used to explain the presence of the built-up edge and surface roughness associated with it at the cutting speed range of 10 to 50 m/min.

This is why, for example, the steels with granular pearlite have the peaks of H_{cp} vs V curves at lower speeds than the steels with lamellar pearlite and ferrite structures -- they have higher cutting temperatures as was shown above. As an additional proof, experiments of surface roughness measurements are discussed (ref. 74) in which the workpiece was heated and cooled and the peaks of H_{cp} vs V curves are seen to shift correspondingly left and right from the room temperature curve (Fig. 133). In addition to temperature effects the tendency of ferrite to form welds with the tool material have a negative influence on the surface quality.

Cutting Forces

Force measurements were obtained with an orthogonal tool cutting a flange of 5 mm width with a cross slide feed of 0.2 mm/rev. giving a chip cross section of 1 mm^2 (Fig. 5). The dynamometer utilized the change of capacitance between condenser plates with varying width of the air gap due to deflections. (Fig. 6, 7) Tools used had 15° rake and 8° clearance angles; cutting speed was 10 m/min.

There is no serious attempt made to explain the lack of correspondence between the power force P_z and various mechanical properties, cutting temperature, wearing ability (K_{uc}) and the tool wear V_{60}. But this lack of correspondence (Fig. 134-137) supports the claim that the cutting force is a separate entity which is included in the concept of machinability.

The basic conclusions are: (1) The heat treatment does not influence the cutting forces if it does not produce very basic structural changes in the metal.

(2) There is a definite connection between cutting forces and the form of cementite particles; they are lower for lamellar pearlite and higher for granular pearlite. Such influence is explained by considering the brittle cementite particles as sources of stress concentrations, the latter being higher with sharp edged lamellar structures.

(3) There is no clear relation between the intensity of tool wear and the magnitude of the cutting forces.

Machinability in high speed cutting

Here Feldstein develops a rather interesting argument to show that machinability indexes obtained with high speed steel tools can be extended into the region of high speed cutting with carbide tools.

The differences in machinability based on structural characteristics and properties of the work material would be rendered useless for high speed cutting if one of the two conditions were satisfied:

(1) Cementite in the work material does not have any abrasive action on carbide tools.

(2) High temperatures in the work material in the cutting zone change its original properties.

The first of these propositions is not true since special investigations ( ) have shown that in the process of wear of carbide tools first the cobalt phase (which is soft) is worn out and then the carbide particles knocked out. Besides the hardness of the carbides can decrease to about half the original value due to high temperatures in the tool. The examination of the second condition shows that whereas the temperatures existing in the chip are high enough for structure transformations but the time for them to occur is not available. The transformation of pearlite into austenite at 100-850°C requires a few tenths of a second to begin (ref. 165), but during cutting only fractions of a thousandth of a second are available.

The data obtained by cutting various steels are given. These were performed by the conventional method of turning. The plots of tool life versus cutting speed curves show that the curves for various steels have the same relative positions in both cases. A graph of relative magnitudes of V_{60} for various steels shows approximately the same behaviour for both tool materials (Fig.176). A plot of V_{60} against hardness of work material reveals considerably less dependence on hardness in the case of carbide tools, and so finally, plotting of V_{60} for carbide tools versus V_{60} for high speed steel tools for different work materials shows that the relation between them is not a direct one (the point does not lie on a 45° line). Feldstein recommends using the slopes of the final plot $\alpha = 0.7$ for steels having $H_B = 120 - 200$ and $\alpha = 0.4$ for steels with $H_B = 200 - 350$ in an expression

$$V_{60}\text{, carbide} = V^1_{60}\text{, carbide}\left(\frac{V_{60}\ \text{HSS}}{V^1_{60}\ \text{HSS}}\right)^{\alpha}$$

where V_{60} - is the quantity to be determined

V^1_{60} - known quantity for a steel which has been studied.

$V_{60\ \text{HSS}}$, $V^1_{60\ \text{HSS}}$ - known values for the same steels

α - the exponent equal to the slope as above

As an additional proof that the wearing ability of the work material does have an effect on the life of carbide tools, plots of wear vs cutting time are shown, where considerably more tool wear is seen for the lamellar pearlite structure than for the granular pearlite for the same steel. (Fig. 179)

The conclusions of this chapter are:

(1) Since the wear of carbide tools primarily depends on the wearing ability of the work material, there is a possibility to increase the life of the carbide tools (by 2 to 5 times) by obtaining granular pearlite structures which give least "abrasiveness." There is no difficulty

with surface finish at high speeds and very little difference in the cutting forces for the lamellar and granular pearlite structures.

(2) Cooling of the cutting zone is unquestionably beneficial and should be used, care being taken to avoid cracking by insuring of continuous flow of the coolant. This is mentioned in connection with the dismissal of the argument that the effectiveness of high speed cutting is due to melting of the contact layers of the chip.

Feldstein's work impresses by the amount of experimentation performed in cutting, mechanical testing and metallurgical analysis. The organization of the material, data analysis, the logical development of the presentation and the careful preparation of specimens are noteworthy. His reasoning has been thought-provoking and in many instances illuminating, at least for the writer of these lines.

The method of facing involves approximations as will be seen from the following section. But if there is enough experimental evidence available to show that it gives essentially same results, the method is worth considering, particularly when one is faced with the task of comparing the machinability of eight different steels with over forty various heat treatments for some of them.

One final comment. It is far from the writer's mind to criticize Feldstein's work in the usual, almost ritualistic manner in which Russian investigators criticize foreign and particularly American technical papers. (See Panchenko, Feldstein, Artamonov.) If the work is experimental, it is accused of "bare empirism" if it is theoretical, it is dismissed as "mathematical formalism;" while Russian writers are invariably credited with having gained insight into the physical mechanism of the process under study.

It seems to us, though, that when one measures the index of wearing ability by a rider which immediately follows a cutting tool (and therefore its wear depends partly on the machinability of the material), when one does this purposely at low speeds as to avoid any temperature effects and then modifies the results by a temperature factor and finally comes out with the direct relationship between what is essentially tool life and ride life, -- one can be accused of going around a circle a bit.

And so Feldstein's triumphant statement (in italics, page 78) that he has obtained conclusive experimental proof of machinability being dependent on an inherent wearing ability (K_{uc}) and an inherent heating effect (V_{θ}) may perhaps be an example of a somewhat typical way of reaching a conclusion of a person with a Marxist turn of mind.

However, any experimental technique which provides valuable data on the tool life by a shorter (and more economical) route should be welcome, and in the case of Feldstein it is at least as good as the "bare empirism" of others.

Explanation of the Method of Facing for Obtaining Tool Life-Speed Curves

The following details of the facing method were taken from A. M. Wolf (Russian spelling - VUL'F) since Feldstein does not fully explain it in his book.

During facing the cutting speed obviously changes from $V_o = \pi d_o N$ to $V_1 = \pi d_1 N$ where d_1 is the value of the diameter when tool failure occurs. In analogy to TV^m = Constant one may write

$$T\,(V^m)_{mean} = C \qquad \text{where} \tag{1}$$

$(V^m)_{mean}$ can be considered the mean ordinate of the curve V^m versus V in the region between V_o and V_1 and then

$$(V^m)_{mean} = \frac{\int_{V_0}^{V_1} V^m\,dV}{V_1 - V_0} = \frac{V_1^{m+1} - V_0^{m+1}}{(m+1)(V_1 - V_0)} \tag{2}$$

The time of cutting from d_o to d_1 is

$$T = \frac{L}{N_1 S} = \frac{d_1 - d_0}{2N_1 S} = \frac{V_1 - V_0}{2\pi N_1^2 S} \tag{3}$$

where L - is the radial distance travelled by the tool.

S - the feed - amount of travel per revolution.

Substituting into (1) the value of V^mmean from (2) and the time T from (3) gives

$$\frac{V_1 - V_0}{2\pi N_1^2 S} \cdot \frac{(V_1^{m+1} - V_0^{m+1})}{(m+1)(V_1 - V_0)} = C \tag{4}$$

If d_o is sufficiently small, this simplifies to

$$V_1^{m+1} \cong C\,(m+1)\,2\pi N_1^2 s \qquad (5)$$

The last equation has two unknowns C and m, and to determine these a second test with a different value of rpm is made and

$$V_2^{m+1} \cong C\,(m+1)\,2\pi N_2^2 \qquad (6)$$

Solving for C and m from the two equations:

$$m = \frac{2 \log N_1/N_2}{\log V_1/V_2} - 1 \;, \text{ AND } \; C = \frac{V_1^{m+1}}{2\pi N_1^2 s\,(m+1)} \qquad (7)$$

From the first of the equations (7)

$$\frac{m+1}{2} = \frac{\log N_1 - \log N_2}{\log V_1 - \log V_2} = \frac{\log N_1 - \log N_2}{\log 2\pi + \log(\tau_1 N_1) - \log 2\pi - \log(r_2 N_2)}$$

and

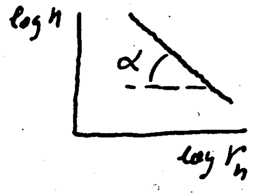
$$\frac{2}{m+1} = \frac{(\log N_1 - \log N_2) + (\log \tau_1 - \log \tau_2)}{\log N_1 - \log N_2} \qquad (8)$$

$$\frac{2}{m+1} = 1 + \frac{\log \tau_1 - \log \tau_2}{\log N_1 - \log N_2}$$

and finally (9)

$$\frac{2}{m+1} - 1 = \frac{1-m}{1+m} = \frac{\log \tau_1 - \log \tau_2}{\log N_1 - \log N_2}$$

The righthand side of the equation (9) can be recognized as the slope of the N versus r_n curve plotted in logarithmic coordinates where r_n is the radius where the tool fails.



then $$\frac{m+1}{m-1} = \tan\alpha \qquad (10)$$

and $$m = \frac{\tan\alpha + 1}{\tan\alpha - 1}$$

The equation (10) simplifies determination of m and guarantees better accuracy since the plot of n versus r_n can be obtained from many points rather than only two. It is advisable then to have a large range of diameters.

It will be apprent that in the case of small work pieces such a range is not available. Also in the case of cutting with carbide tools when the criterion of failure is taken as a given size of wearland it is rather difficult to obtain the corresponding radius during facing. For such cases cutting is done in several passes and a correction suggested apparently by Feldstein is used. This correction is very briefly outlined in Wolf's book.

A. Y. Artamonov in a book entitled Machinability of High Strength Cast Iron (Nodular) reports results of experimental investigations (1950-1954) with carbide and some ceramic tools. He investigated optimum tool geometry for best tool life, the effect of cutting conditions on cutting forces and surface roughness, machinability of high strength cast irons compared to steel and ordinary cast iron and the influences of content, mechanical properties, microstructure and heat treatment on machinability.

The first chapter of the book, besides giving the chemical content of cast irons used (Table 2) and their microstructure (Table 3), is devoted to rather elaborate discussion of the mechanical properties. Concerning the chemical properties a quantity called "equivalent amount of bound carbon" is introduced ($C_{\text{св},\text{э}}$). This has to do with the fact that Si, Ni, Cu and other additions help toward graphitization of cast iron while Mn, Mo, Cr and others hinder the graphitization. The equation

$$C_{\text{св},\text{э}} = C_{\text{св}} + 0.25\,Mn + 0.33\,P + 0.166\,Cr - 0.1\,Ni + 0.75\,Mo \qquad (1)$$

where $C_{\text{cв}}$ = total amount of carbon minus amount of graphite is the amount of bound carbon in the cast iron and the % content of various elements is multiplied by approximate numerical coefficients obtained from the literature.

To describe the mechanical properties in the plastic region a quantity Sc is used (Table 5); it is essentially an "ultimate stress" for compression tests which cannot be obtained with ordinary testing. Details of the method are omitted here since they are not of direct interest, but the recipe is as below.

(1) Several compression specimens are tested having different diameter (d) to height (h) ratios. Stress is obtained from the load P by the formula

$$p = \frac{4P}{\pi d_0^2}(1-q) \quad \text{where} \quad q = \frac{h_0 - h}{h_0}$$

Stress P is plotted against the degree of deformation q (Fig. 11, Fig. 81a) for all specimens.

(2) Several values of d/h are obtained for certain values of q from:

$$\frac{d}{h} = \frac{d_0}{h_0}\,\frac{1}{(1-q)^{3/2}}$$

(3) Next, a plot of stress versus d/h is prepared for all specimens and lines q = constant are extrapolated to d/h = 0, obtaining a series of intercepts Sc. (Fig. 12, 14, 81b)

(4) The intercept values from the above are plotted against corresponding q values which are supposed to be the strain hardening curve.

On the same plot a curve of so-called fictitious tension stresses is drawn according to equation (8)

$$\sigma_{bm} = S_c (1-q)$$

The latter curve has a maximum (ultimate strength) and the value on the S_b vs q curve corresponding to that maximum is taken as the "characteristic compression stress" S_{bc}. (Figs. 15, 81c)

Artamonov recommends the following approximate relations for S_{bc} (equations 18, 19)

$H_B = 2.2\ S_{bc} + 14.2$ for high strength cast iron

$H_B = 1.88\ S_{bc} + 12.7$ for cast irons with lamellar graphite.

Also, for all cast irons:

$$S_{bc} = \frac{C_{cB.\text{э}} + 0.74}{0.02} \qquad \text{(See eq. 1)}$$

The wearing ability (δ) or the abrasiveness of the various cast irons is measured exactly as done by Feldstein, only the rider was made of cast iron instead of a tool material. The values given for δ (table 6) are seen to increase with increasing %C and they correspond particularly well with C_{cB}.

Artamonov mentions rather serious defects of this measurement since it depends on speed and other conditions of the test, roughness of the surface produced by the tool, properties and uniformity of the rider material, etc.

The experiments for determining Tool Life - Speed curves were performed by conventional turning rather than by accelerated methods because of the novelty of the materials under study. Speeds for 20 min. tool life (V_{20}) and one hour tool life (V_{60}) are chosen for comparison since the first is associated with temperature wear and the second with abrasive wear. Cutting conditions used were: rake angle 10°, clearance angles 8°, side and end cutting edge angles 60° and 15°, nose radius 0.5 mm, depth of cut 2 mm, feed 0.2 mm. The workpiece was cast with an annulus cross section for better uniformity.

TOOL LIFE

The main finding of the above tests can be summarized as follows: Tools of the TK type (with titanium carbides) at speeds of 50 - 60 m/min wear out mostly by forming a wearland and also rounding of (microscopic chipping) of the cutting edge. At higher speeds or smaller amounts of titanium carbides and also when cutting very hard cast irons (H_B = 250 - 350) a crater is formed which is similar to the process of wear on BK tools (tungsten carbide only). The BK tools at speeds of

60 - 70 m/min form both crater and wearland with no apparent chipping of the cutting edge. Essentially three mechanisms of wear are recognized: (1) High temperatures due either to heavy cutting or hardness of the work material contribute to the easier removal of cobalt from the friction surfaces; (2) High temperatures also contribute to the increase of the chemical activity between chip and tool; and (3) Fatigue phenomena associated with discontinuous cutting.

The plots of tool life vs cutting speeds for various cast irons (Fig. 34, 35, 37, 38) show that the curves for different tools sometimes cross each other. This is explained by the probable fatigue phenomena and differences in the wear resistance of carbide tools. In fact fatigue strength and wear resistance for carbides have an inverse relationship, the tools with little cobalt content being harder but less tough. Then tools like T30K4 (30% TiC, 4% Co) and BK 2 (2% Co) at low speeds undergo fatigue destruction on a microscopic scale near cutting surfaces. At high speeds (less cutting time) there are not sufficient amount of cycles to cause fatigue and the relative tool life of these tools is higher because of their higher wear resistance.

A comparison with a ceramic tool (ZM-322, Fig. 39) shows it superior to a carbide tool above about 400 fpm.

The conclusion of this section is that BK 2 (2% Co, rest tungsten carbide) has the best wear properties but is too brittle for heavy cutting. And so BK 6 is recommended in all cases for cutting high strength cast iron except for finish cutting (Table 8).

OPTIMUM TOOL GEOMETRY

Tests performed at various cutting conditions changing one variable at a time (Table 1, Fig. 40) reveal an optimum tool geometry: rake angle -5°, clearance angles 12°, end cutting edge angle 12°, nose radius 1 mm.

Effect of Various Cutting Conditions on Tool Life

The influence of cutting speeds on tool life is expressed by the equation $T - C/V^{m}$ and the values for C, M, V_{20} and V_{60} are obtained from the experimental data for 17 different cast irons and one steel for comparison (Table 9); T vs V curves are also given (Fig. 41). A wearland of 0.9 - 1.2 mm is recommended as failure criterion for any speeds (Fig. 42) in virtue of the fact of a sharp increase in wear rate at those values.

For comparison tool life curves for a ceramic tool (Fig. 42) and tools for cutting with inverted depth to feed ratio are given (Fig. 44). "Micro"-chipping of ceramic tools is intensive, and they are considered successful only for finish cutting of ferritic cast irons which do not contain free cementite.

Next, the effects of depth of cut (Fig. 45) and feed (Fig. 46, 47) are investigated and experimental equations are obtained in the form: speed equals a constant divided by the tool life, depth and feed raised to some powers for different depth to feed ratios (eq. 29 - 32).

Use of coolants (10% solution of emulsol is strongly recommended because of considerable tool life increases (Fig. 48) and also much better surface finish. No difficulties with the cooling system were observed as is the case when cutting ordinary cast irons.

The effect of heat treatment of cast iron on tool life was studied apparently without conclusive results. For one cast iron (Fig. 50a) annealing produces about 15% increase of tool life; for another cast iron (Fig. 50b) normalization produced only half the tool life compared to the cast state. The subject is abandoned with the statement that changes in machinability as a result of heat treatment are important and they are due to resulting changes in the cutting temperatures.

Since considerable plastic deformation takes place in cutting malleable cast irons (chip length ratios reach 0.6), cutting temperature was considered important and was measured by the two-tool thermocouple method. Temperatures up to 1100°C were recorded (Fig. 53). Comparison of V_{60}

and V_{20} with cutting temperatures shows no direct correspondence between them (Table 11), and Artamonov concludes that both the cutting temperature and the abrasiveness of the work material determine the tool wear. The character of the dependence of the cutting temperature on cutting speed, depth and feed are very similar to that obtained in cutting steel.

Cutting Forces

Results of the force measurements are given in the form of rather self-explantory plots of forces vs speeds and also of inverse chip length ratio and the width of contact between the chip and the tool (Fig. 55-58). It is stated that the behavious is analogous to that of steel and the existence of maxima and minima at lower speeds is associated with the built-up edge formations.

A comparison of plots of cutting forces and the inverse chip length ratio versus cutting temperature reveals a correspondence of the maxima at 600°C (Fig. 61) from which the conclusion is made that the cutting speed influences the forces and the chip length ratio mainly through the cutting temperatures. Plots of the coefficient of friction between chip and tool (equation 38) versus cutting speed (Fig. 64a) and cutting temperature (Fig. 64b) have qualitatively the same shape as the ones for forces and chip length ratio, but it is assumed that for the first approximation the coefficient of friction may be considered almost independent from the cutting forces or feed and is determined by the cutting temperature.

The specific cutting energy at a given cutting temperature cannot be considered independent of feed as it is possible to do approximately for steel (Fig. 65). Apparently this is due to discontinuity of the chips at higher feeds in which case less energy is required for cutting.

To obtain simple formulas for an approximate determination of the required cutting force a plot of the specific energy vs feed at a constant temperature is prepared (Fig. 66). It is seen that the specific energy keeps decreasing with increasing depth of cut (feed). The express for the specific energy (Q) is written in the form:

$$Q = \frac{S_{бc}^{n}}{a^{m}}$$

and the exponents n and m are found to be 1.0 and 0.226. ($S_{бc}$ is the "characteristic ultimate" stress.)

Surface Finish

The results of tests on surface finish are given in the form of plots of the root-mean-square height of asperities vs cutting speed (Fig. 67). Malleable cast irons occupy intermediate position between steels and ordinary cast irons. There is considerable built-up edge formation and associated with it surface roughness.

Properties of Cast Iron and Machinability

In this section there follows a lengthy discussion of attempts to find a practical index of machinability based on some properties of cast iron. Materials having one or more similar properties are grouped and results of tests on tool life are compared with no definite conclusions.

The best correlation is obtained between V_{60} and the variables discussed above $C_{cb.3}$ (% effective bound carbon; Fig. 76) and S_{bc}("ultimate" stress in compression; Fig. 79); the latter particularly good when tri-axial compression test is used (Fig. 80). The above two quantities are considered physically sufficiently interconnected to give the same effect on machinability (Figs. 28, 29).

Recommended practical equations (including ordinary cast irons) are:

$$V_{60} = \frac{92.5}{C_{cb.3}^{1.30}} \qquad (43)$$

$$V_{60} = \frac{4.22 \times 10^4}{S_{bc}^{1.35}} \quad \text{and} \quad V_{60} = \frac{3.84 \times 10^4}{S_{bc}^{1.35}} \qquad (46)$$

$$V_{60} = \frac{3.84 \times 10^4}{S_{8c}^{\,1.35}} \qquad (47)$$

for 0.2 mm/rev and 0.4 mm/rev respectively.

Artamonov considers the measurements of the index of abrasiveness or wearing ability as too uncertain to be used for the determination of machinability unless they are properly standardized as a result of further studies.

Finally, approximately, and without including ordinary cast irons, V_{60} can be obtained from the Brinnel hardness by

$$V_{60} = \frac{\text{Constant}}{\left(H_B\right)^{1.35}} \qquad (44)$$

Artamonov's book again is impressive because of the amount of experimentation done. In fact, it is an almost parallel study of cast irons to that of Felstein on the machinability of steel, except that being a more recent work, it deals with carbide tools rather than high speed steel. It is by no means as well organized in the overall presentation and the data analysis, but it pleases by its careful and more cautious discussion, being the work of perhaps a less imaginative and more conservative personality.

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