INTERNATIONAL COOPERATIVE RESEARCH PROGRAM ON TOOL WEAR

ester ern
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FOREWORD

This Final Technical Report covers all work performed under Contract AF 33(615)-2159 from 16 November 1964 to 15 November 1965. The manuscript was released by the authors on 28 September 1966 for publication as an RTD Technical Report.

This contract with The University of Michigan, Ann Arbor, Michigan was initiated under Manufacturing Methods Project 8-338, "Formulation of International Standards for Cutting Tool Performance." It was accomplished under the technical direction of Mr. Floyd L. Whitney, Advanced Fabrication Techniques Branch, Manufacturing Technology Division, AF Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

Professor L. V. Colwell of The University of Michigan, Department of Mechanical Engineering served as Project Director for all but a short portion of the project. He was followed by Professor J. C. Mazur who was responsible for technical direction of the laboratory program. Others who participated actively in the program and in the preparation of reports were Professor L. J. Quackenbush and Mr. J. M. Hardy.

The primary objective of the Air Force Manufacturing Methods Program is to develop, on a timely basis, manufacturing processes, techniques and equipment for use in economical production of USAF materials and components. This program encompasses the following technical areas:

> Rolled Sheet, Forgings, Extrusions, Castings, Fiber and Powder Metallurgy, Component Fabrication, Joining, Forming, Material Removal, Fuels, Lubricants, Ceramics, Graphites, Nonmetallic Structural Materials, Solid State Devices, Passive Devices, and Thermionic Devices.

Your comments are solicited on the potential utilization of the information contained herein as applied to your present or future production programs. Suggestions concerning additional Manufacturing Methods Development required on this or other subjects will be appreciated.

This technical report has been reviewed and is approved.

Melvin E. Fields

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Chief, Manufacturing Technology Division
Air Force Materials Laboratory

ABSTRACT

This is the fourth and final report of the series under this contract. It includes coverage of forces and shear zone mechanics, wear of American and European carbide and high speed steel cutting tools, and accelerated tests for evaluating cutting performance. In addition, the report summarizes the objectives, experimental procedures, and related activities of the OECD/CIRP international cooperative research program in metal cutting as detailed in Interim Reports 1, 2, and 3.

The program has shown that it is possible to work successfully among various laboratories and across international boundaries to achieve specific goals. The exchange of information has proved to be not only a valuable check upon the repeatability and validity of results, but has led to improvements in measuring techniques and associated instrumentation for more reliable and more consistent interpretations.

The results have helped to identify those areas which need more intensive studies for evaluation of causes and effects of metal cutting behavior. Phase II, a study of steels of different microstructures and properties, is an important next step in the expansion of the OECD/CIRP program.

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PART I

FORCES AND SHEAR ZONE MECHANICS IN MACHINING XC45 STEEL

Research on cutting forces and the mechanics of cutting has been the responsibility of a subgroup of the main OECD/CIRP committee under the chairmanship of Mr. M. F. Eugene of the French Central Armament Laboratories (LCA). Seven laboratories are participating in this work, including the Cincinnati Milling Machine Company and the Carnegie Institute of Technology in the United States.

The results of the work done have been summarized by Mr. Eugene for presentation during the OECD/CIRP meetings in Paris, France in September, 1966. The following information is a translation of his Rapport Concernant Les Recherches Effectuees Au Sein Du Sous-Groupe "Efforts Et Mecanique De Coupe" (Report on the Research Done by the Subgroup "Mechanics of Cutting and Cutting Forces).

SUMMARY

In the first phase of this work, the methods of measurement employed have been investigated, certain tests have been standardized and, above all, the different dynamometers used have been compared. After comparing the results, it was decided to construct a standard dynamometer.

A fundamental problem has arisen in connection with the corrections to be applied to the forces as measured; two approaches have been followed and from these it has been possible to decide upon the best method of correcting the results obtained in future tests. Analysis of results obtained with the XC45 steel in different structural states has shown that there are two ways in which the cutting forces change in relation to feed, and these must serve as guidelines for future research.

I. JUSTIFICATION OF THE SUBGROUP ACTIVITY

When the work group was formed in 1961, a general program of the studies to be made was presented. Analytical parameters were to be studied in order to link them as precisely as possible to the behavior of the tools. This would make it possible to predict cutting behavior, and would be of immediate value for industrial usage in selecting the most economical cutting conditions.

First, this program was to study all the grades of nonalloyed steels ranging from low carbon contents up to carbon contents of 0.8%, respectively, in different structural grades. However, after a first important series of tests on a 0.45% carbon steel, it has been decided that the tests would be run on steels alloyed with nickel-chromium and with chromium-molybdenum, which are commonly used in industry.

The second goal was the comparison of the known theoretical data on cutting, to define their region of validity, to complete the data, and to try to link the mechanical and physical characteristics involved in the cutting to the characteristics measurable on the machined material. As an implicit consequence, the work material was studied as a function of strain rate and temperature. Such studies give some hope of finding new or better metallurgical solutions for either the work material or tool material.

Due to the scope of such an undertaking, the tasks would necessarily have to be spread. The assignment of the subgroup "Mechanics of Cutting and Cutting Forces" is to take all the measurements pertinent to the cutting with precision, and also to detect any peculiarity susceptible to provide complementary information appropriate to the perfection of our analytical and technological knowledge.

II. RESEARCH PROGRAM

Before beginning the research program, it was necessary to compare the methods used to measure cutting forces and chip thickness (needed for calculation of shear angle), to calibrate and measure cutting temperatures, to find the real values of the feeds indicated by the machine used, and to find the actual cutting speeds.

A. COMPARISON OF DYNAMOMETERS

In the beginning, the results from four laboratories were compared—Aachen, Delft, Liege, and Paris. Each laboratory used its own dynamometer to machine a CK 53N steel with a high speed steel tool (rake angle = 30° and $V = 15$ m/min = 49 fpm) and with a carbide tool (rake angle = 6° and $V = 150$ m/min = 492 fpm). These tests were run in orthogonal section on rounds. The tangential force F_z and the lateral force F_x were measured as a function of feed and ranged from 100 to 900 kg (220 to 1980 lb) for which the dynamometers could be compared. Five successive tests were run for each cutting condition to determine a median value.

The agreement of the results obtained with the high speed steel was relatively good with regard to the tangential force, but significant, unacceptable deviations were observed when measuring the lateral force (Figure 1). The results with the carbide tool at high speeds showed deviations for both the tan-

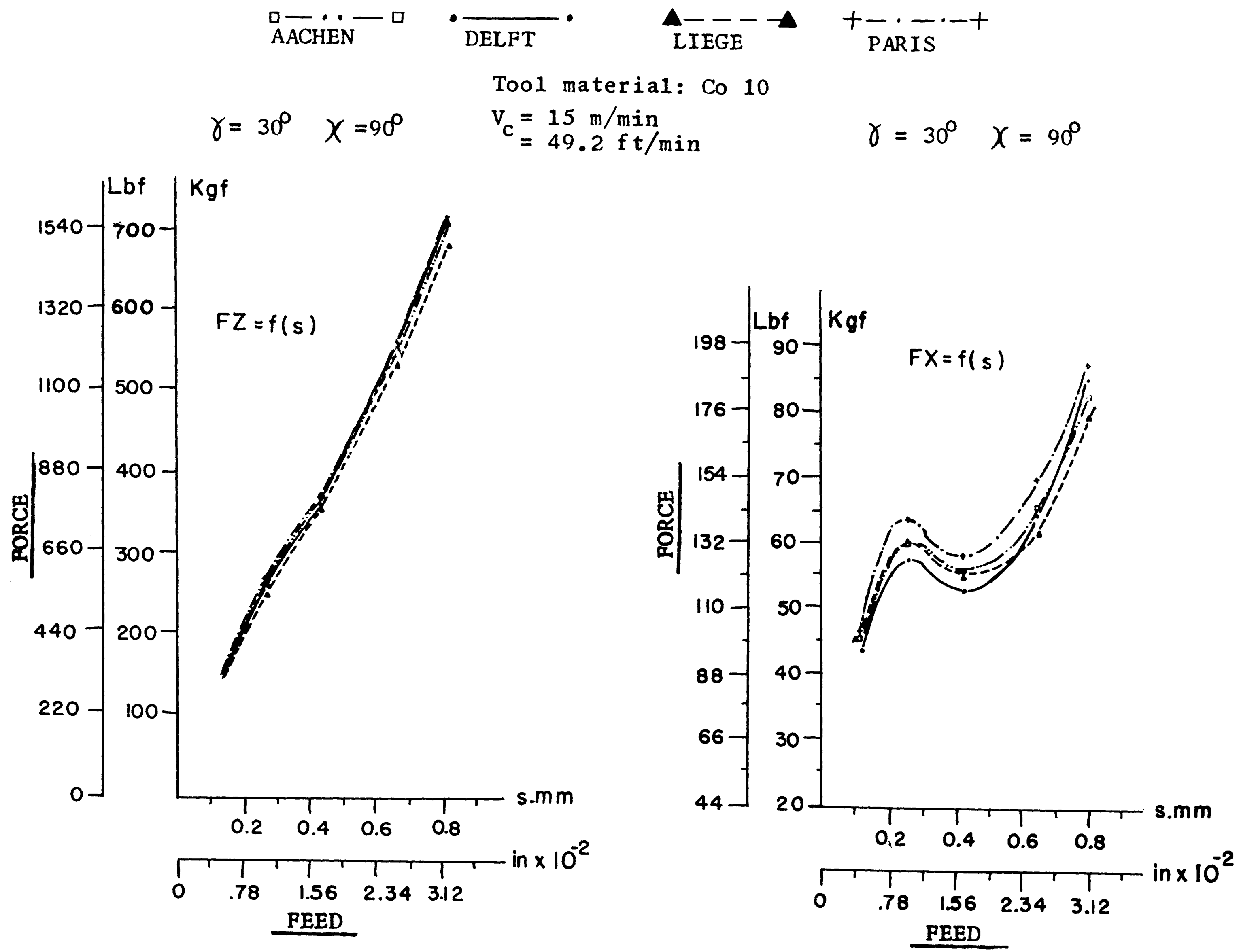


Figure 1. Comparison of cutting forces determined by dynamometers at four laboratories.

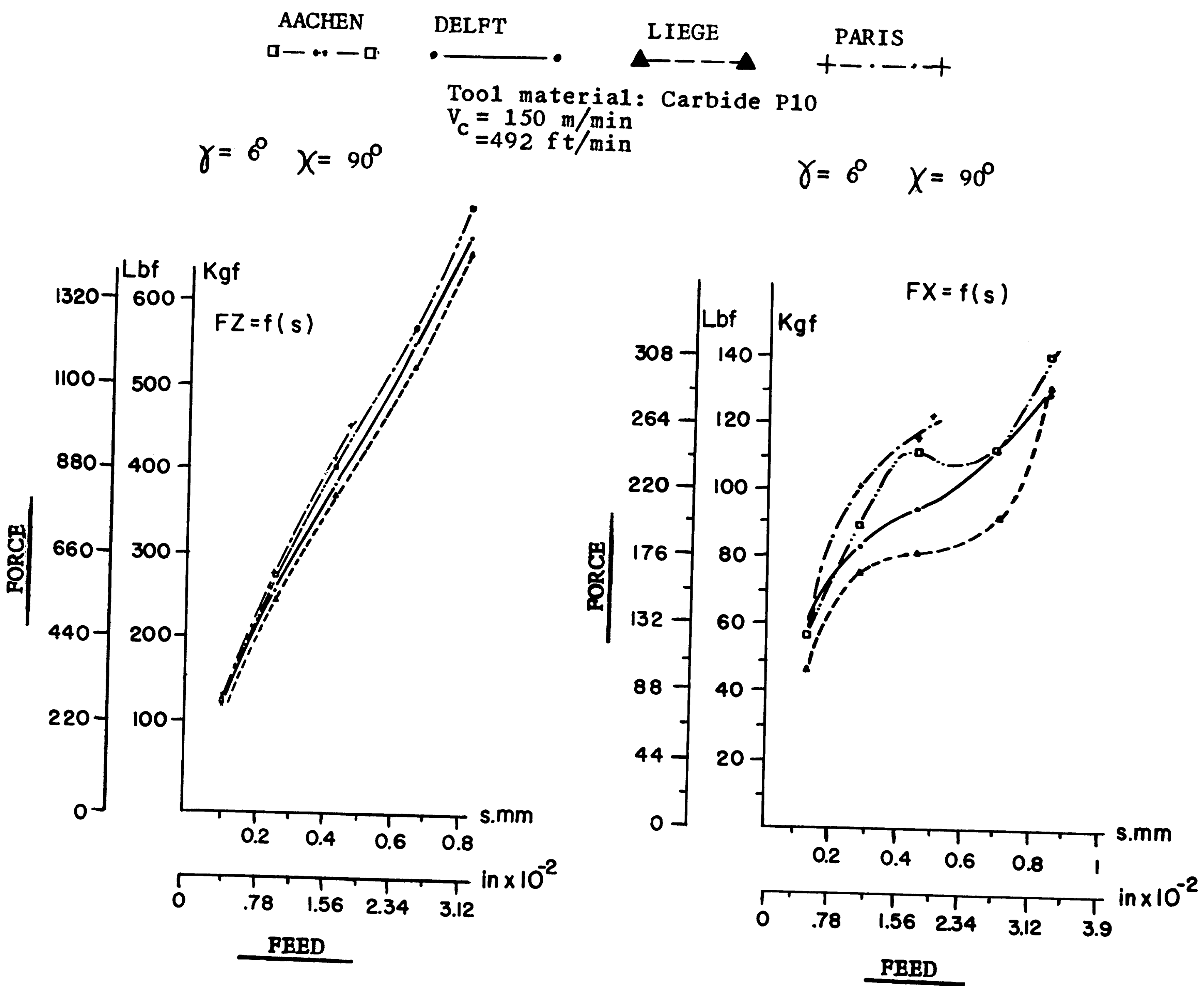


Figure 1—Concluded

gential and lateral forces. The deviations for the lateral forces were particularly important. It was presumed that the disparity of results could be produced by differences in the vibration behavior of the machines used in the different laboratories. It was decided that the tests would be rerun with the same dynamometers in one laboratory, Aachen, with sections taken from the same bar of CK 53N steel.

The second series of tests confirmed the previous results, within a 5% margin of error. A third comparison was tried by locating the precise position of the tests in a given bar of annealed XC45 steel at a specific radius of the bar. The steel used at Aachen was an extension of the same steel used at Paris at the same radius, with both high speed steel and carbide cutting tools. The differences in the forces F_z and F_x as measured for high speed steel tools in the two laboratories was of the order of 1%.

The tests run with carbides showed a systematic variation of 5% for the tangential force and of 12.5% for the lateral force. A similar comparison between measurements at Paris and Delft showed variations of the same order of magnitude.

Two conclusions could be drawn from these experiments:

1. In such comparisons, the homogeneity of the bars used has to be considered, not only along the length, but also in cross section.

2. The more pronounced variations of the results obtained at higher cutting speeds seem to be the consequence of the vibration behavior of the dynamometers used (natural frequency).

Because of these results, it has been decided to build a standard dynamometer, as proposed by the president of Group C (Dr. Opitz). First, however, the mechanical and physical characteristics of the dynamometers used at present had to be compared. Their natural frequency varied from 500 to 1200 H_z.

The committee in charge of choosing the standards decided that the standard dynamometer should:

1. measure the three orthogonal cutting forces, F_x, F_z, and F_y;

2. have a sufficient sensitivity without, however, reaching load deformations capable of disturbing the cutting (deflection < 10 u);

3. have high natural frequencies, > 3000 H_z along the three directions;

4. be exempt from mutual interaction of the forces;

5. not be influenced by the temperature, either by means of a particular location of the measuring device in the instrument, or by means of cooling by a water circuit;

6. present a practical, integrated, and permanent arrangement for the measurement of cutting temperatures;

7. assure the best possible arrangement of the piece and the mandrel of the lathe;

8. be capable of use in cutting with fluid.

A dynamometer following these conditions is being realized at Aachen; it is inspired by the principle of the dynamometer conceived at the Polytechnical Institute in Zurich which measures forces by means of a piezoelectric quartz crystal and provides a natural frequency definitely higher than 3000 H_z.

B. SOME PARTICULARS OF MEASUREMENT

To calculate shear angle of the chip and to determine the rate of deformation of the metal, it is necessary to get precise measurements of the chip thickness. The work group had to compare the methods used and to propose to the participating laboratories the method which is best adapted to the type of chip obtained. Five methods have been considered: the direct measurement of the thickness is not possible for all types of chips; the method of weighing a defined length of chip has given the best results for chips that are slightly curled and helical; for chips of small length, tightly curled and spiraled, the preferred method is to use a planimeter on an enlarged photograph of a cross section.

In the study of the forces involved in plastic deformation during cutting, the value of the rate of deformation is very important; tests have shown that a 5% relative error in this value can induce a 15% corresponding error on the energy of deformation. The comparison between such tests and the phenomena observed during cutting shows that it is necessary to be extremely careful when measuring the cutting ratio.

The measurements of the average temperatures at the tool-chip interface and the calibrations that they imply have also been considered. Recommendations have been made, particularly for calibration of the electromotive thermoelectric force of the two materials in contact. It is suggested not to weld nor braze the two elements, work material—tool material, but to clamp them. One of the advantages of this method is that it maintains a contact pressure between the two elements during the temperature increase. The heating must take place in a neutral atmosphere (cracked ammonia). These precautions make possible good reproducibility of the calibrations because constant contact of the hot joint is assured.

III. RESULTS OF TESTS ON XC45 STEEL

A. CORRECTIONS OF THE GROSS FORCES MEASURED

The first phase of the cooperative studies was mainly concerned with the fundamental problem of the corrections to be made to the gross forces measured by the dynamometer. This would make possible more precise calculations of the forces and energies of the elastic and plastic deformation in chip formation, and of the forces and energies induced by the friction of the chip on the tool.

It is known, for example, that at small feeds the disturbing forces induced by the presence of a built-up edge and by end shearing, can represent a very important part of the total cutting force, up to 50% at very low feeds. As reference, Figure 2 represents the distribution of the forces involved in the formation of a chip.

Two methods for correcting forces have been considered:

1. the method proposed by P. Albrect (Cincinnati Milling), and;

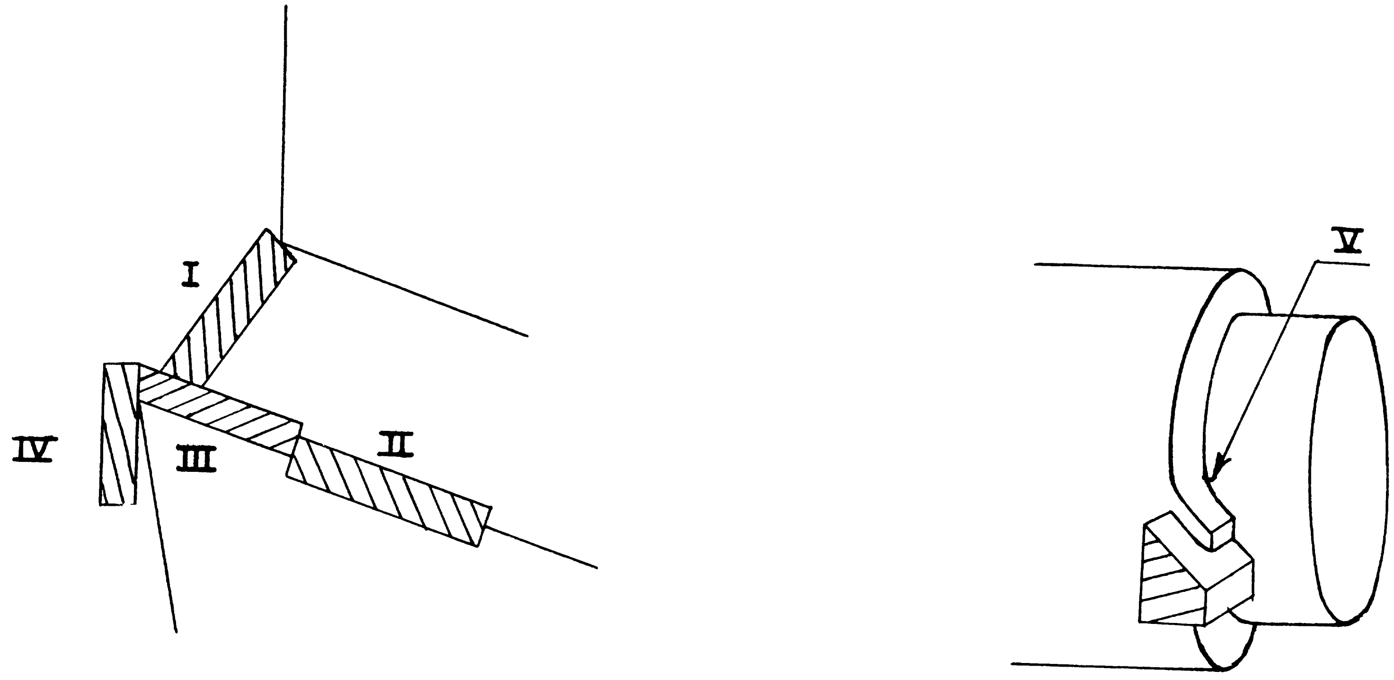
2. the method of F. Eugene.

The first method considers that two disturbing forces, P_1 and P_2, appear at the tool edge, and a principal force, Q, (Figure 3) appears on the rake face. In orthogonal cutting, the tangential force $F_z = P_1 + Q\cos(\tau_Q - \gamma)$ and the lateral force $F_x = P_2 + Q\sin(\tau_Q - \gamma)$.

The values of P_1 and P_2 can be determined from a plot of forces F_z and F_x as a function of feed for a defined cutting speed (Figure 4). On these plots, a line is drawn parallel to the somewhat asymptotic part of each of the two curves. P_1 and P_2 are represented, respectively, by the differences between the drawn lines and the plots of the measured gross forces. Mr. Albrecht finally uses the diagram of the tangential force, F_z, as a function of the lateral force, F_x, that synthesizes the method (Figure 5a). Figure 5b represents results obtained by Cincinnati Milling in machining annealed XC45 steel with a carbide tool; Q is practically proportional to the feed whereas P increases up to a certain feed and then stays practically constant.

By means of the results of the comparative tests, and having taken into account the intense formation of a built-up edge (Figure 5c), Mr. P. Albrecht of the Cincinnati Milling Machine Company laboratory, proposes the following formulas for calculation of Q_1 and Q_2:

$$Q_1 = \tau b s \frac{\cos(\gamma - \tau_Q)}{\sin \phi \cos(\phi - \gamma + \tau_Q)}$$



Forces involved in the cutting

I. Forces produced by the shearing.

II. Friction forces.

III. Forces produced by the loose edge.

IV. Forces produced by the frontal friction.

V. Forces produced by the end shearing.

Figure 2. Forces involved in cutting.

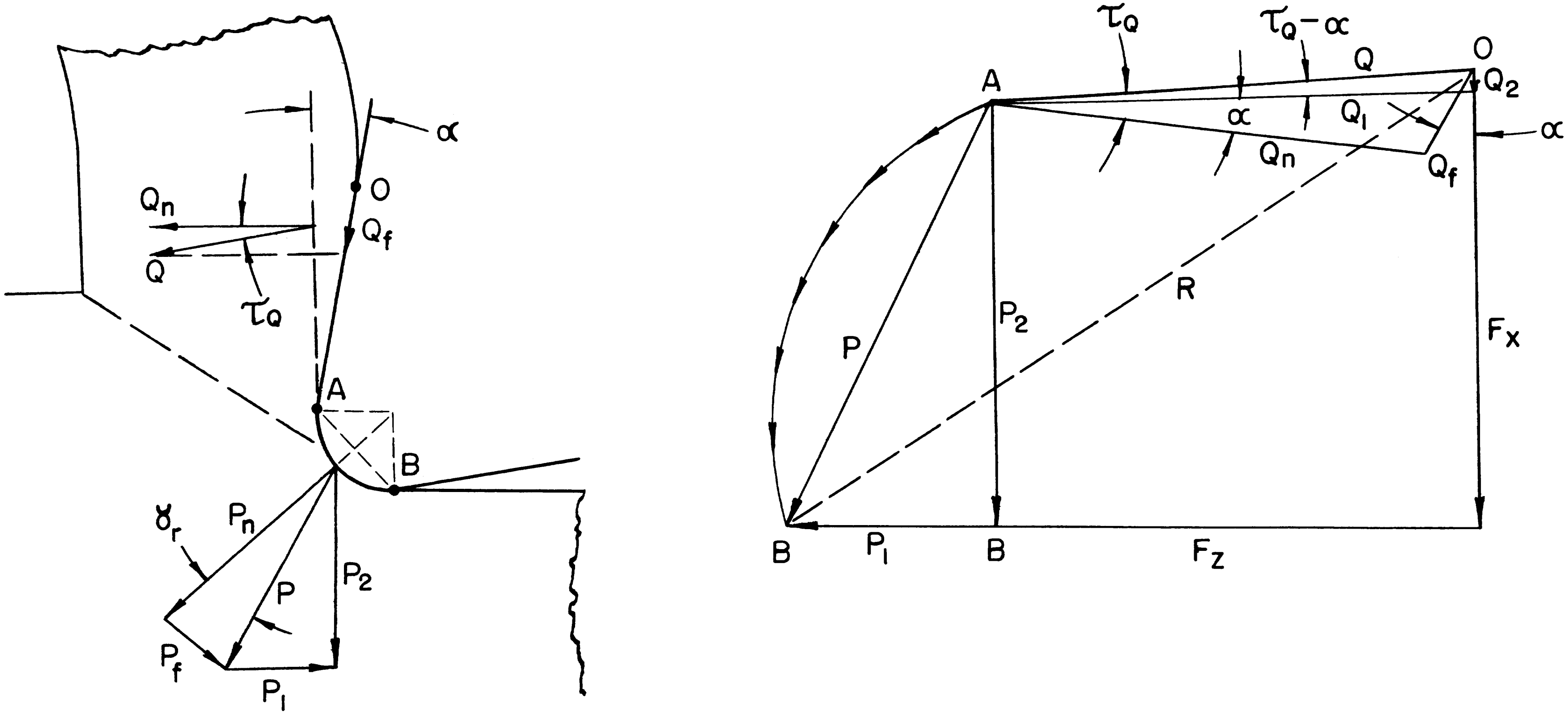


Figure 3. Force analysis proposed by P. Albrecht, Cincinnati Milling Machine Company.

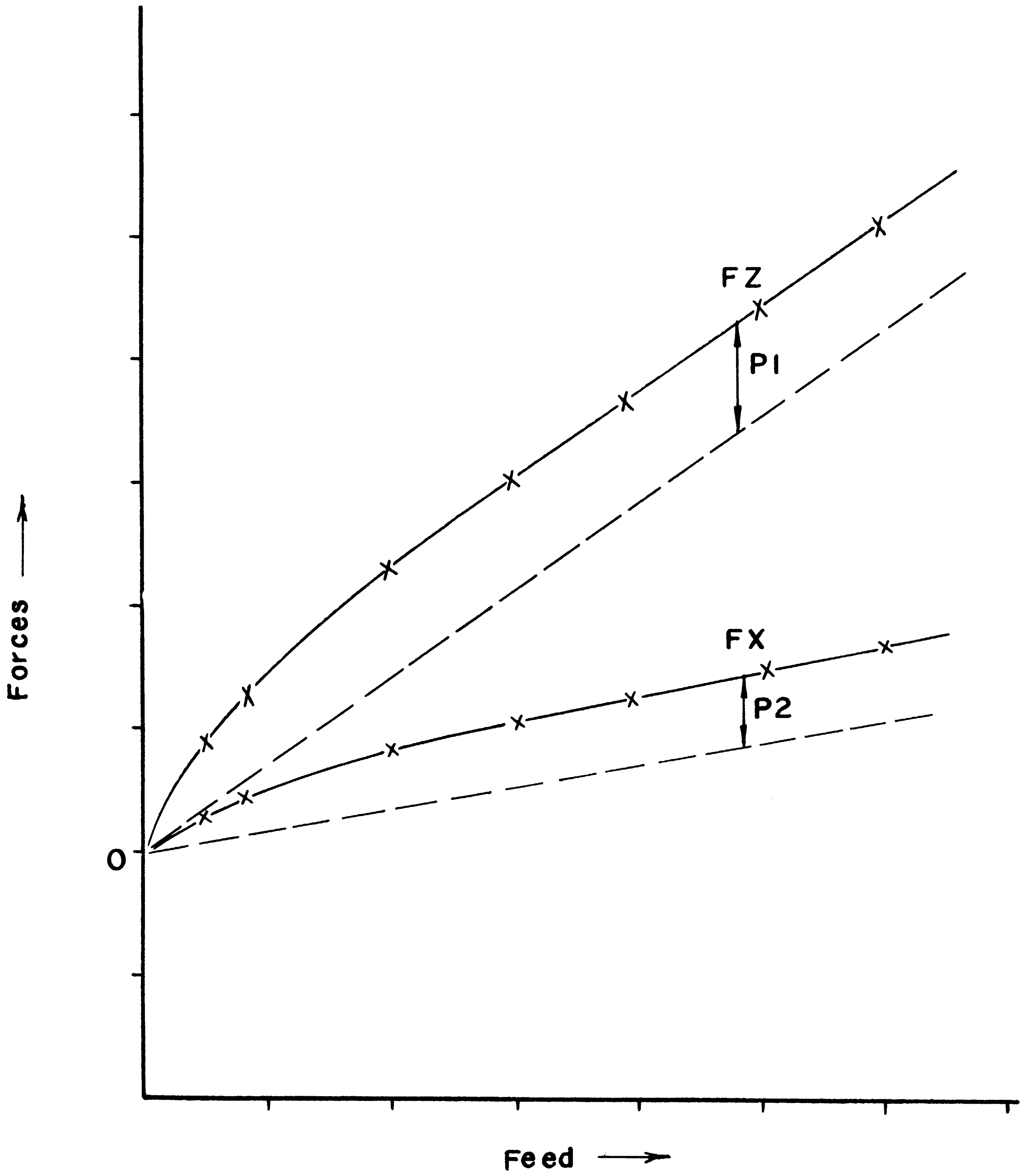


Figure 4. P. Albrecht method for determining force components P_1 and P_2 of Fig. 3.

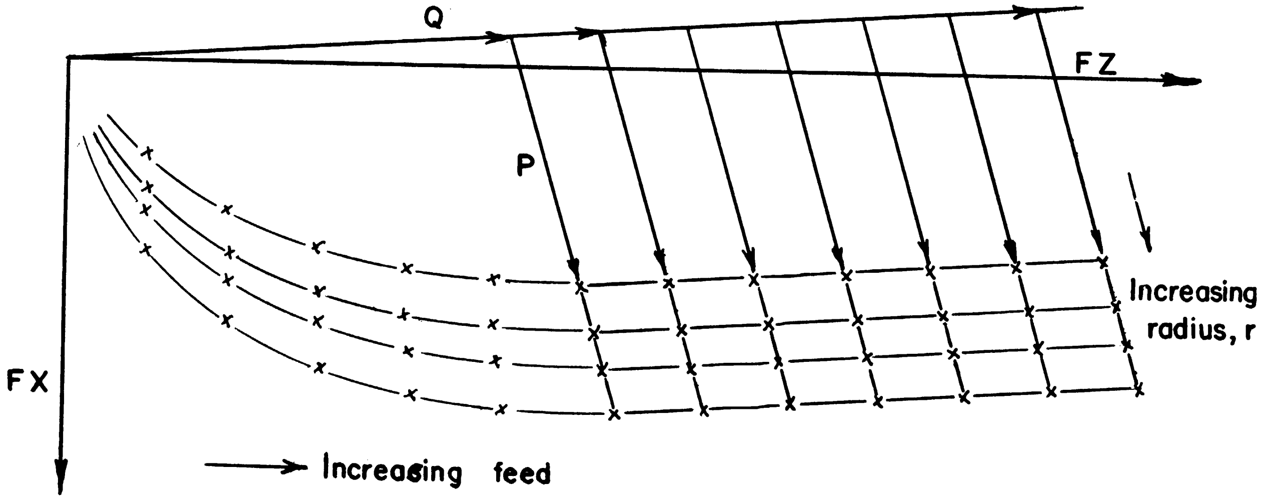


Figure 5a. Determination of the directions of the forces P and Q.

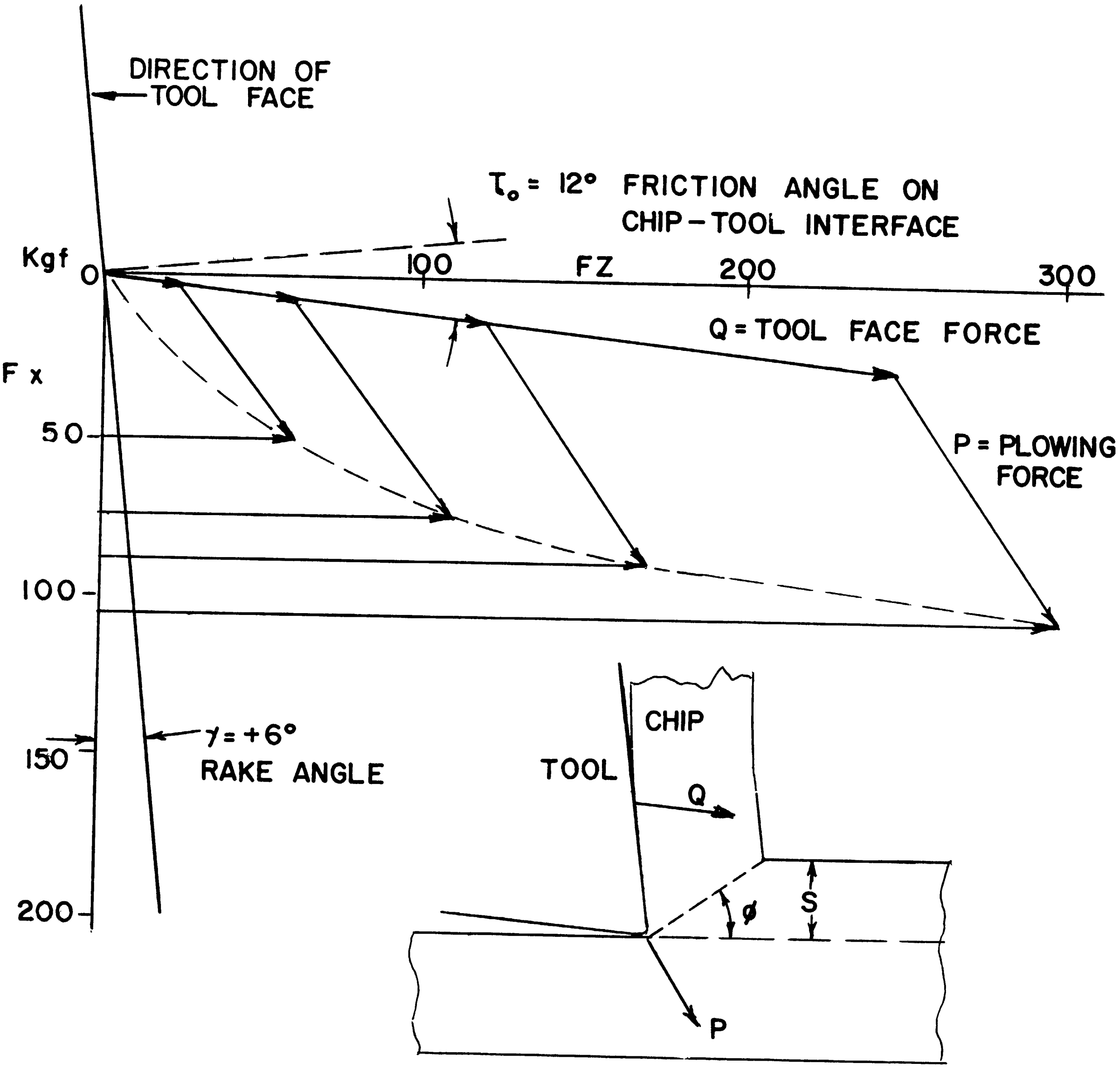


Figure 5b. P-Q force diagram.

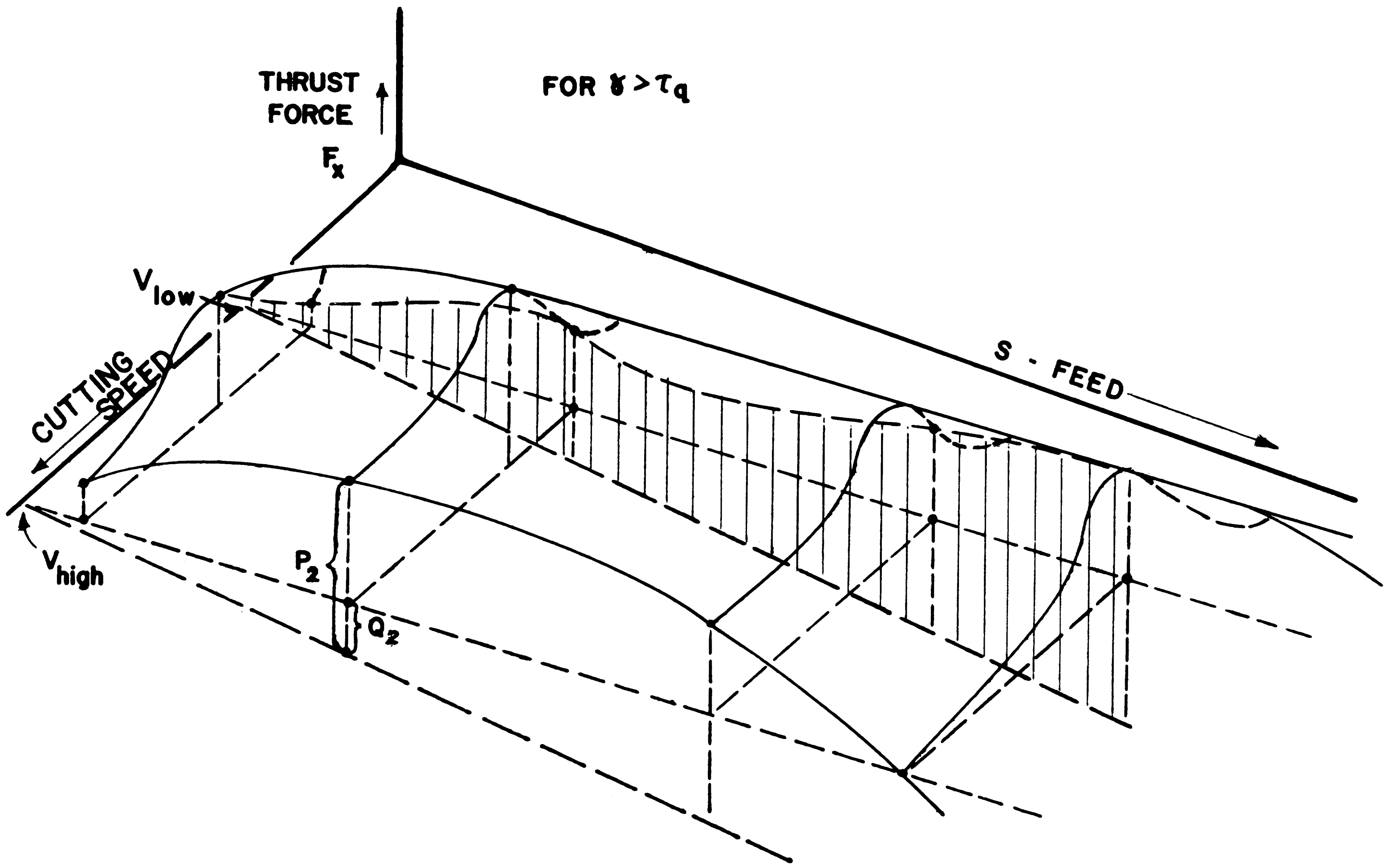


Figure 5c. Three dimensional plot showing dependence of cutting forces on cutting conditions (P. Albrecht).

$$Q_2 = bs \frac{\sin(\gamma - \tau_Q)}{\sin \phi \cos(\phi - \gamma + \tau_Q)}$$

where τ is the shear strength of the machined material.

From this method of the interpretation of the forces, it follows that the coefficient of friction of the chip on the tool, τ_ϕ, is independent of the angle of the tool, whereas with the previous method of using gross forces, this coefficient was observed to increase markedly when the tool rake angle is increased; this is a paradox difficult to accept. The Albrecht method of correction seems to be convenient mainly for cutting conditions compatible with the use of carbide tools.

The second method [for correcting gross force measurements], used at the Laboratoire Central de l'Armement, is of interest mainly with respect to cutting conditions typical of high speed steel tools. The cooperative tests made on the XC45 steel, for semiorthogonal cutting rounds, as well as for pure orthogonal cutting on tubes, the simplest of cutting conditions, have produced initial curves which look very characteristic (Figure 6).

The diagram of the tangential force, F_z, and of the lateral force, F_x, as functions of feed for relatively low cutting speeds, shows for each of the forces considered, a curve segment with the parabolic appearance (a-b), followed by a straight line segment (b-c); the junction of these two segments corresponds to a critical feed, A_c, and the straight line segment bc goes through the origin.

When machining a given material at a given cutting speed, the value of A_c tends to increase when tool rake angle increases.

The parabolic curve sgement, ab, is the consequence of the disturbing forces due likely to the presence of a built-up edge or to frontal friction. The curve segment, bc, is representative of the forces produced by the shearing and rubbing. The critical point, A_c, indicates the cutting conditions for which the disturbing forces produced by the presence of a built-up edge become negligible with respect to the forces which arise from the elastic and plastic deformation of the metal during chip formation, and the friction force of the chip on the tool. These forces are proportional to the chip section.

The same tests run at increasing speeds show that the critical feed, A_c, decreases to finally reach a minimum value at a sufficient cutting speed.

For a given tool geometry, the law of regression of A_c as a function of cutting speed, V_c, is of the form:

$$V_c A_c^{-n} = \text{Constant}$$

Annealed steel XC45
γ =25° χ=90° V_c=10m/mn
Tool EW 9 Co10

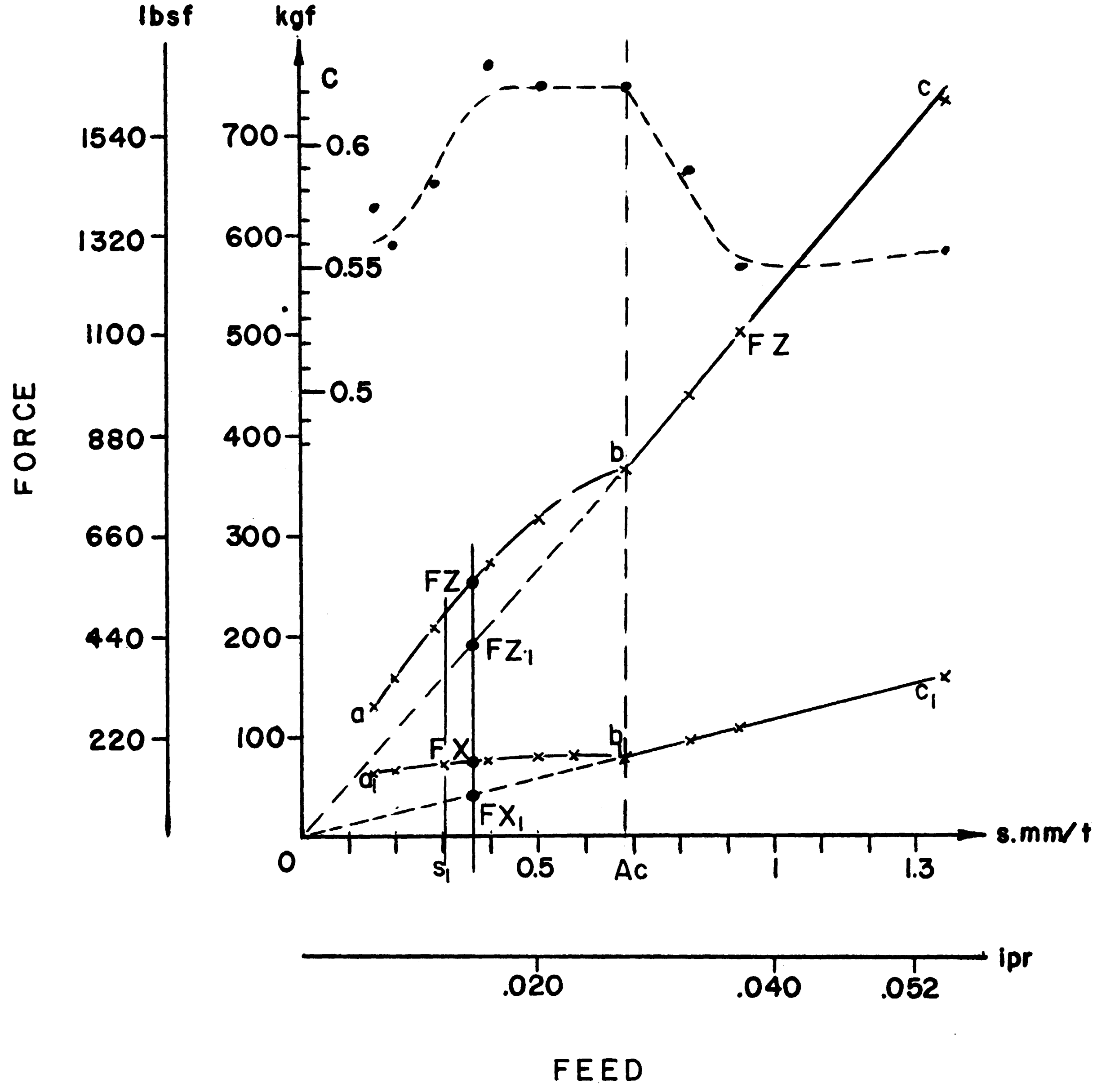


Figure 6. Tangential and lateral forces and cutting ratio as a function of feed, showing linear force-feed behavior beyond critical feed (CIRP-OCDE).

The critical feed, A_c, and the exponent, n, vary with the chemical composition of the machined metal, its structural state, and the geometry of the tool.

On the other hand, the tests have shown that the critical feed corresponds to a temperature on the chip-tool interface of about 450°C (842°F), and the presence of this temperature explains the increase of A_c with the tool rake angle; thus it can be postulated that A_c is a function of the feed, the cutting speed, and the temperature:

$$A_c = f(s, V_c, \theta_c)$$

The comparison of critical feeds on the XC45 steel in four different structural states (annealed, overheated, hardened and tempered at 650°C, and hardened and tempered at oscillating temperature) shows that the critical feed, A_c, representative of the behavior of the built-up edge, is related to the resistance to decohesion, K_{UF}.

The forces F_z and F_x and the rate of deformation of the chip, C, are shown in Figure 6 as a function of feed. The rate of deformation is the ratio of the thickness of the chip to the feed, s. It is observed that this rate is maximum (minimum chip thickness) at the critical feed, A_c, and decreases more or less rapidly beyond this feed. It can be presumed that it is the consequence of the fictitious rake angle caused by the built-up edge which has its maximum volume for the critical feed, A_c.

On the other hand, it has been observed that the critical feed, A_c, corresponds to the minimum value of the tangential force considered as a function of the cutting speed. More complete observations remain to be made, incorporating the analyses made at Aachen and Cincinnati with different methods.

Fragments of the built-up edge sloughed off by the chip are very small at feeds below the critical feed, but increase rapidly at feeds above critical, and even more rapidly at higher cutting speeds. This sloughing off has a considerable influence on the friction between chip and tool. On the other hand, Aachen has shown an increase in frontal tool wear as a result of sloughing off of built-up edge. It seems that this mode of removal must take place before the critical feed, A_c, is reached. However, more tests have to be made.

The critical feed and its attendant factors have both an analytical and a practical significance. For example, the sloughing off of built-up edge which starts at A_c and which effects the friction between chip and tool, explains to a large extent the spread in behavior of the high speed steel tools. It is a factor which will have to be considered when testing the wear of such tools.

Figure 6 has shown that the variation of F_z and F_x is proportional to the feed at feeds greater than critical, and that curve segments bc of b_1c_1 pass through the origin by interpolation. Also, for feeds smaller than A_c, the measured forces are definitely higher than the forces read from the interpolated straight segments ob-ob_1. It is inferred that the lateral and tangential forces, after correction for the disturbing effects of the built-up edge, will be F_{z1} and F_{x1} for a feed s_1. However, in the zone of influence of the built-up edge, the factor C is also influenced by the mode of machining (pure orthogonal cutting on a tube versus the semiorthogonal cutting on a solid piece). For the subsequent calculations of the shearing force, F_s, and of the lateral compression force, F_n, the corrected forces can be used only by taking into account a corresponding correction of the value of the contraction coefficient, C; in order to do that, an average value of C obtained at feeds beyond the critical, A_c, can be used but with a degree in uncertainty. In fact, it is more precise, when comparing the mechanical and physical characteristics of the work material to the cutting characteristics, to make these comparisons for feeds equal to or greater than A_c.

In making these tests, the cutting is generally done on a solid piece; implicitly, a secondary shearing is produced at the end of the tool. This shearing affects the cutting forces in a way that cannot be neglected.

The comparisons between orthogonal cutting on solid rounds and orthogonal cutting on tubes in the machining of XC45 steel in four structural states has shown that for orthogonal cutting on tubes:

1. The tangential force, F_z, is appreciably reduced, from 5 to 17% according to the structure of the steel, the tool rake angle, and the cutting speed. It has not been possible to determine the respective influences of the three factors.

2. The reduction of tangential force is proportional to the feed.

3. The lateral force, F_x, is affected little if at all.

4. The contraction ratio of the chip (C) is often strongly reduced, which seems to indicate that the behavior of the built-up edge is a function of the two cutting modes, but as yet it has not been possible to determine a law of connection between cause and effect. It seems useless to correct the cutting forces without taking into account the variations of the factor C with the machining mode.

B. PECULIARITIES CONCERNING CUTTING FORCES WITH HIGH SPEED STEEL TOOLS

Figure 7 shows variations of the forces F_z and F_x as a function of feed, and indicates a second peculiarity for cutting speeds greater than 15 m/min (49 fpm). Beyond feeds corresponding to A_c, the forces F_z and F_x increase

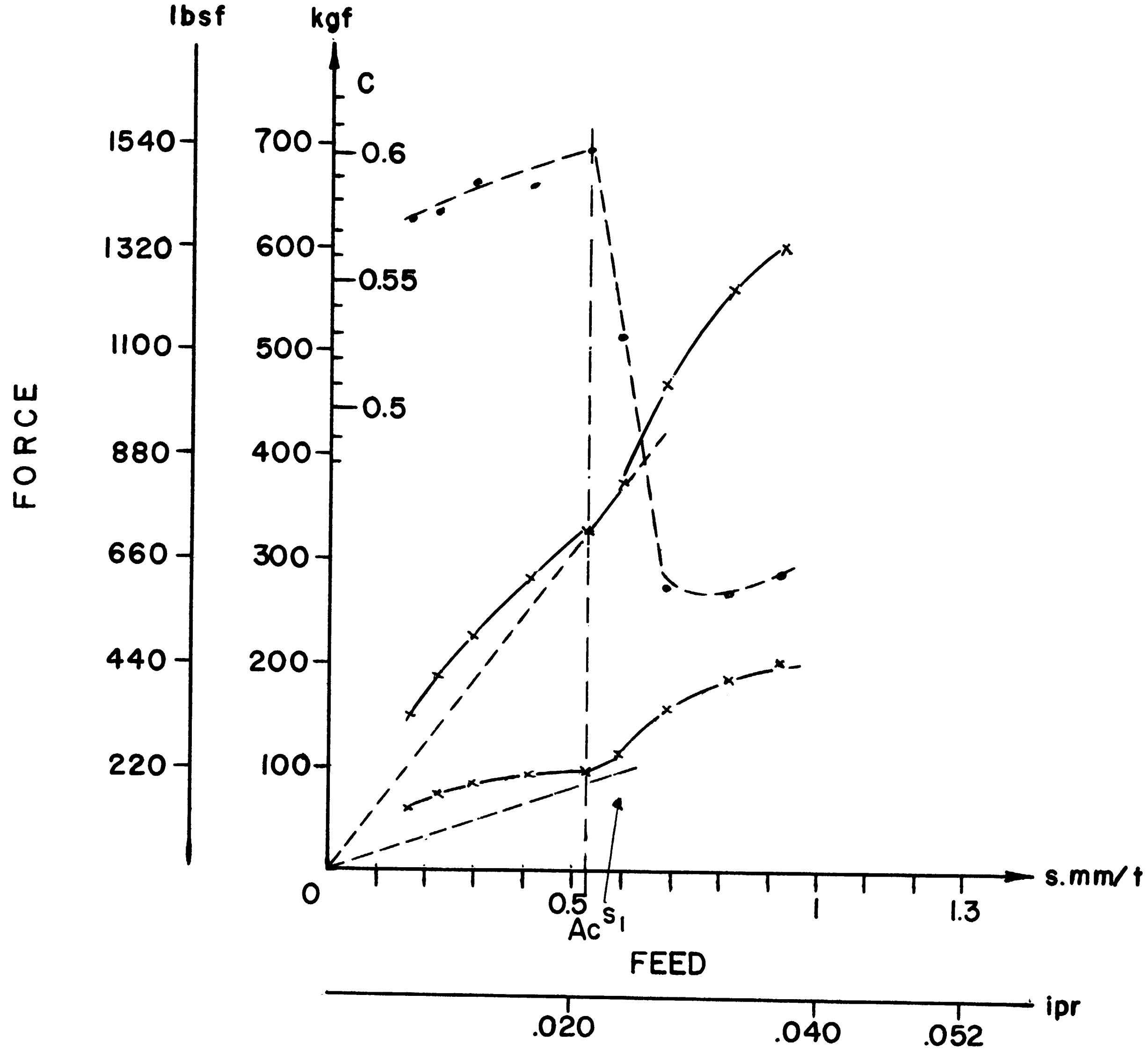


Figure 7. Tangential and lateral forces and cutting ratio under conditions (V > 15 m/min) which give nonlinear force-feed behavior beyond critical feed (CIRP-OCDE).

proportionately to the feed up to feed, s_1. At higher feeds, the increase in forces is not proportional to feed. This phenomena is more pronounced if the forces are changed into specific volumetric cutting energy, $W_c = F_z/sb$, and if the values are plotted on logarithmic coordinates.

Figure 8 shows the behavior of the annealed XC45 steel, but does not show the preceding phenomenon for cutting speeds of 10 to 20 m/min (33-65 fpm) for tool rake angle = 20°. It begins at a cutting speed of 40 m/min (130 fpm). For 10 and 20 m/min, each curve is formed by a sloping segment of a straight line which ends at the critical feed, A_c, and is followed by a horizontal segment of a straight line indicating that beyond A_c, W_c is proportional to the feed. The slope of the first segment is the consequence of the disturbing forces caused by the presence of a built-up edge, relative values of which decrease with the feed according to an exponential law with respect to the forces which arise from elastic and plastic deformations and the friction of the chip on the tool.

For the cutting speed of 40 m/min, the peculiarity observed from the feed s_1 (Figure 7), starts by an upturning of the energy curve after a rather small additional feed.

Figure 9 shows the behavior of XC45 steel, hardened and tempered at temperatures oscillating from 700° to 760°C (1292°-1400°F). For a cutting speed of 10 m/min, a first sloping segment ends at the critical feed, A_c; it is followed by a small horizontal segment; beyond the specific energy increases rather abruptly and then decreases. This corresponds to the peculiarity represented in Figure 7 (for a cutting speed of 40 m/min). By increasing the cutting speed, one increases the intensity of the phenomenon which has a strong tendency to appear as soon as the critical feed, peculiar to the cutting speed considered, is reached.

In the field affected by this phenomenon, the calculations of shear stress, τ_s, show that this value is smaller than it is outside the field, the shear angle is decreased, and, consequently, chip cross section is appreciably increased. At the present time, there is no explanation for this phenomenon. It seems to be a thermal phenomenon affecting the mechanical properties of the material, probably before it passes into the shear plane. If this is true, the problem is relatively complex because the following factors come into play: the thermal energy caused by elastic and plastic deformations of the material along the shear plane; the rate at which heat is taken off by the chip and; the physical properties of the work material (conductivity, specific heat, density).

In any case, it seems necessary to know, on the one hand, the temperature of the chip in the shear plane, ϕ, that different researchers have tried to measure or to calculate, and, on the other hand, the variation of the mechanical properties of the machined material in terms of the temperature. We know that this variation is not uniform for certain properties.

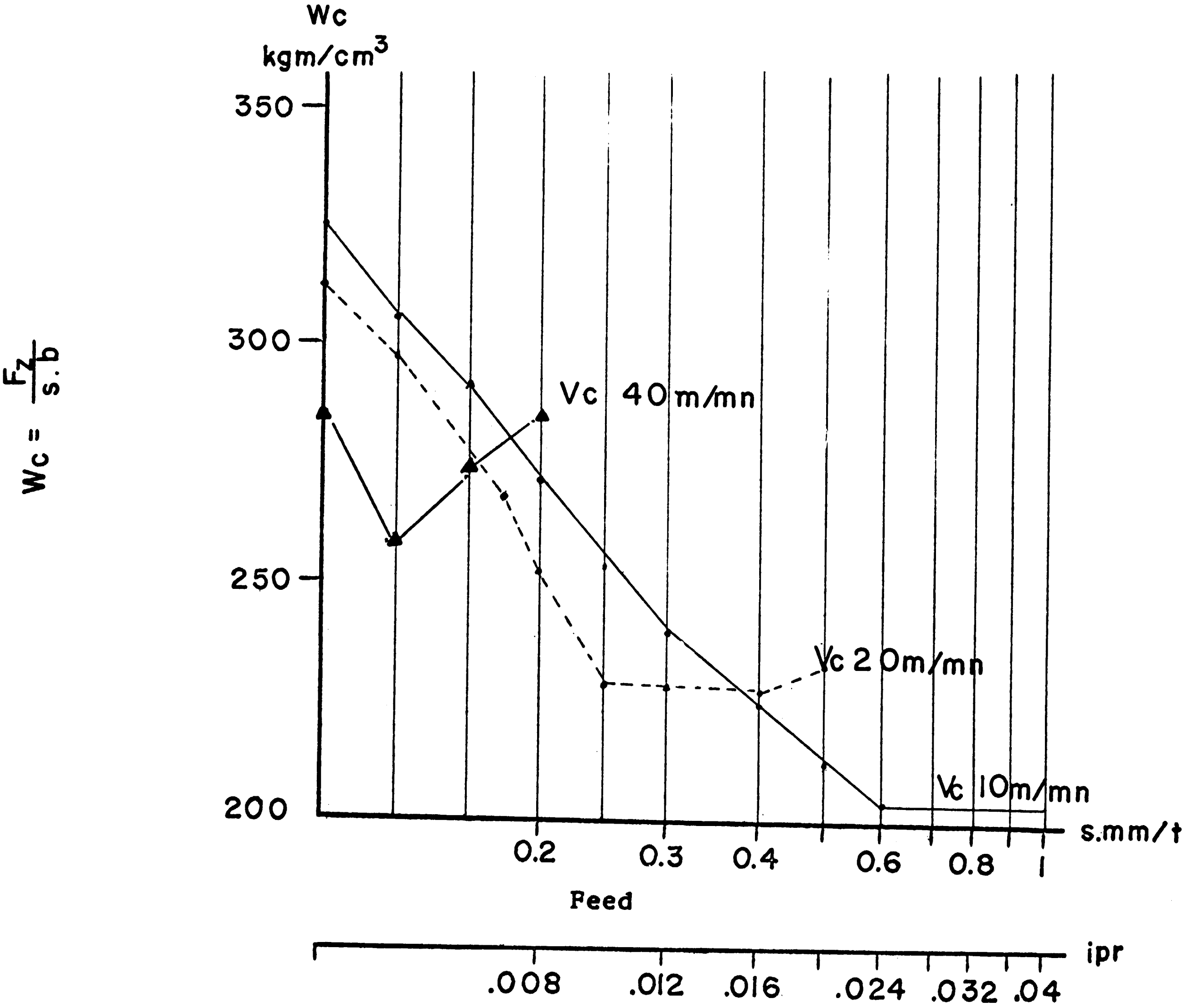


Figure 8. Specific volumetric cutting energy versus feed at various velocities for annealed XC45 steel (CIRP-OCDE).

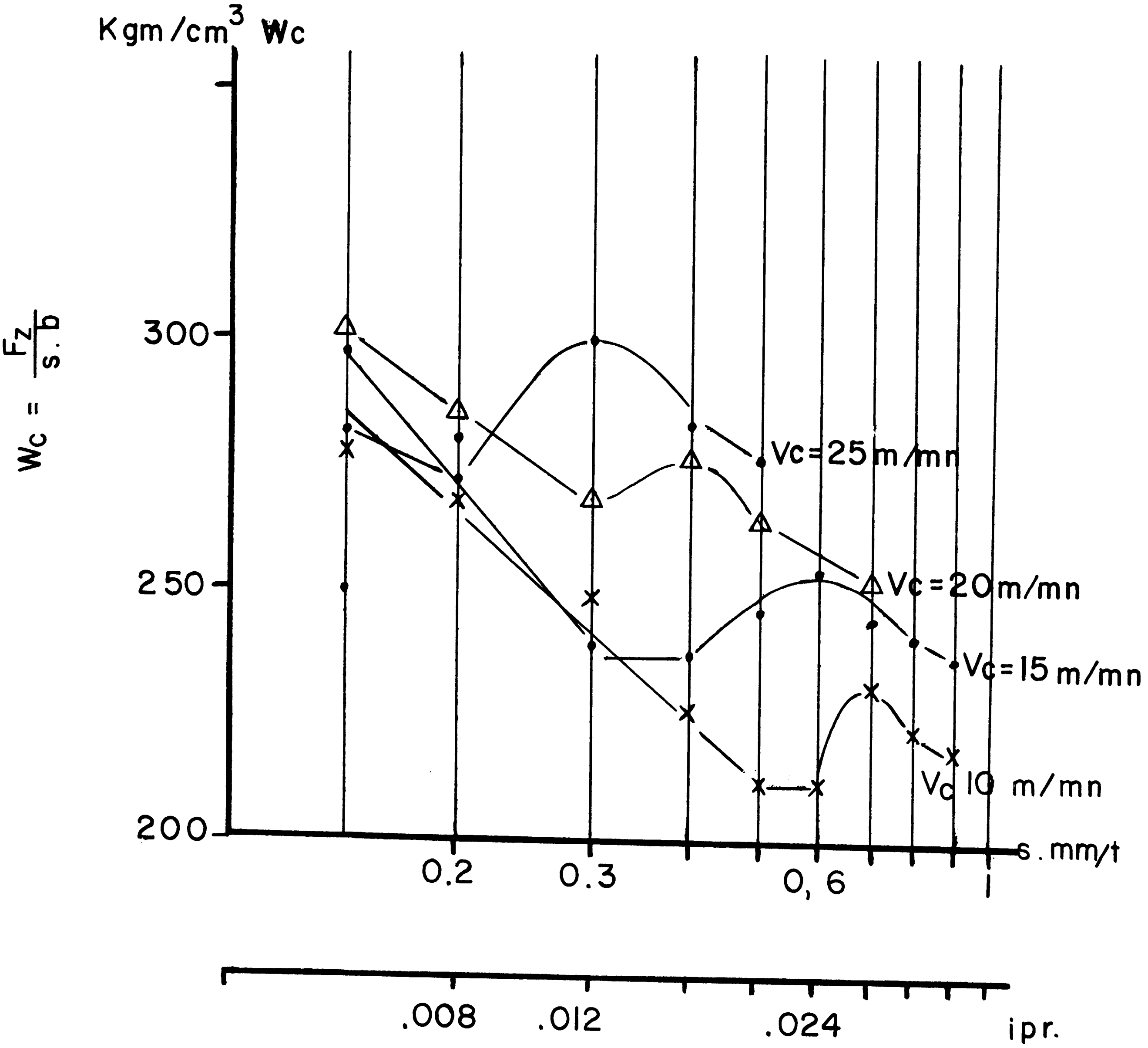


Figure 9. Specific volumetric cutting energy versus feed at various velocities for hardened and tempered (700-760°C) XC45 steel (CIRP-OCDE).

Annealed steel XC45
Tool EW 9 Co10
$\gamma=25^\circ$ $\chi=90^\circ$
X **Semi-orthogonal** cutting on rounds
.. Pure orthogonal cutting on tube

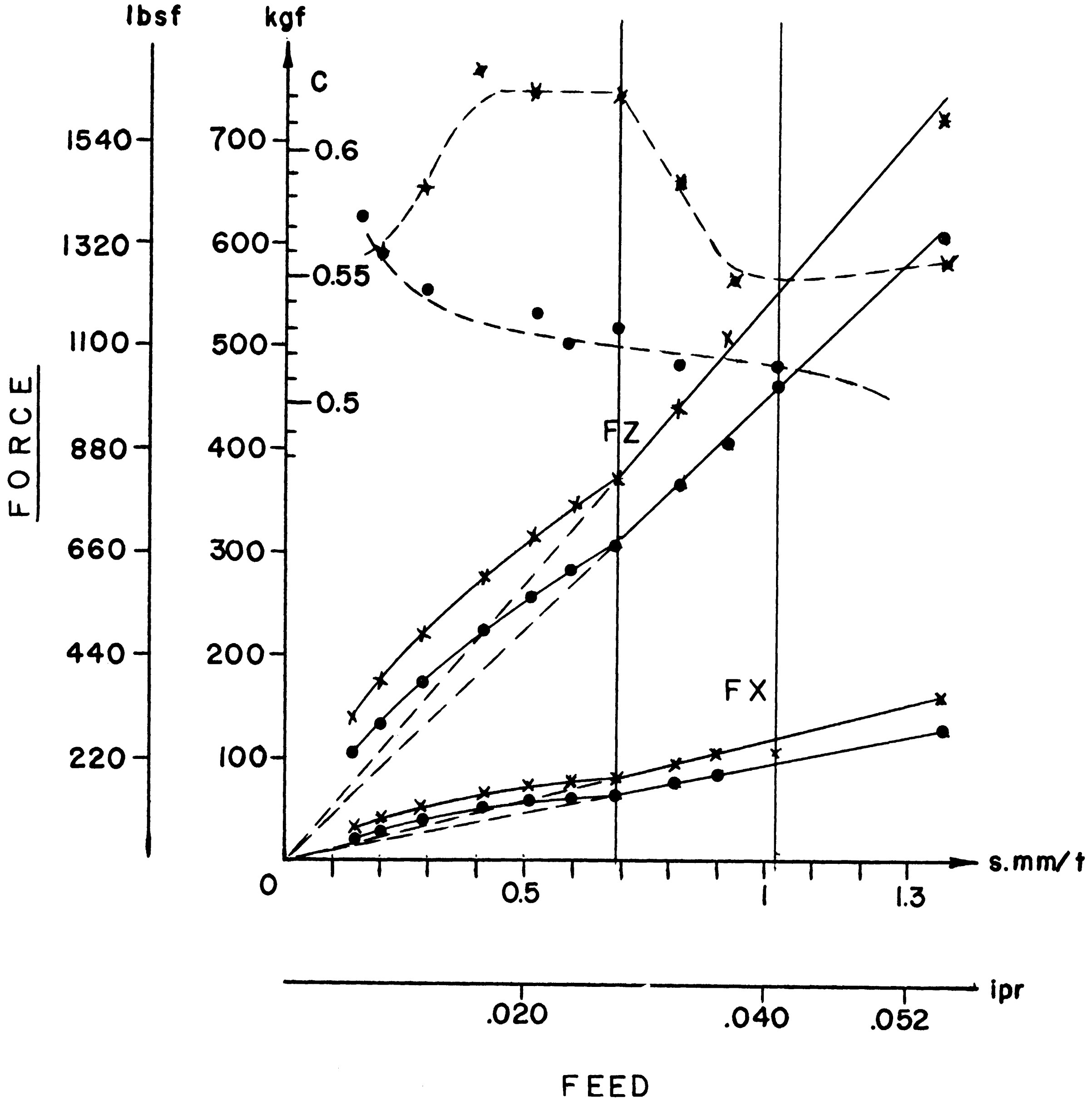


Figure 10. Comparison of cutting forces and cutting ratios under identical cutting conditions for semiorthogonal and pure orthogonal cuts (CIRP-OCDE).

The Laboratoire Central de l'Armement has been interested in the angle of maximum deformation of the chip, ψ. It seems that the theoretical maximum deformation obtained by a geometrical type analysis does not always correspond to the maximum deformation observed in the type of chip which gives a built-up edge. Since this characteristic is so important in studies of plastic deformation of the chip, it seems useful to observe and measure it.

Tests have led this same laboratory to believe that the shearing work, W_s, proceeding from the present classical theories, can be decomposed into work of elastic deformation, W_{de}, work of plastic deformation, W_{dp}, and the frictional work. Tests run on XC45 steel in four structural states at different cutting speeds, tool rake angles, and feeds (66 conditions) have shown a satisfactory correlation between W_s and $W_{de} + W_{dp}$. This study will be followed on the Ni-Cr and Cr-Mo steels by the participants of the work group [Phase II]. If this method is confirmed and completed, it will have the advantage of making possible the comparison of what happens in cutting on the basis of measurable mechanical characteristics of the work material under consideration, independently of the cutting phenomenon. However, the problems due to friction will not be resolved.

Analyses of plastic deformations made at the Laboratoire Central de l'Armament independently of elastic deformations on the XC45 steel show that the plasticity would be relatively little affected by the structural state in the four cases considered.

IV. CONCLUSIONS

For future fundamental analyses and correlation studies between the mechanical and physical properties of the machined material and the cutting characteristics, and after having taken into account the observations made during the preliminary study of the XC45 steel and also the economical and practical factors, it is advised:

A. For the tests at cutting speeds compatible with the use of high speed cutting tools:

1. determine the critical feed, A_c, according to the nature and the structure of the work material, the cutting speeds, and the tool rake angles for cutting a solid bar (semiorthogonal cutting); and

2. use a feed equal to or greater than A_c (previously determined) for turning on a tube (pure orthogonal cutting), to note all the factors, C and Θ_c, as well as the angle of maximum deformation, ψ, as observed on the longitudinal median plane of the chip.

B. For tests at cutting speeds compatible with the use of carbide tools:

1. run tests on a solid bar for feed greater than 0.2 mm/rev (0.008 ipr) and speeds greater than 50 m/min, the critical feed, A_c, being very small ($\leq$ 0.2 mm/rev, built-up edge nonexistent). It will, however, be necessary to run a limited number of tests on a tube to determine the corrections concerning the shearing on the end of the tool.

It will be essential to determine the mechanical characteristics of the steels as a function of the temperature for each structural state.

PART II

WEAR ON AMERICAN AND EUROPEAN CARBIDE TOOLS IN MACHINING XC45 STEEL

This chapter covers two sections relative to carbide tool wear: (1) European carbides and influence of factors other than tool or work material properties, and (2) preliminary tests with American carbides. The two sections relate particularly to results from tests conducted at The University of Michigan.

I. TESTS RESULTS WITH EUROPEAN CARBIDES

Most of the results with European carbides, P10 and P30, were reported in Part I of Interim Report No. 3. However, the tool wear behavior observed at The University of Michigan was unique among the results from seven other participating laboratories and merits additional mention. The results are compared in Figure 11.

The dashed lines in Figure 11 represent the range of scatter or dispersion of flank wear and crater ratio measurements, for given cutting conditions, from European laboratories at Aachen, Delft, Liege, Munich, Zurich, L.C.A. Paris, and T.H. Goteborg. The individual results were coordinated by Dr. H. Opitz of Aachen in a report dated August 6, 1964. Ranges in measurements of 3:1 or more are noted, but, with one exception (flank wear, Figure 11e), no abnormal changes in wear rates occur with time. However, The University of Michigan results do show some contrasts which were repeatable.

A. FLANK WEAR

In normal test sequences, the workpiece is chucked at one end and supported by a heavy duty live center at the other in keeping with recommended procedures. Under these conditions, flank wear correlates very well with European results at short cutting times, but increases very rapidly in latter stages, to cause early termination of the tests. A change to a carbide tipped dead center in the tailstock gave no improvement in flank wear behavior. However, when the work was turned between centers with a live center in the tailstack, flank wear values fell within the scatter band of European results. All other factors were held constant when work holding methods were altered.

The variations in flank wear behavior point to some sort of instability or lack of rigidity in the system. They have important practical significance, for they show how widely results can vary even though general cutting conditions remain the same. There must, of course, be a valid explanation. Subsequent inquiries have revealed that the lathe used in these tests was the only one in participating laboratories that was resting on vibration isolators and, therefore, not lagged to the floor. It is also housed in a laboratory on a

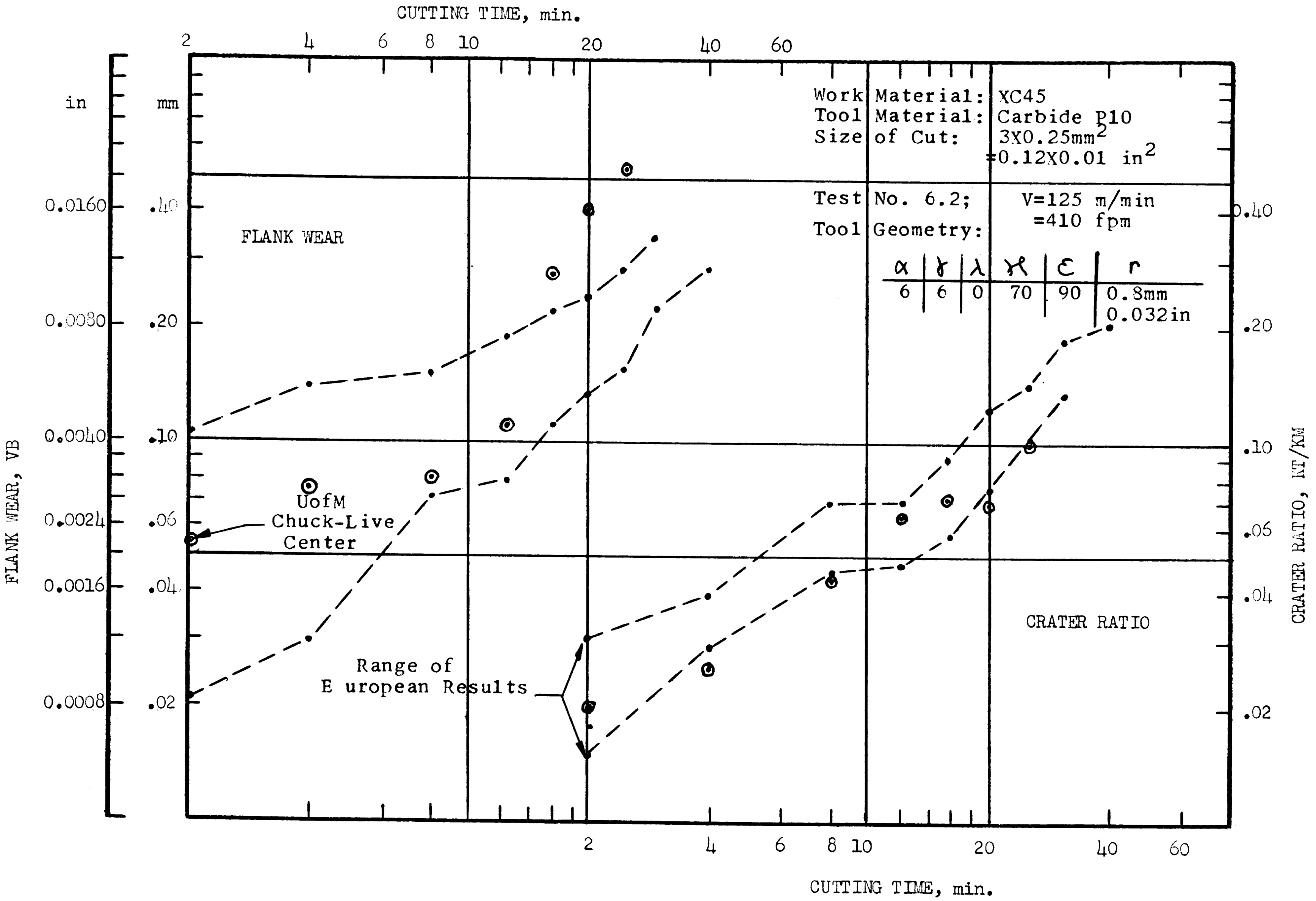


Figure 11. Plots of average flank wear and crater ratio versus cutting time for European P10 and P30 carbide grades. Dashed lines represent range of scatter of results from European laboratories. University of Michigan results are indicated.

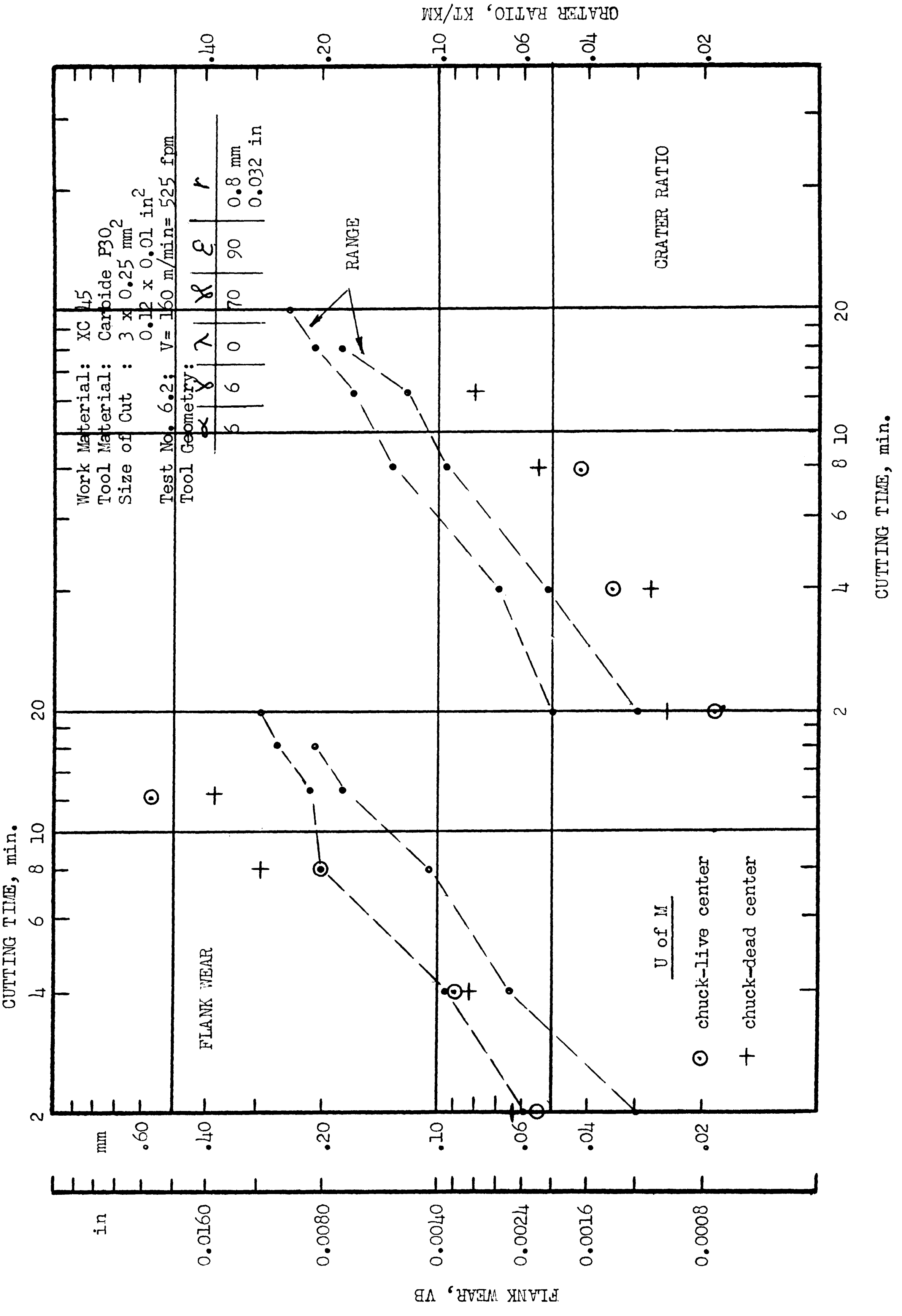


Figure 11—Continued

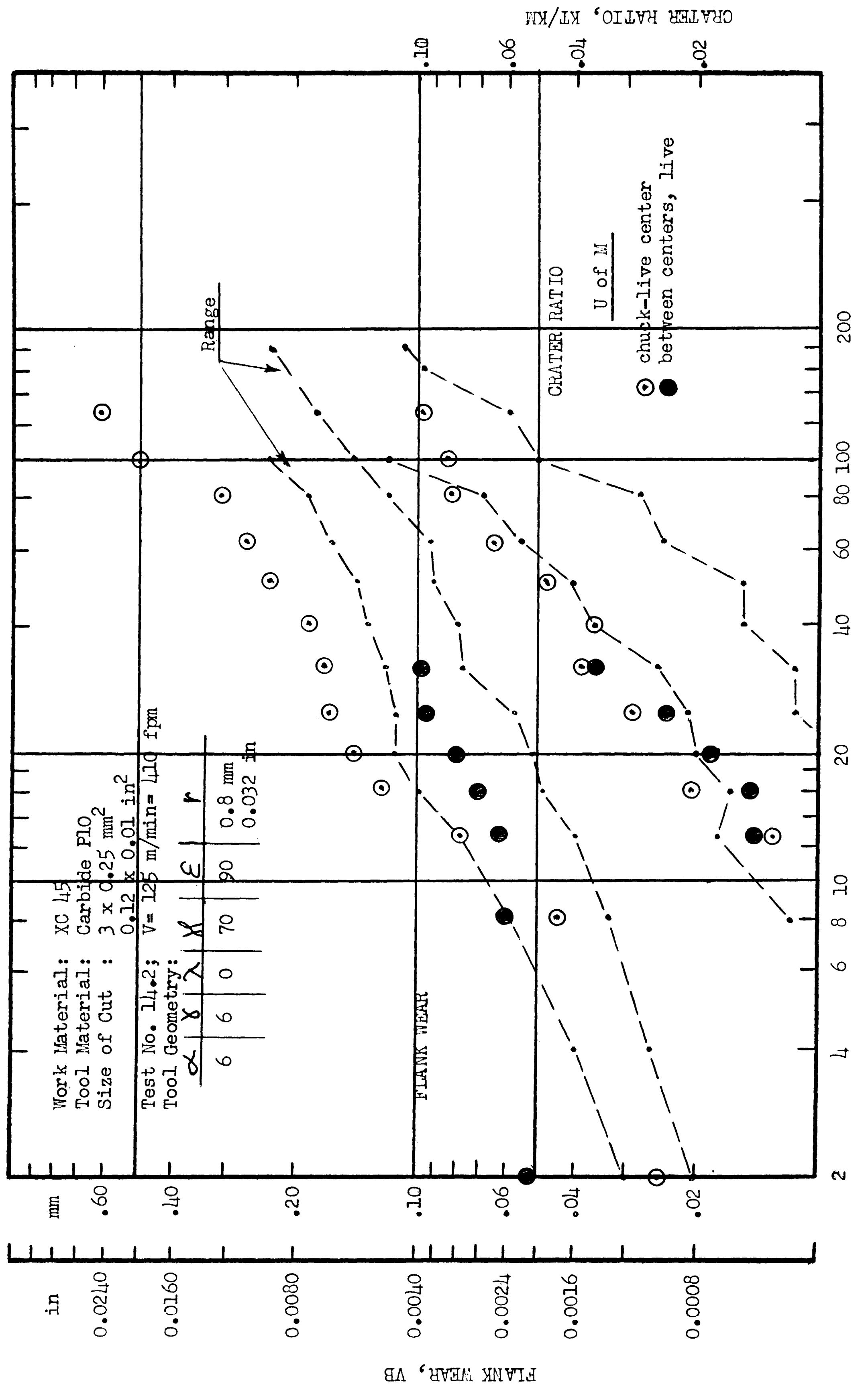


Figure 11—Continued

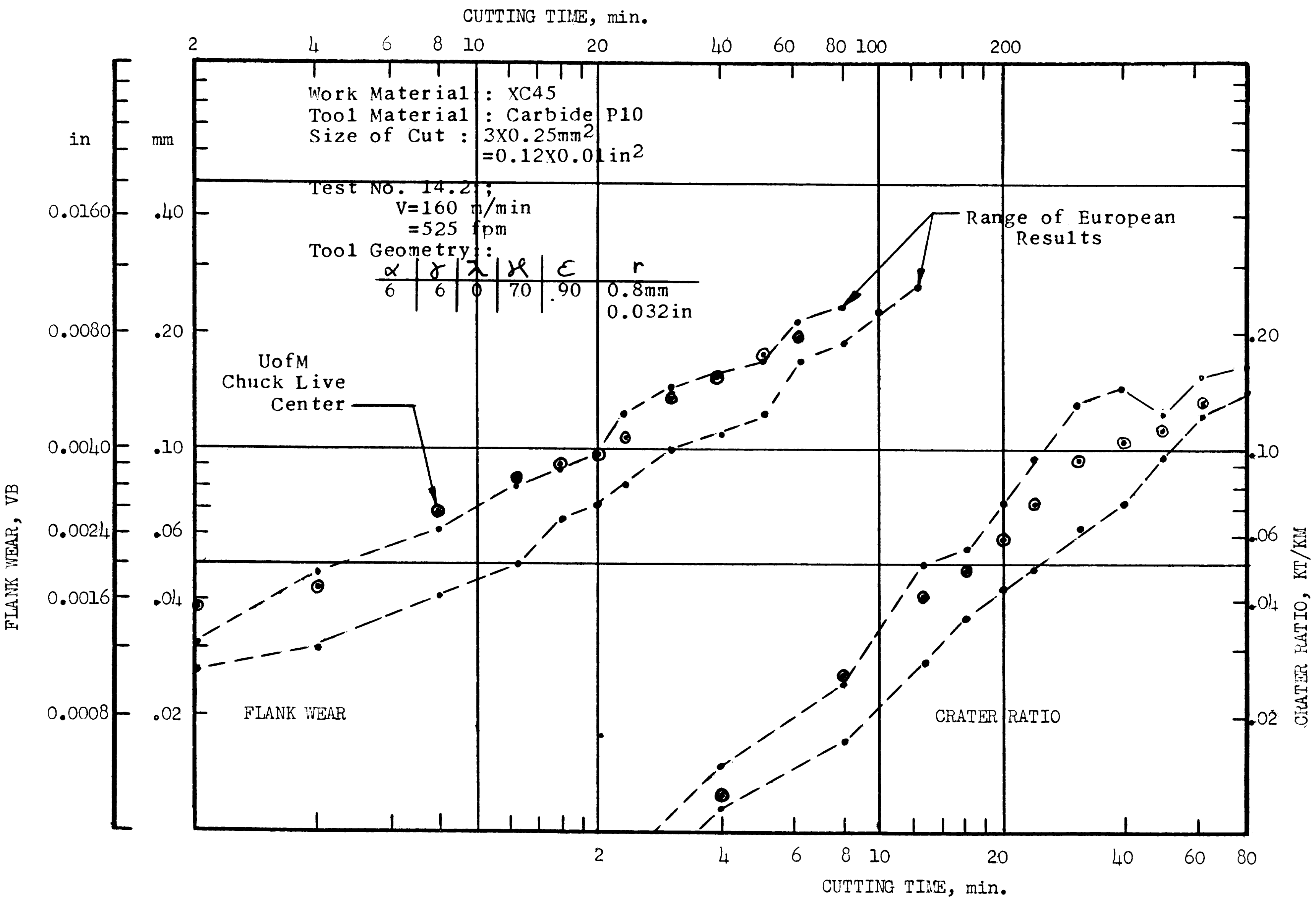


Figure 11—Continued

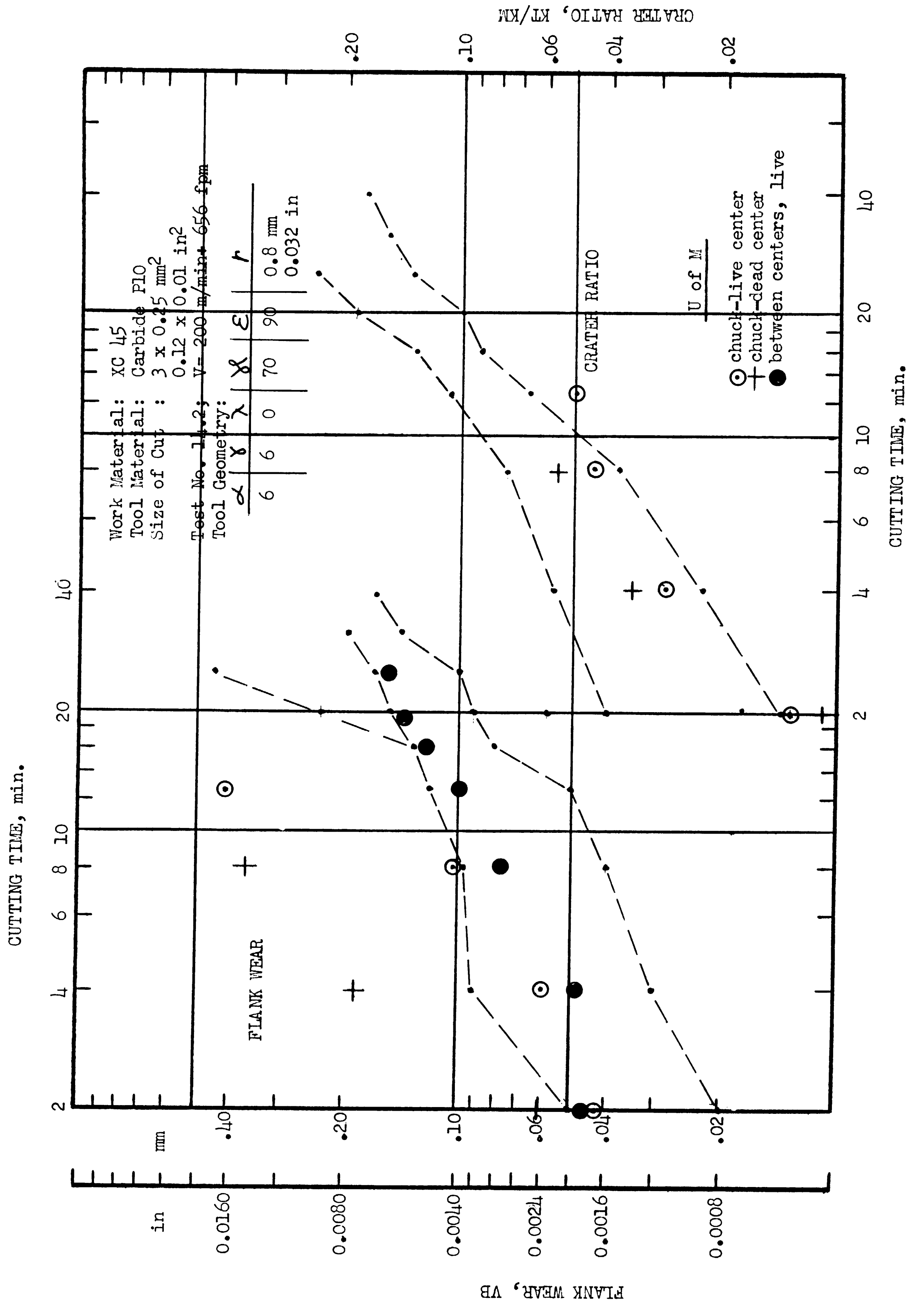


Figure 11—Concluded

first floor level. In contrast, European lathes were not only lagged solidly, but most of them were set at ground level on one meter thick concrete bases.

B. CRATER WEAR

Crater ratios (the depth of the deepest part of the crater, KT, over the distance from the deepest part of the crater to the existing cutting edge, KM) were not as sensitive to the factors which influenced flank wear, and University results, for the most part, correlated very well with the results from other laboratories. However, Figure 11b shows that the ratios for the P30 carbide at a velocity of 525 fpm were substantially lower. That this behavior is other than coincidental is substantiated by the results shown in Figure 12. The curves represent crater profiles along the line AA, as identified in Figure 13, and compare the size and shape of the crater resulting from identical tests at The University of Michigan and Aachen laboratories. The Aachen results were taken from the previously mentioned report by Dr. Opitz. Unfortunately, this was the only common cutting condition for which representative crater information was available, and it is not known just how typical these results are. The University results, however, were repeatable.

The fact that there are differences in behavior, makes it imperative that answers be resolved if there is to be complete faith in interchangeability of information. The various factors involved should and will be investigated to greater depth as the OECD/CIRP cooperative program continues.

II. PRELIMINARY TESTS WITH AMERICAN CARBIDES

Complete investigations with American carbide tools are scheduled for later phases of the tool wear program. However, a few grades have been used in an introductory series to observe patterns of tool wear behavior, and to provide some "tie-in" with the wealth of European information already available for the XC45 work material. Other than the carbides, the methods and techniques of investigation were those of the main cooperative wear program.

A. CUTTING TOOLS

The cutting tools for this investigation were provided by Kennametal, Inc. for both positive and negative rake angles in all standard carbide grades. However, only the grades listed below were on hand at the time of the initial test series. Conversion to equivalent grades among various manufacturers is always dangerous, but Table A-III in Interim Report No. 1 lists the P10 and P30 European carbides as most nearly equivalent in composition to Kennametal grades K5H and K2S, respectively. All tools were of the same size and shape, and the same tool holders were used for both foreign and domestic carbides.

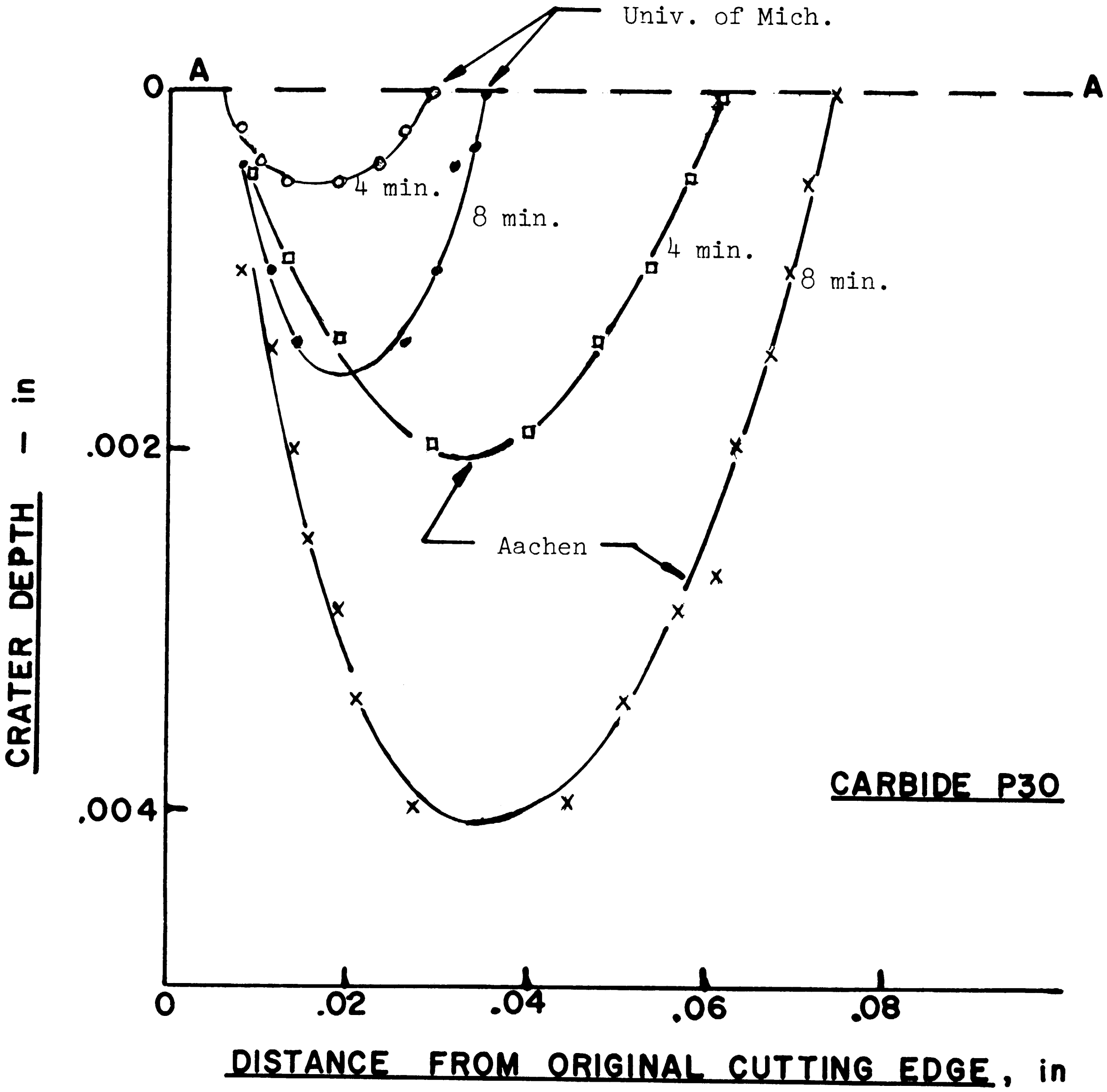


Figure 12. Crater profiles along line AA (identified in Fig. 13) from results at Aachen and The University of Michigan for cutting conditions listed in Fig. 11b.

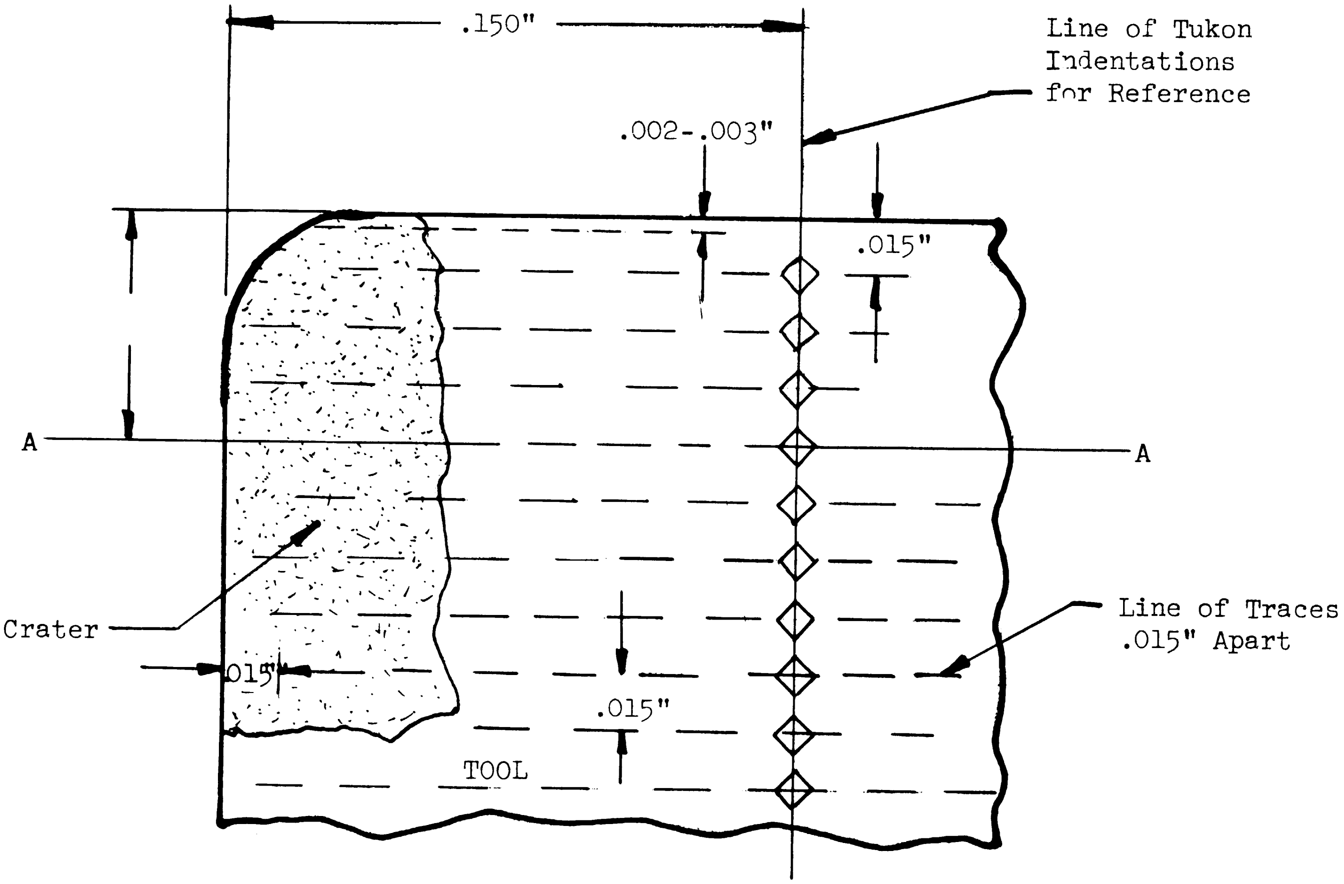


Figure 13. Top view of tool face showing the paths of the traces made on a Proficorder to provide information for mapping crater profiles. Original traces through Tukon indentations before cutting maintained original distance to cutting edge. Single traces along line AA were used to plot crater profile normal to the cutting edge, as in Fig. 21.

Rake Angle	Kennametal Carbide Grade K2S	 K5H	 K6	 K21	 K68
Negative	X		X	X	X
Positive		X		X	

B. CUTTING CONDITIONS AND TEST PROCEDURES

For comparative purposes, cutting conditions were held constant for all carbide grades and for both negative and positive rake angles. The conditions are indicated in Table I, and they are the same as those listed in Figures 11b and 11d for the European carbides. Flank wear, crater ratio, and particularly crater profile served as a basis for comparison.

Crater profiles were determined from multiple traces in the tool face on a micrometrical "Proficorder" along the paths illustrated in Figure 13. Points at several levels of depth were located on each trace and plotted to give the crater profiles in Figures 14 through 30. The Tukon hardness indentations shown in Figure 13, and original traces along the paths before cutting, served as references for the crater measurements. More direct comparisons among various carbides were made by plotting the crater depth variations along the line AA as identified in Figure 13. This is the same location and path used to determine crater ratio. Flank wear and crater ratio are listed in Table I for all tools, including the European grades.

Cutting times are all relatively short in this exploratory investigation, with only three tools carried as long as 8 min. However, there are meaningful differences in behavior. Crater widths vary by almost 4:1, and crater depths vary by more than 50:1 among the grades at 2 min cutting times. Crater width is as much as 8 times the feed rate. These data should become more meaningful as data for other carbide grades are added.

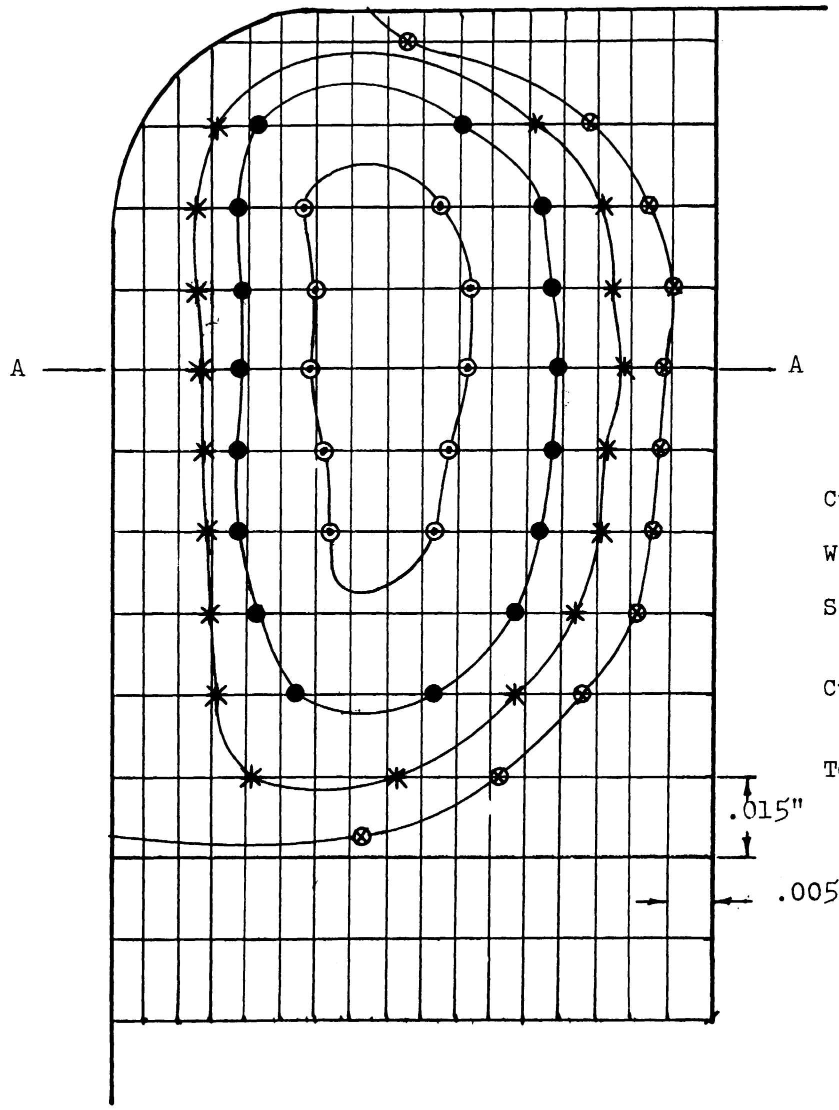
C. CARBIDES WITH NEGATIVE RAKE

The crater profiles shown in Figures 14 through 20, and the results listed in Table I verify clearly that there are two distinct classes of carbides among the four grades tested. The K6 and K68 grades are of a similar class, and both show wide, relatively deep craters and high flank wear at the end of two minutes cutting time. In contrast, the K2S and K21 grades have narrow, shallow craters and relatively low flank wear. The relative depths of the craters are shown more convincingly in Figure 21.

TABLE I. RESULTS OF COMPARATIVE WEAR TESTS

Work Material: XC45 Steel, Heat No. 0656
Size of Cut: 3×0.25 mm^2
0.12×0.010 in.^{2}
Cutting Velocity: 160 m/min = 525 fpm

Tool No.	Carbide Grade	Flank Wear, VB			Crater Ratio, KT/KM			Tool Geometry					
		2 min	4 min	8 min	2 min	4 min	8 min	α	γ	λ	χ	ε	r
A1	K2S	.0033"	.0048"	.0072"	.025	.046	.082	6	-6	-6	70	90	0.8mm 0.032"
A271	K21	.0028"	.0032"		.015	.022							
A91	K6	.0080"			.096								
A151	K68	.0099"			.122								
A658	K21	.0027"			.023			6	6	0	70	90	0.8mm 0.032"
A558	K5H	.0013"			.0075								
589	P10	.0015"	.0018"		.0085	.013							
610	P30	.0022"	.0037"	.0044"	.019	.034	.068						



CRATER DEPTH

⊗ - 0.0 μ in. 0 μm
✱ - 1,600 μ in. 40 μm
● - 3,200 μ in. 80 μm
⊙ - 4,800 μ in. 120 μm

Cutting Time: 2 min.

Work Material: XC 45 (0656)

Size of Cut: 3 x 0.25 mm^2
0.12 x 0.01 in^2

Cutting Velocity: 160 m/min = 525 fpm.

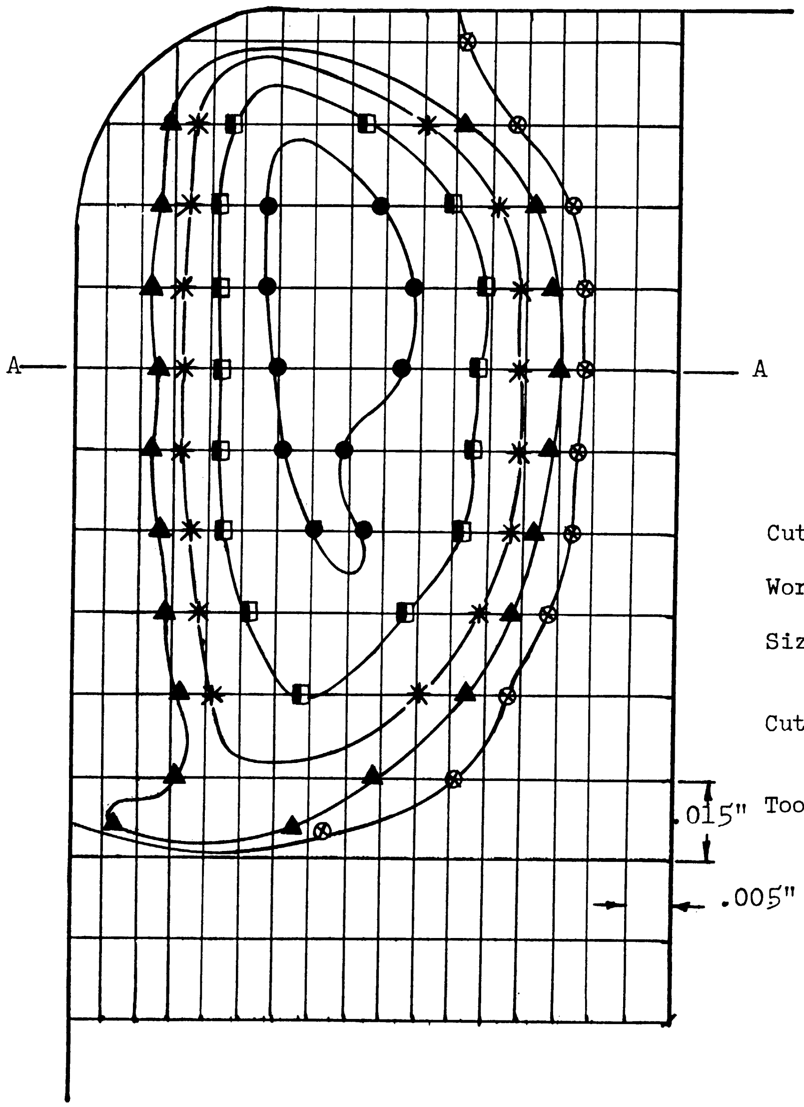
Tool Material: K68 Carbide

TOOL GEOMETRY

α	γ	λ	κ	ε	r
6	-6	-6	70	90	0.8mm 0.032in

SCALE 50:1

Figure 14. Mapping of crater on face of K68 carbide grade at cutting time of 2 min with negative rake and cutting conditions indicated.



CRATER DEPTH

⊗ - 0.0 μin. 0 μm
▲ - 800 μin. 20 μm
✱ - 1,600 μin. 40 μm
◧ - 2,400 μin. 60 μm
● - 3,200 μin. 80 μm

Cutting Time: 2 min.

Work Material: XC 45 (0656)

Size of Cut: 3 x 0.25 mm^2
0.12 x 0.01 in^2

Cutting Velocity: 160 m/min. =
525 fpm.

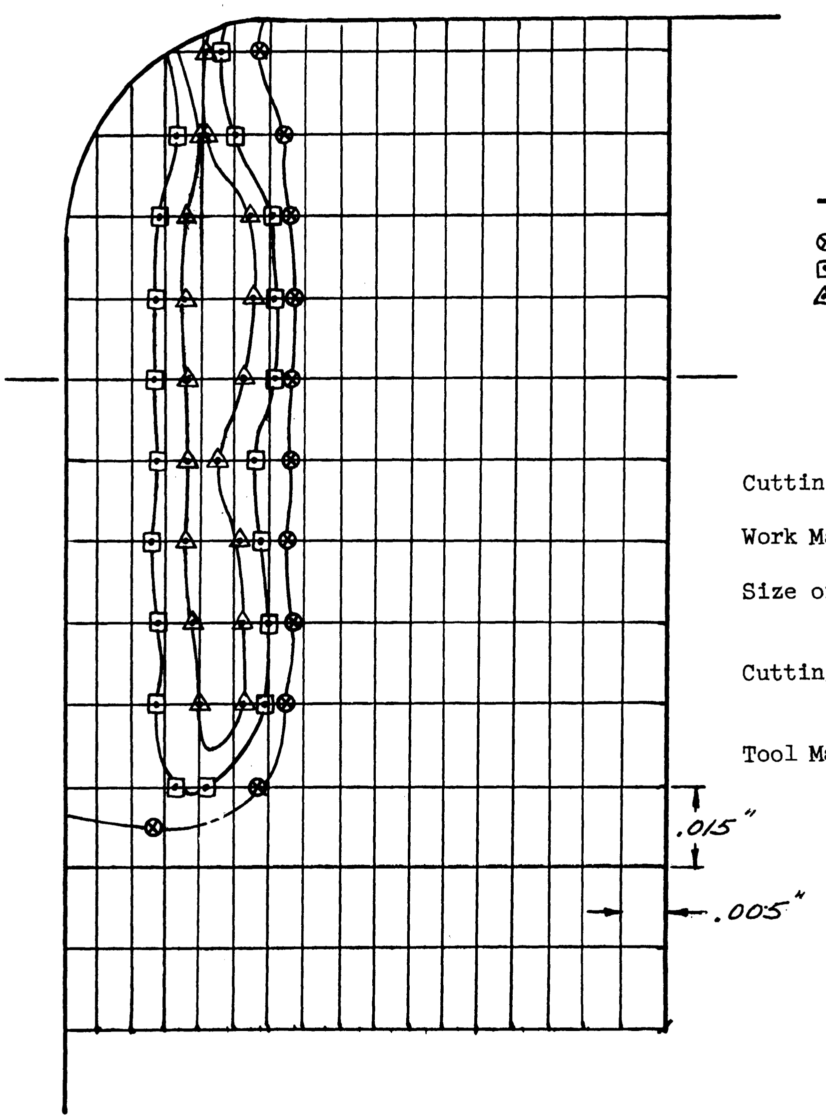
Tool Material: K6 Carbide

TOOL GEOMETRY

α	γ	λ	$\varkappa$	ε	r
6	-6	-6	70	90	.8mm .032in

SCALE 50:1

Figure 15. Mapping of crater on face of K6 carbide grade under same conditions listed in Fig. 14.



CRATER DEPTH

⊗ - 0.0 μin. 0 μm
⊡ - 100 μin. 2.5 μm
△ - 200 μin. 5 μm

Cutting Time: 2 min.

Work Material: XC 45 (0656)

Size of Cut: $3 \times 0.25\ \text{mm}^2$
$0.12 \times 0.01\ \text{in}^2$

Cutting Velocity: 160 m/min. ≃
525 fpm.

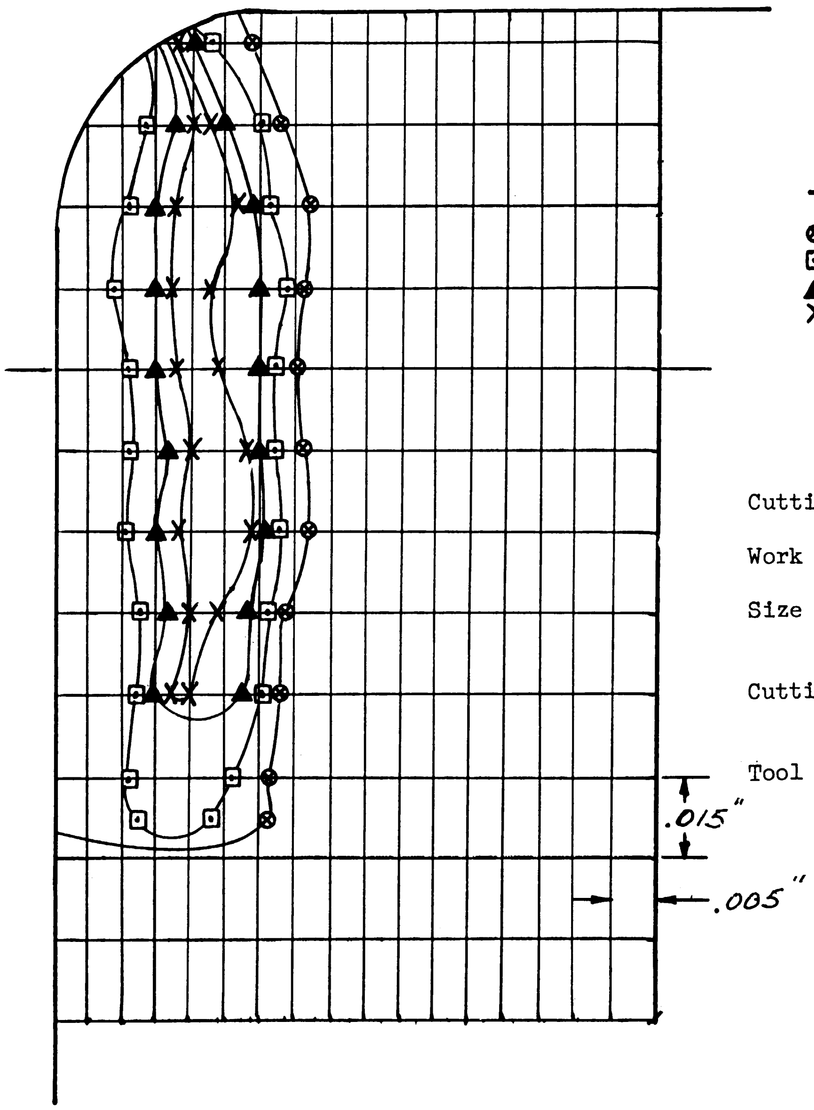
Tool Material: K21 Carbide

TOOL GEOMETRY

α	γ	λ	χ	ε	r
6	-6	-6	70	90	.8mm .032in

SCALE 50:1

Figure 16. Mapping of crater on face of K21 carbide grade under same conditions listed in Fig. 14.



CRATER DEPTH

⊗ - 0.0 μin. 0 μm
⊡ - 100 μin. 2.5 μm
▲ - 300 μin. 7.5 μm
X - 400 μin. 10 μm

Cutting Time: 4 min.

Work Material: XC 45 (0656)

Size of Cut: 3 x 0.25 mm^2
0.12 x 0.01 in^2

Cutting Velocity: 160 m/min = 525 fpm.

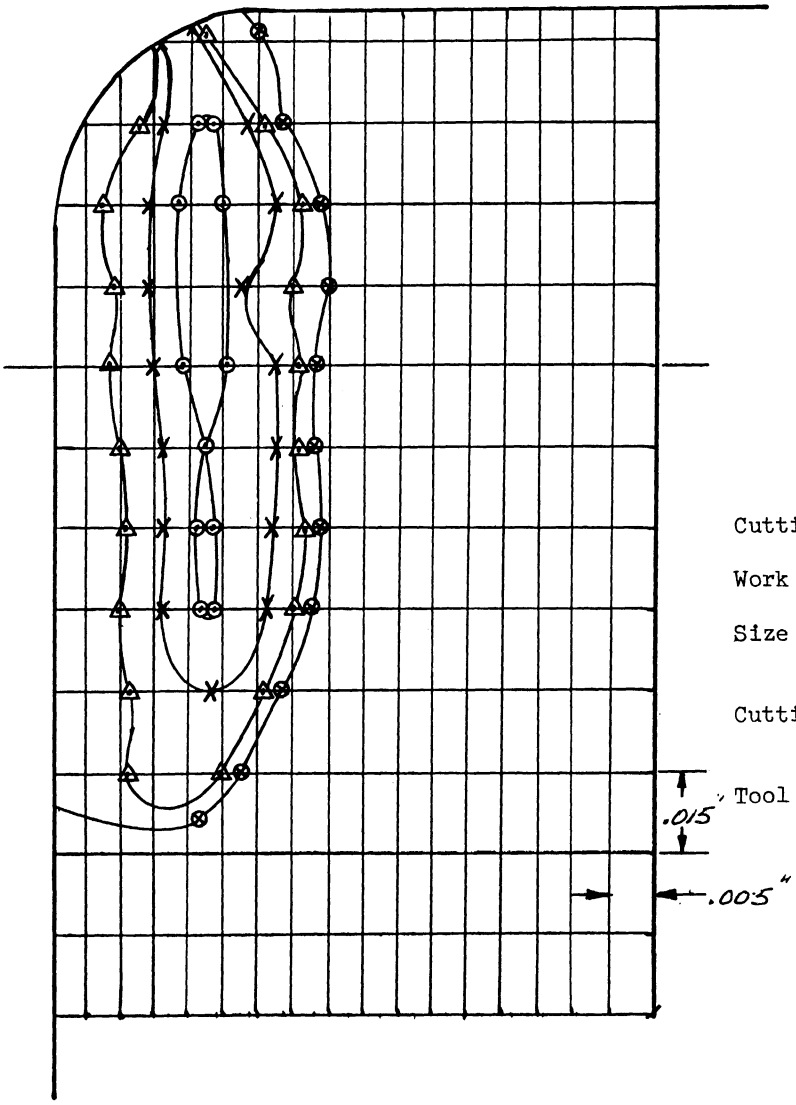
Tool Material: K21 Carbide

TOOL GEOMETRY

α	γ	λ	ϰ	ε	r
6	-6	-6	70	90	.8mm .032in

SCALE 50:1

Figure 17. Tool of Fig. 16 with crater at end of 4 min cutting time.



CRATER DEPTH

⊗ - 0.0 μin. 0 μm
△ - 200 μin. 5 μm
× - 400 μin. 10 μm
⊙ - 600 μin. 15 μm

Cutting Time: 2 min.

Work Material: XC 45 (0656)

Size of Cut: 3 x 0.25 mm^2
0.12 x 0.01 in^2

Cutting Velocity: 160 m/min = 525 fpm.

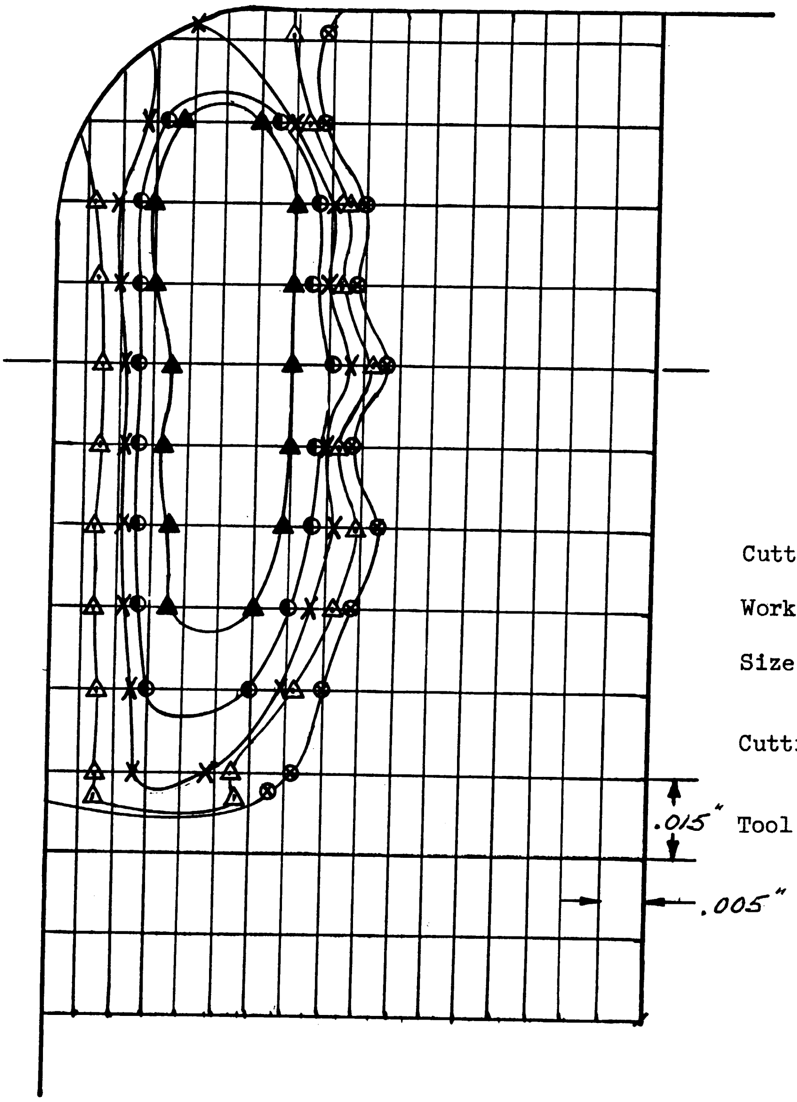
Tool Material: K2S Carbide

TOOL GEOMETRY

α	γ	λ	κ	ε	r
6	-6	-6	70	90	.8mm .032in

SCALE 50:1

Figure 18. Mapping of crater on face of K2S carbide grade under same conditions listed in Fig. 14.



CRATER DEPTH

⊗ - 0.0 μin. 0 μm
△ - 200 μin. 5 μm
X - 400 μin. 10 μm
◐ - 600 μin. 15 μm
▲ - 800 μin. 20 μm

Cutting Time: 4 min.

Work Material: XC 45 (0656)

Size of Cut: 3 x 0.25 mm^2
0.12 x 0.01 in^2

Cutting Velocity: 160 m/min = 525 fpm.

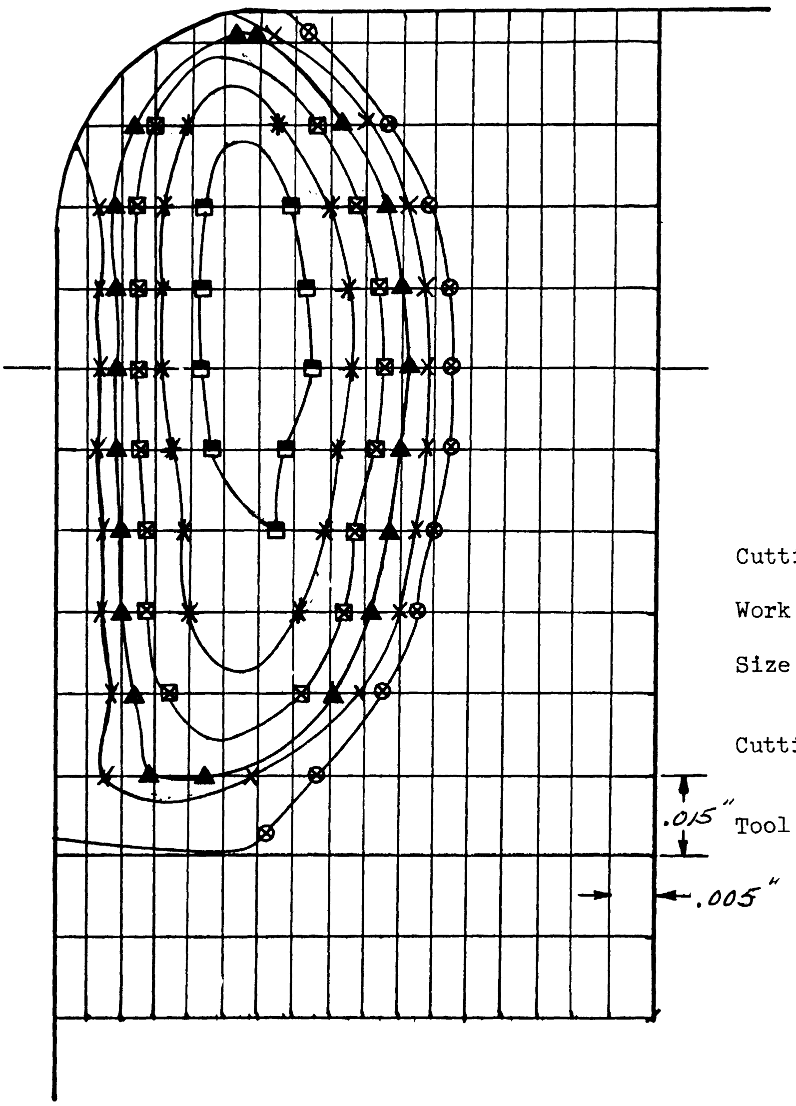
Tool Material: K2S Carbide

TOOL GEOMETRY

α	γ	λ	χ	ε	r
6	-6	-6	70	90	.8mm .032in

SCALE 50:1

Figure 19. Tool of Fig. 18 with crater at end of 4 min cutting time.



CRATER DEPTH

⊗ - 0.0 μin. 0 μm
× - 400 μin. 10 μm
▲ - 800 μin. 20 μm
⊠ - 1,200 μin. 30 μm
✱ - 1,600 μin. 40 μm
▣ - 2,000 μin. 50 μm

Cutting Time: 8 min.

Work Material: XC 45 (0656)

Size of Cut: 3 x 0.25 mm^2
0.12 x 0.01 in^2

Cutting Velocity: 160 m/min = 525 fpm.

Tool Material: K2S Carbide

TOOL GEOMETRY

α	γ	λ	κ	ε	r
6	-6	-6	70	90	.8mm .032in

SCALE 50:1

Figure 20. Tool of Fig. 18 with crater at end of 8 min cutting time.

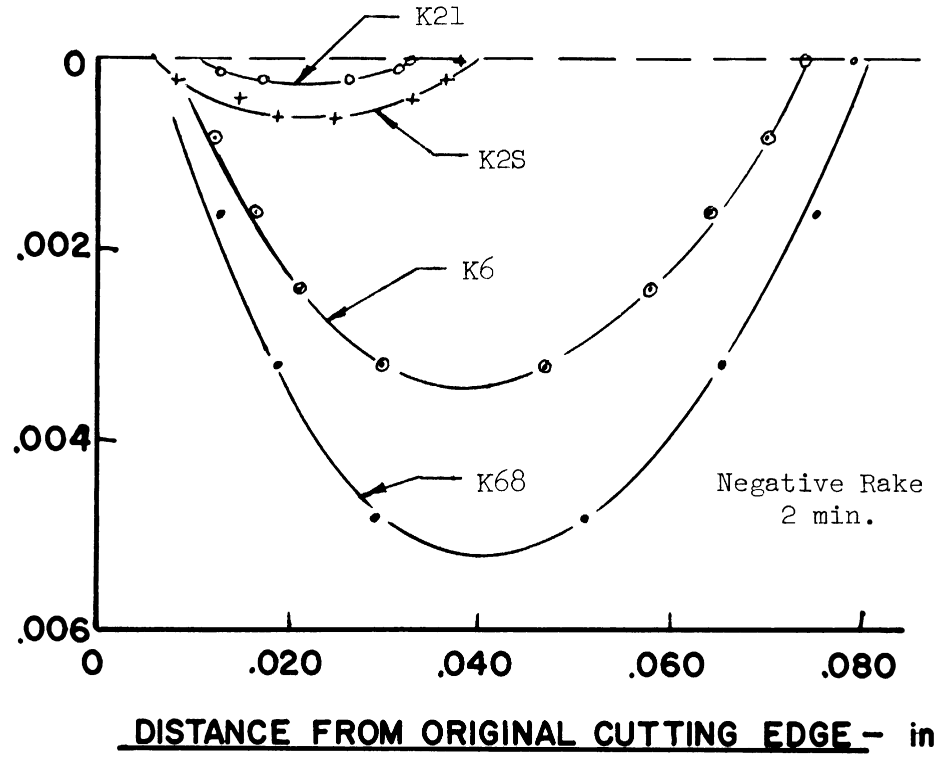


Figure 21. Crater profiles along line AA for negative rake tools in Figs. 14, 15, 16 and 18; cutting time, 2 minutes.

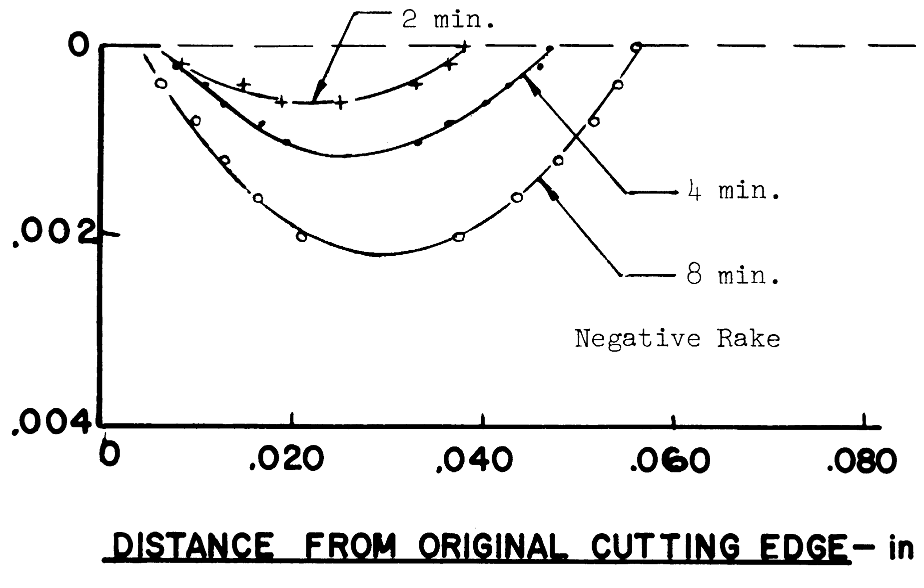


Figure 22. Crater profiles along line AA for 2, 4, and 8 minute cutting times on K2S carbide. Results from Figs. 18, 19 and 20.

The progress of wear with time may be observed for the K21 and K2S grades in Figures 16 and 17, and Figures 18, 19, and 20, respectively. Figure 22 compares the crater profiles at 2-, 4-, and 8-min intervals for the K2S carbide along the path, AA. These show a typical effect in that the deepest part of the crater moves away from the cutting edge as the crater increases in size.

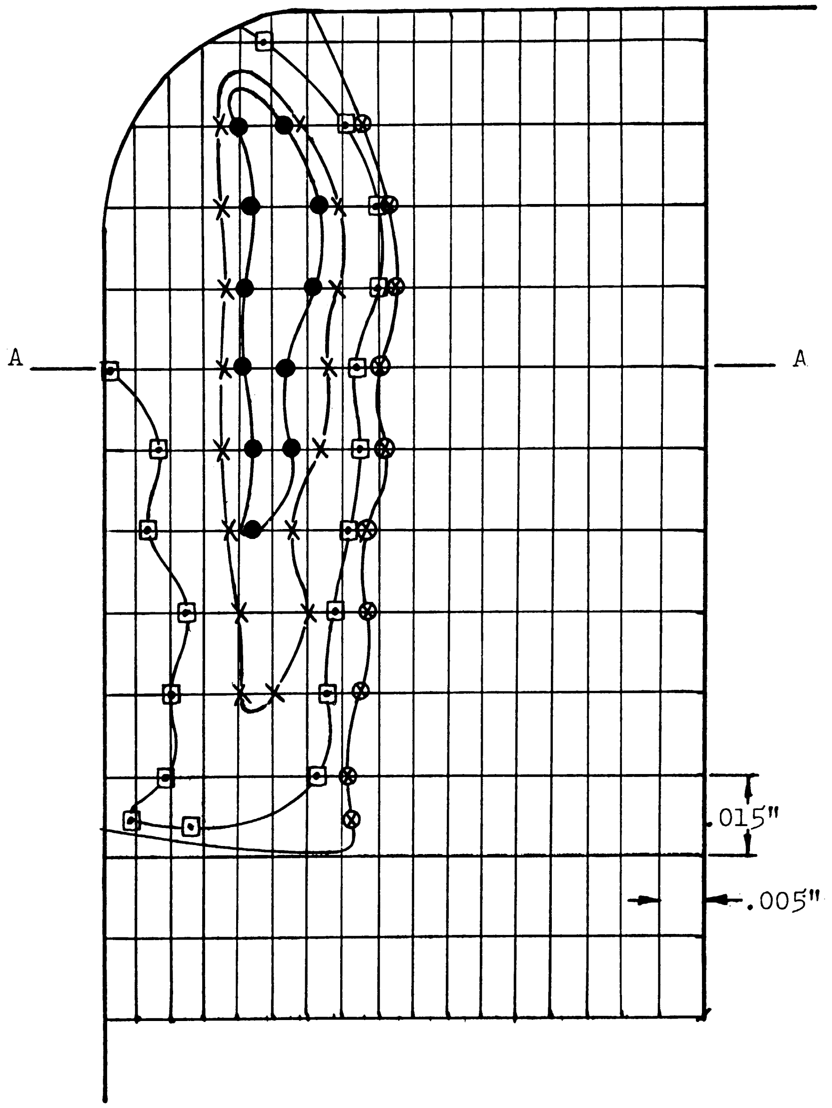
The differences between the two classes of carbides are quite evident. However, cutting times are short, and any attempt to evaluate the performance of carbides in any one class would be mere speculation, even though one grade may have more wear than another. However, the crater profiles reveal some differences between them which may or may not be significant in time. For example, the K6 carbide has a crater only 2/3 as deep as the K68 grade, but it has a broader band of wear at the nose and gives evidence of some grooving at the depth-of-cut line, where the crater wear is very abrupt. The K21 grade has the least wear of the four carbides, but there is a potential source of trouble, as Figures 16 and 17 show a groove or rut at the nose which has a tendency to be as deep as the crater itself. A groove also exists on the K2S carbide, but the groove is shallower than the crater. In either case, the wear is still very small

D. CARBIDES WITH POSITIVE RAKE

Flank wear and crater ratio results with positive rake angles are listed in Table I, and the crater profiles are shown in Figures 23 through 28. Crater profiles along line AA are compared in Figure 29. The P10 and K5H carbides show the least wear, while the K21 grade shows the most. Wear magnitudes are all quite small, however.

Even though cutting time is short and wear is in its early stages, there are two observations which relate to wear behavior among the carbides: (1) variations in crater shape, and (2) size and location of crater and its relationship to crater ratio. The first of these is substantiated by observations made during the tool life tests on European carbides, where craters were observed at regular intervals of time for as long as two hours of cutting. Almost without exception, the P10 and P30 carbides developed the two distinct crater shapes illustrated in Figure 30 (a) and (b), respectively, and indicative of the crater profiles in Figures 25 through 28. The crater on the P30 grade was very uniform and parallel to the cutting edge along its full length. At advanced stages of wear, however, the crater approached the shape of Figure 30 (c). All of the American carbides tested to date have shown craters typical of the sketch in (c) to at least some degree.

The second observation concerns the relationship between the craters and the flank wear and crater ratio results on carbides P10 and K5H. The results in Table I show virtually identical values for flank wear and crater ratio on the two materials. However, Figures 24, 25, and 29 show a difference in the



CRATER DEPTH

⊗ - 0.0 µin. 0 µm
⊡ - 100 µin. 2.5 µm
X - 400 µin. 10 µm
● - 500 µin. 12.5 µm

Cutting Time: 2 min.

Work Material: XC45(0656)

Size of Cut: 3x0.25 mm^2
0.12x0.01in^2

Cutting Velocity:

160 m/min = 525 fpm

Tool Material:

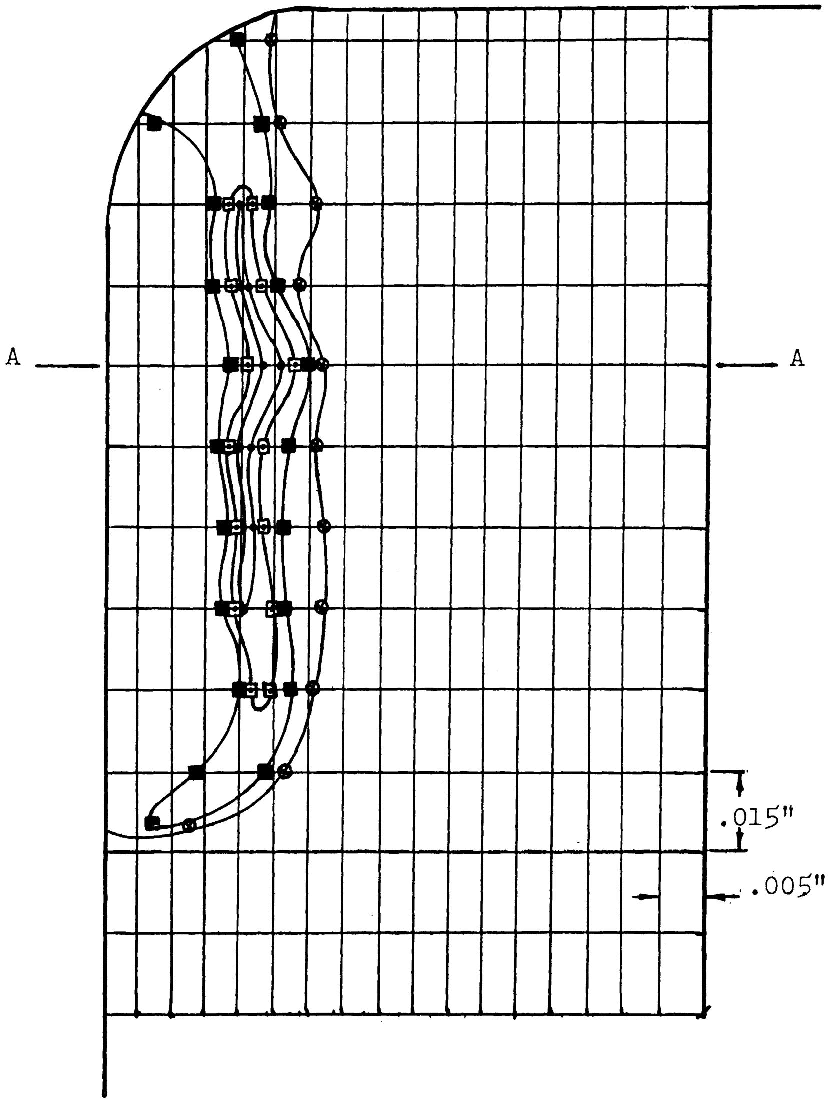
K21 Carbide

TOOL GEOMETRY

α	γ	λ	κ	ε	r
6	6	0	70	90	0.8mm 0.032in

SCALE 50:1

Figure 23. Mapping of crater on face of K21 carbide grade at cutting time of 2 min with positive rake and cutting conditions indicated.



CRATER DEPTH

⊗- 0.0 µin. 0 µm
■- 50 µin. 1.2 µm
▣- 100 µin. 2.5 µm
•- 150 µin. 3.8 µm

Cutting Time: 2 min.

Work Material: XC45(0656)

Size of Cut: 3x0.25 mm^2
0.12x0.01 in^2

Cutting Velocity:
160 m/min - 525 fpm

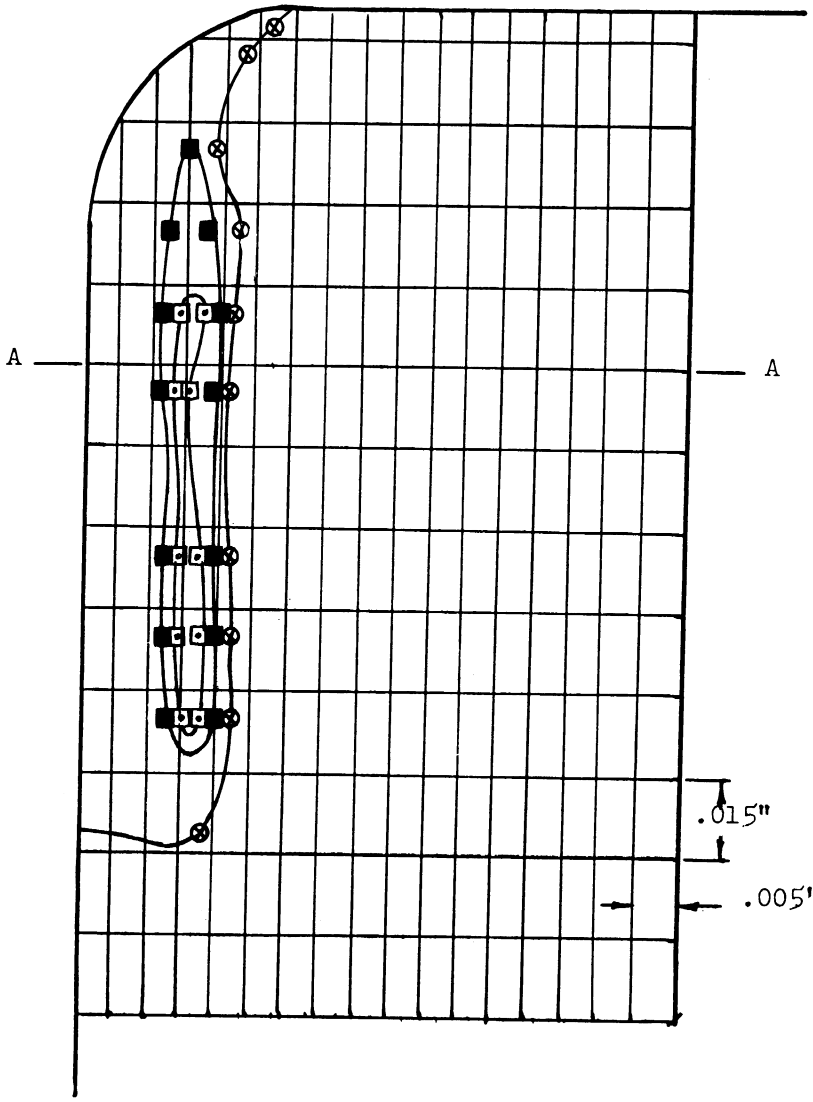
Tool Material:
K5H Carbide

TOOL GEOMETRY

α	γ	λ	κ	ε	r
6	6	0	70	90	0.8mm .032in

SCALE 50:1

Figure 24. Mapping of crater on face of K5H carbide grade under same conditions listed in Fig. 23.



CRATER DEPTH

⊗ - 0.0 µin.. 0 µm
■ - 50 µin. 1.2 µm
⊡ - 100 µin. 2.5 µm

Cutting Time: 2 min.

Work Material:
XC45 (0656)

Size of Cut:
3 x 0.25 mm^2
0.12 x 0.01 in^2

Cutting Velocity·
160 m/min =.525 ipm

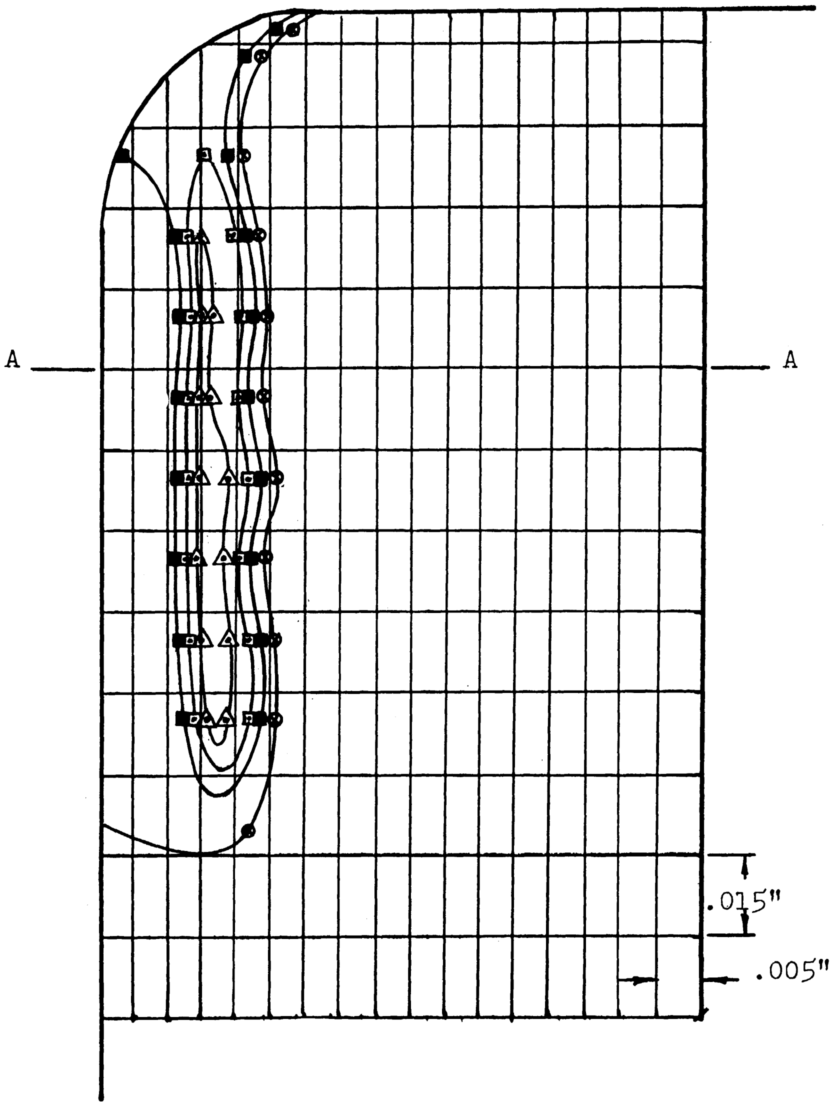
Tool Material:
P10 Carbide

TOOL GEOMETRY

α	γ	λ	κ	ϵ	r
6	6	0	70	90	0.8mm .032in

SCALE 50:1

Figure 25. Mapping of crater on face of European P10 carbide grade under same conditions listed in Fig. 23.



CRATER DEPTH

○ - 0.0 μin. 0 μm
■ - 50 μin. 1.2 μm
⊡ - 100 μin. 2.5 μm
▲ - 200 μin. 5 μm

Cutting Time: 4 min.

Work Material:
XC45 (0656)

Size of Cut:
$3 \times 0.25 \text{ mm}^2$
$0.12 \times 0.01 \text{ in}^2$

Cutting Velocity:
160 m/min = 525 fpm

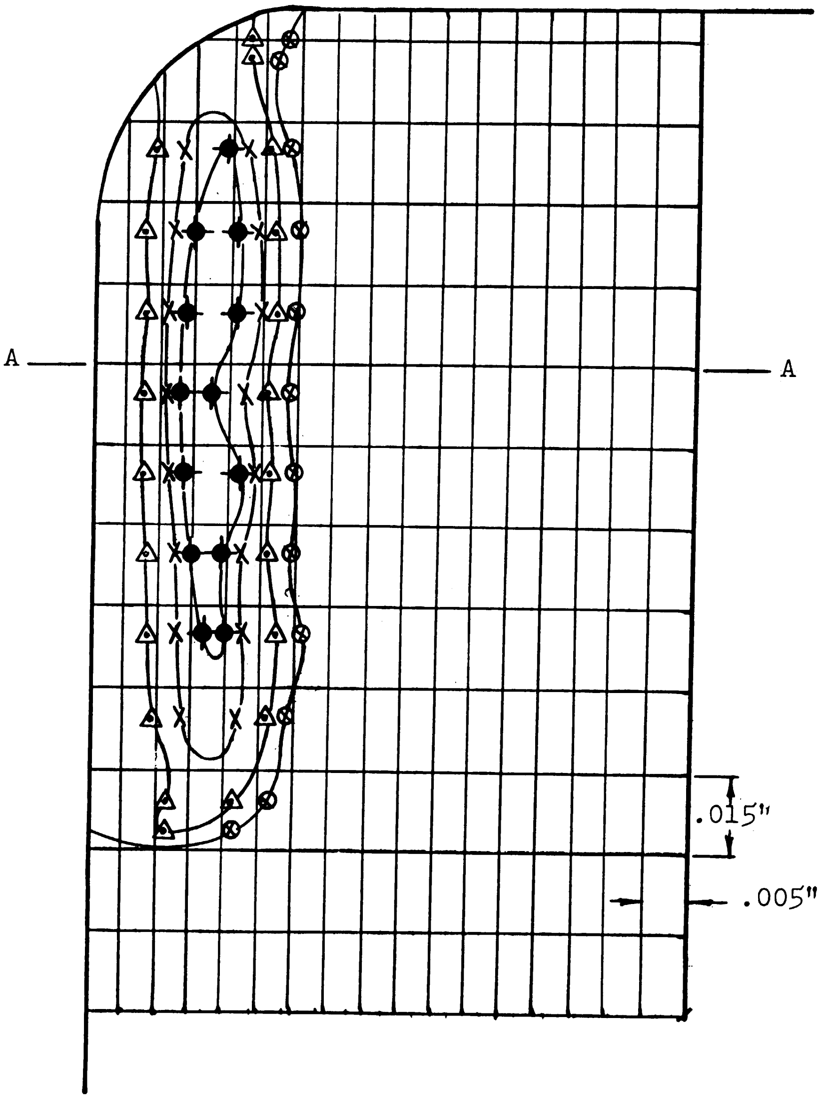
Tool Material:
P10 Carbide

TOOL GEOMETRY

α	γ	λ	κ	ε	r
6	6	0	70	90	0.8mm .032in

SCALE 50:1

Figure 26. Tool of Fig. 25 with crater at end of 4 min cutting time.



CRATER DEPTH

○- 0.0 μin. 0 μm
Δ- 200 μin. 5 μm
×- 400 μin. 10 μm
◆- 500 μin. 12.5 μm

Cutting Time: 4 min.

Work Material:
XC45 (0656)

Size of Cut:
3 x 0.25 mm^2
0.12 x 0.01 in^2

Cutting Velocity:
160 m/min = 525 fpm

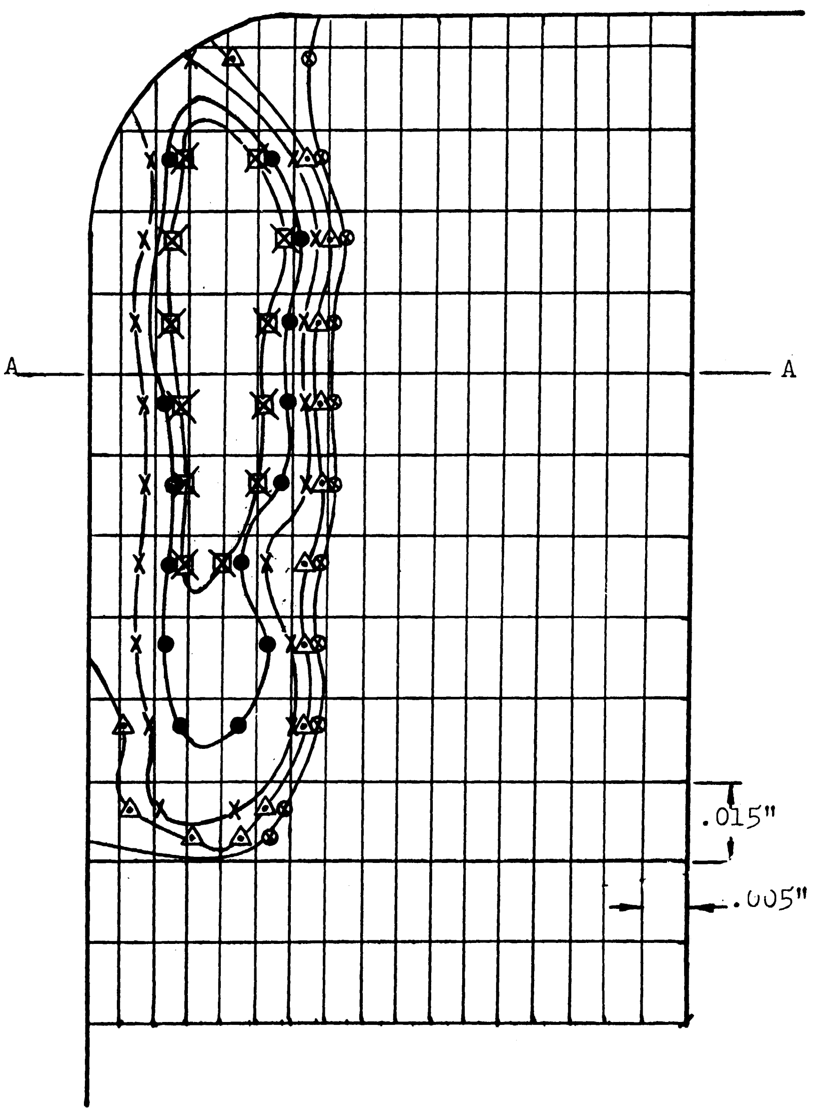
Tool Material:
P30 Carbide

TOOL GEOMETRY

α	γ	λ	κ	ε	r
6	6	0	70	90	0.8 mm .032in

SCALE 50:1

Figure 27. Mapping of crater on face of European P30 carbide grade at cutting time of 4 min with cutting conditions same as those listed in Fig. 23.



CRATER DEPTH

⊗- 0.0 μin. 0 μm

△- 200 μin. 5 μm

×- 400 μin. 10 μm

●- 1000 μin. 25 μm

☒- 1400 μin. 35 μm

Cutting Time: 8 min.

Work Material:
XC45(0656)

Size of Cut:
3 x 0.25 mm^2
0.12 x 0.01 in^2

Cutting Velocity:
160 m/min = 525 fpm

Tool Material:
P30 Carbide

TOOL GEOMETRY

α	γ	λ	χ	ε	r
6	6	0	70	90	0.8mm .032i

SCALE 50:1

Figure 28. Tool of Fig. 27 with crater at end of 8 min cutting time.

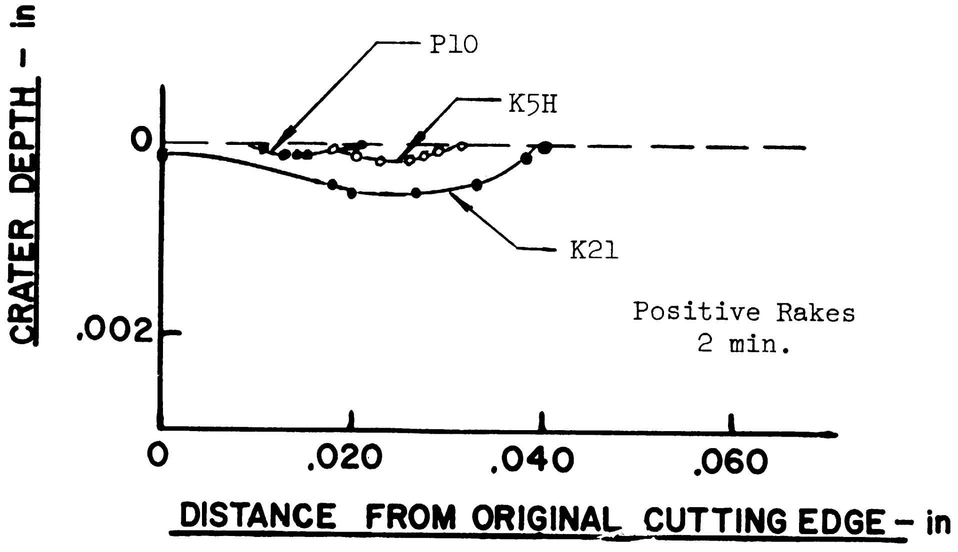


Figure 29. Crater profiles along line AA from Figs. 23 through 25 for positive rake carbides.

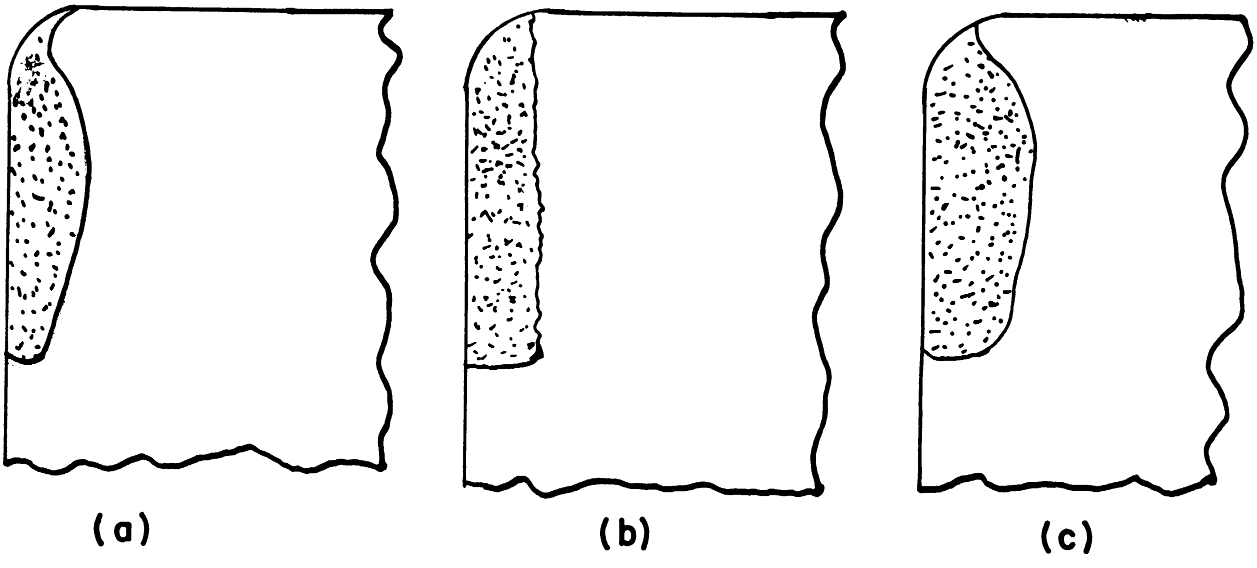


Figure 30. Representative crater wear patterns found in wear studies of various carbides; (a) typical of P10, (b) typical of P30, (c) typical of American grades to date.

depth and location of the crater. The actual maximum crater depths along line AA were 190 μ in. and 120 μ in. for the K5H and P10, respectively, but the distances from the maximum depth locations to the existing cutting edges also differed by the same proportion. Therefore, the crater ratios were still similar.

Whether these relationships between the crater and crater ratio are typical or merely coincidental is not known at this time because of the limited experience in the use of crater ratio as a criterion of tool life. In the previously cited example, illustrated in Figure 12, the smaller craters were accompanied by lower crater ratios. However, these were related to the same cutting tool material. If the same crater ratio can represent different crater conditions, particularly when, say different carbides are compared, what does it imply? The answer to this question is undoubtedly of more importance in relating wear phenomena than in practical application to determination of tool life. The significance of these measurements and observations is covered briefly in a closing section.

E. NEGATIVE RAKE VS. POSITIVE RAKE ANGLES

Only one carbide, K21, was common to both negative and positive rake angle tools. As a result, the information is not very conclusive. However, the positive rake tool showed a wider and deeper crater, as indicated in Figure 31, and more edge wear around the nose. There was no difference in flank wear.

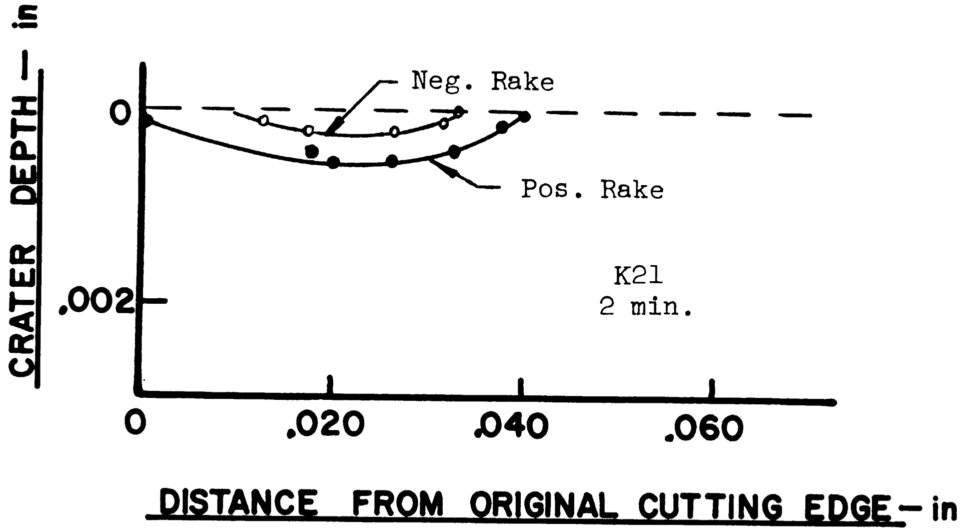


Figure 31. Comparison of crater profiles along line AA for negative and positive rake tools.

F. SIGNIFICANCE OF CRATER WEAR MEASUREMENTS

Tracing and plotting of crater profiles is a tedious and time consuming task. Therefore, if the time is to be well spent, the results themselves must serve a useful purpose. The most logical and the most important purpose is to contribute information which may be used to develop a general relationship between wear behavior and various metal cutting parameters.

Tool wear is an extremely complex phenomena. It is complex because it is related to a number of simultaneous causes which are themselves affected by cutting conditions and which, in turn, influence wear rates. The investigation of cutting temperatures, particularly temperature distributions at the tool-chip interface, will play a prominent role in the study of wear behavior. This will lead to improved efficiencies, not only in cutting processes, but in tool materials as metallurgists learn more and more about the kind of properties that are required. If cutting temperatures influence the rate of wear, it follows that temperature distributions will influence the pattern of wear. Therefore, the shape, size, and depth variations of the crater, and the location of critical depth regions with respect to cutting conditions, provide useful information for correlated studies.

PART III

WEAR ON AMERICAN AND EUROPEAN HIGH SPEED STEEL TOOLS IN MACHINING XC45 STEEL

I. EUROPEAN HIGH SPEED STEEL TOOLS

Of the many phases included in the OECD/CIRP international cooperative program, investigations of tool wear and tool life with European high speed steel cutting tools have proved to be the least successful. Large and inconsistent variations in results have been the rule rather than the exception, not only among participating laboratories, but from test to test in individual laboratories. Consequently, only limited progress has been made.

Most of the blame for the inconsistent results has fallen upon the high speed steel selected for these investigations. Some remedial measures have been taken, but results are still not acceptable.

A. TEST PROCEDURE

Test procedures are identical to those used in the carbide tests. Total failure often served as the criterion for tool life, but flank wear values of 0.2 and 0.4 mm (.008 in.-.016 in.) and crater ratios of 0.1 and 0.2 were used when possible.

B. TOOL MATERIAL

The tool material selected for this program is a cobalt grade EW9Co10 (German designation) high speed steel with the chemical analysis shown in Table II, and the heat treatment indicated in Table III. The finished tools were 23.5 mm (0.94 in.) square by 145 mm (5.8 in.) long overall, with a H.S.S. section 35 mm (1.4 in.) long butt welded to a regular steel shank. The Jessop-Saville works in Sheffield, England made the steel, and the Rohn works in Sassenheim, Netherlands made the tools and carried out the heat treatment. Professor Pekelharing of the Technological University of Delft was responsible for carrying out the coordinated effort. The information in this section is taken from his report "The Manufacture and Testing of Butt-Welded H.S.S. Tools for CIRP Group "C," July, 1963.

A great deal of effort went into the production of the tools. Ingots, billets, and bars were all marked and related. Inclusions, grain size, and carbide distribution were observed, and only those bars which fulfilled all of the requirements were selected for final processing. However, variations were still apparent, for the tools gave very erratic results. Variations of 25:1 were encountered in tool life tests at given cutting conditions.

TABLE II. CHEMICAL COMPOSITION OF EUROPEAN HIGH SPEED STEEL

GRADE (German)	Chemical Composition, %										
	C	Mn	Si	S	P	Ni	Cr	W	V	Co	Mo
EW9 Co10	1.3	0.33	0.30	0.009	0.014	0.16	4.54	9.65	3.58	10.10	4.00

TABLE III. HEAT TREATING CYCLES FOR EUROPEAN H.S.S. TOOLS

Treatment	Temperature and Time
Preheat	Up to 450°C(842°F) for 1 hr
1st Salt Bath	850-900°C(1562°-1652°F) for 4 min
2nd Salt Bath	1200°C(2192°F) for 4 min
Salt Quench	550°C(1022°F) for 4 min and air cool
Multiple Temper	590°C(1094°F)
Tempering Time, hr	$\frac{1}{2} + \frac{1}{2}$
Hardness, Rc	64.5 - 65

After the large dispersions were reported, the "Metal Cutting" committee of CIRP decided to make 20 solid tools to eliminate any possible effects of welding, and to modify heat treatment slightly to improve carbide distribution for more homogeneous structures. One of these changes was to raise the austenitizing temperature to 1220°C (2228°F). Information is not available on other changes made, but results were not improved appreciably.

C. TEST RESULTS

Figures 32 and 33 represent sample results of typical behavior encountered in the high speed steel investigations. These were compiled at the Aachen and Liege laboratories from tests on the 20 revised tools. The tool identification numbers 11A1 through 11A20 are code numbers to relate the tool to the ingot and billet from which it came:

11 = Ingot No. 11
A = Billet No. 1
1-20 = position of tool along bar, starting at the bottom

Figure 32 shows a variation in tool life among the tools from 12.5 min to more than 80 min at which point four tools had not yet failed. There is no prominent correlation evident between tool life and Vickers hardness. Figure 33 shows little if any correlation between tool life and flank wear or crater ratio. The dashed lines represent the range of values among all tools. Other results not included, show that relative tool lives are unpredictable among the tools, as complete reversals in position can occur.

Four of the tools, 111A14, 15, 16 and 20 were eventually sent to The University of Michigan. The results of tool life tests based upon complete failure are shown in Figure 34. There is much less dispersion than what these same tools show in Figure 32, and what is more the relative results were better, with tool 11A16 giving consistently the best performance.

One factor which must play at least some part in the inconsistent behavior of these tools is the tool shape, itself, and in turn, its effect upon chip flow. The chip was continuous from beginning to end of cut, tended to curl around itself and the tool, and required constant attendance to keep the tool free. In a test with American H.S.S. tools, in which the same tool shape was retained, the chip was allowed to take its own course as it wound around the tool, and the tool failed in less than a minute. When the test was repeated and the chip carried off continuously with care, the tool life was 5.5 and 6.5 min in two attempts.

Tool Material: EW9 Co10

Work Material: CK 53 I

Size of Cut: 3 x 0.2 mm^2
0.12 x 0.008 in^2

Cutting Velocity: 44m/min = 144 fpm

Tool Geometry:

α	γ	λ	$\varkappa$	ε	r
6	30	0	90	87	0.5 mm 0.020"

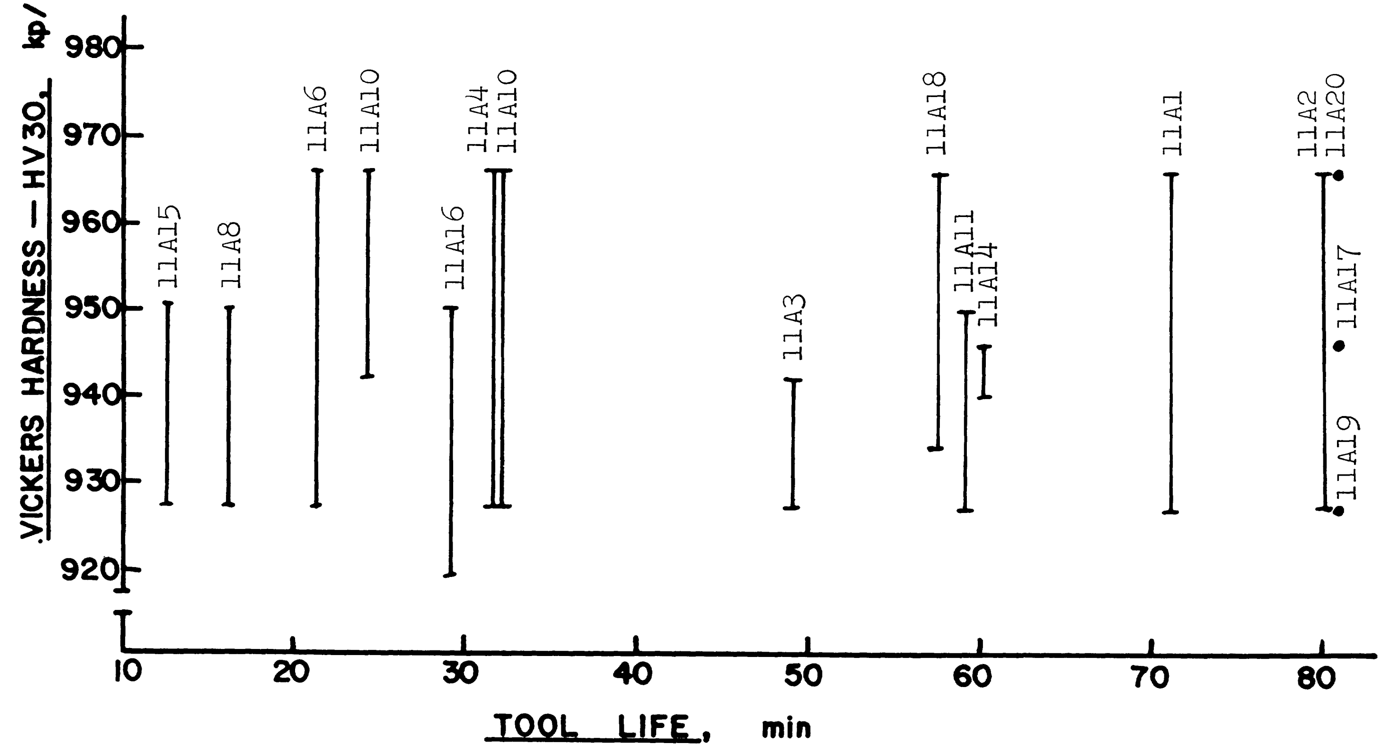


Figure 32. Range of tool life among European EW9Co10 H.S.S. tools prepared for cooperative study.

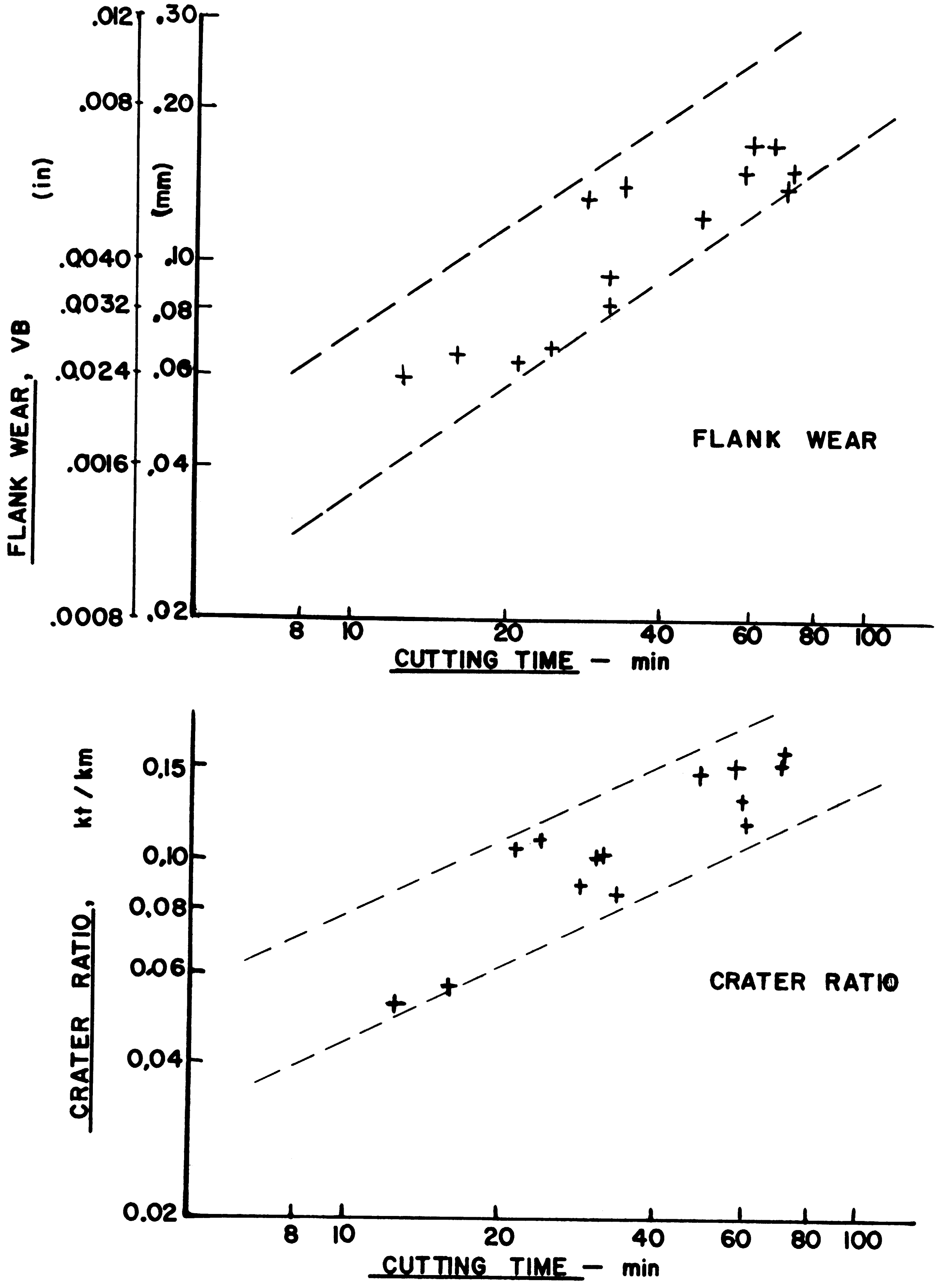
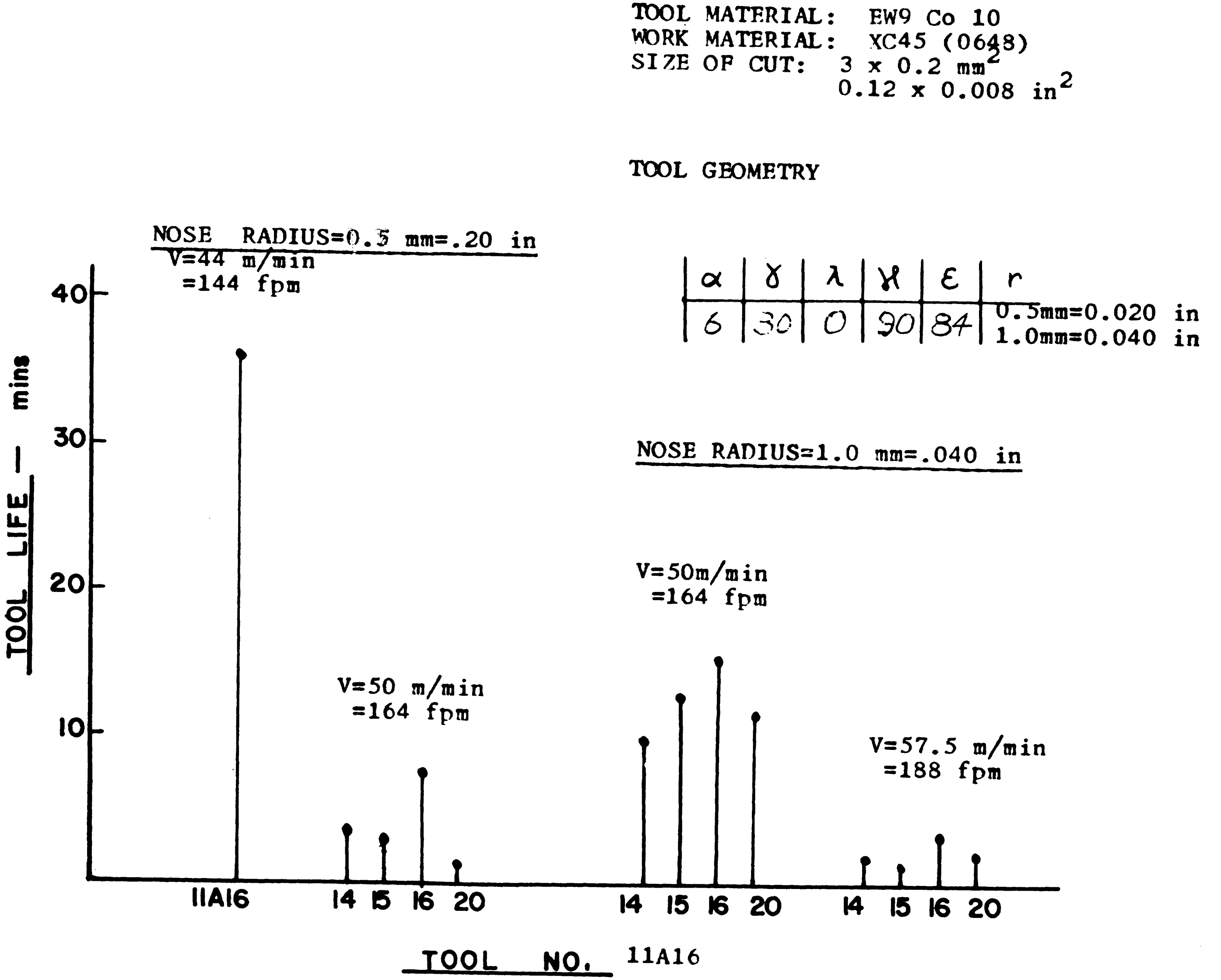


Figure 33. Flank wear and crater ratio vs. time for tools of Fig. 32. Dashed lines represent ranges of measurement on all tools. Crosses indicate values at time of tool failure.



α	γ	λ	χ	ε	r
6	30	0	90	84	0.5mm=0.020 in 1.0mm=0.040 in

Figure 34. Results of tool life tests at The University of Michigan with tools 11A14, 15, 16 and 20 of Fig. 32.

II. AMERICAN HIGH SPEED STEEL TOOLS

Partly because of the difficulty experienced by preselecting a single European H.S.S. grade, and partly because there was knowledge to be gained by using more than one composition, four American H.S.S. grades were selected for study. Testing has been confined to conventional tool life tests, with total tool failure as the criterion for tool life. General test procedures have been followed, except that flank wear and crater wear measurements were not made.

A. TOOL MATERIALS

The tools were provided by the Latrobe Steel Company in standard 1/2 in. square tool bits. The identifications, chemical analyses, and heat treating cycles are tabulated in Tables IV and V. In every grade, the tools represent the product of a single bar of steel to minimize the influence of minor variations in chemistry or mill processing. All tools were checked for hardness and found to be within the desired limits indicated in Table V. Two cobalt grades are included, although neither is directly comparable to the European steel. It may be of interest to note that the greatest apparent difference in heat treatment for the American and European tools is in tempering temperature and time.

B. TEST PROCEDURE

Tools were mounted in a 15° solid block tool holder set at 90° to the work axis. Test bars were held in a chuck at one end and supported by a live center at the other. The tool shape and the size of cut were the same as those used with the European H.S.S. tools. They remained constant for all grades in the standard tests. Elasped cutting time to total failure determined tool life.

C. TEST RESULTS

The test results are plotted in Figure 35. First it is interesting to note that the differences among all tools in Fig. 35 (c) are no more than 20%, and usually less, with respect to cutting velocity for a given tool life. This includes the European EW9Co10 grade. Also of interest, is the fact that the cobalt grades gave the most erratic behavior, which, of course, is in keeping with the experience on the EW9Co10 material. However, a change in side cutting edge angle on the Dynacut tool (which had the greatest dispersion of results with the standard tool shape) not only reduced scatter, but modified the form of tool failure from the nose of the tool to the flank. Results are plotted in Figure 35 (b). Attempts to reduce scatter of results by reducing side rake angle were not effective.

TABLE IV. IDENTIFICATION OF AMERICAN HIGH SPEED STEEL TOOLS

Quantity	Tools Numbers**	Latrobe Grade	AISI Type	Chemical Composition, %*								
				C	Si	Mn	W	Cr	Mo	V	Co	S
30	69- 98	Electrite Double Six XL	M-2	0.84	0.31	0.25	6.30	4.07	5.04	1.79	-	0.012
30	99-128	Electrite Crusader	M-3	1.21	0.25	0.26	5.53	4.13	5.41	3.18	-	0.012
31	1- 31	Electrite Dynacut	M-43	1.17	0.37	0.27	2.40	3.74	7.60	1.57	7.75	0.018
37	32- 68	Electrite Super Cobalt	T-5	0.85	0.23	0.33	18.43	4.18	0.74	1.94	7.97	0.017

*Supplied by Latrobe Steel Company

**Inclusive

TABLE V. HEAT TREATING CYCLES FOR AMERICAN H.S.S. TOOLS*

Treatment	Electrite Double Six M-2	Electrite Crusader M-3	Electrite Dynacut M-43	Electrite Super Cobalt T-5
Preheat (Salt)	1550°F	1550°F	1550°F	1550°F
Austenitize (Salt)	2220°F	2220°F	2175°F	2300°F
Salt Quench	1050°F	1050°F	1050°F	1050°F
Air Cool	125°F	125°F	125°F	125°F
Multiple Temper	1025°F	1025°F	1000°F	1025°F
Tempering Time, hr	2+2	2+2	2+2+2	2+2
Hardness Aim, Rc	64-66	65-67	68-70	64-66

*Supplied by Latrobe Steel Company

The results seem to imply that the behavior of the cobalt grades is due to other than normal wear processes. These grades are sensitive to vibrations, particularly when less-than-optimum tool shapes are used. Future studies should include investigations of tool shape and its influence on the relative behavior of these tools.

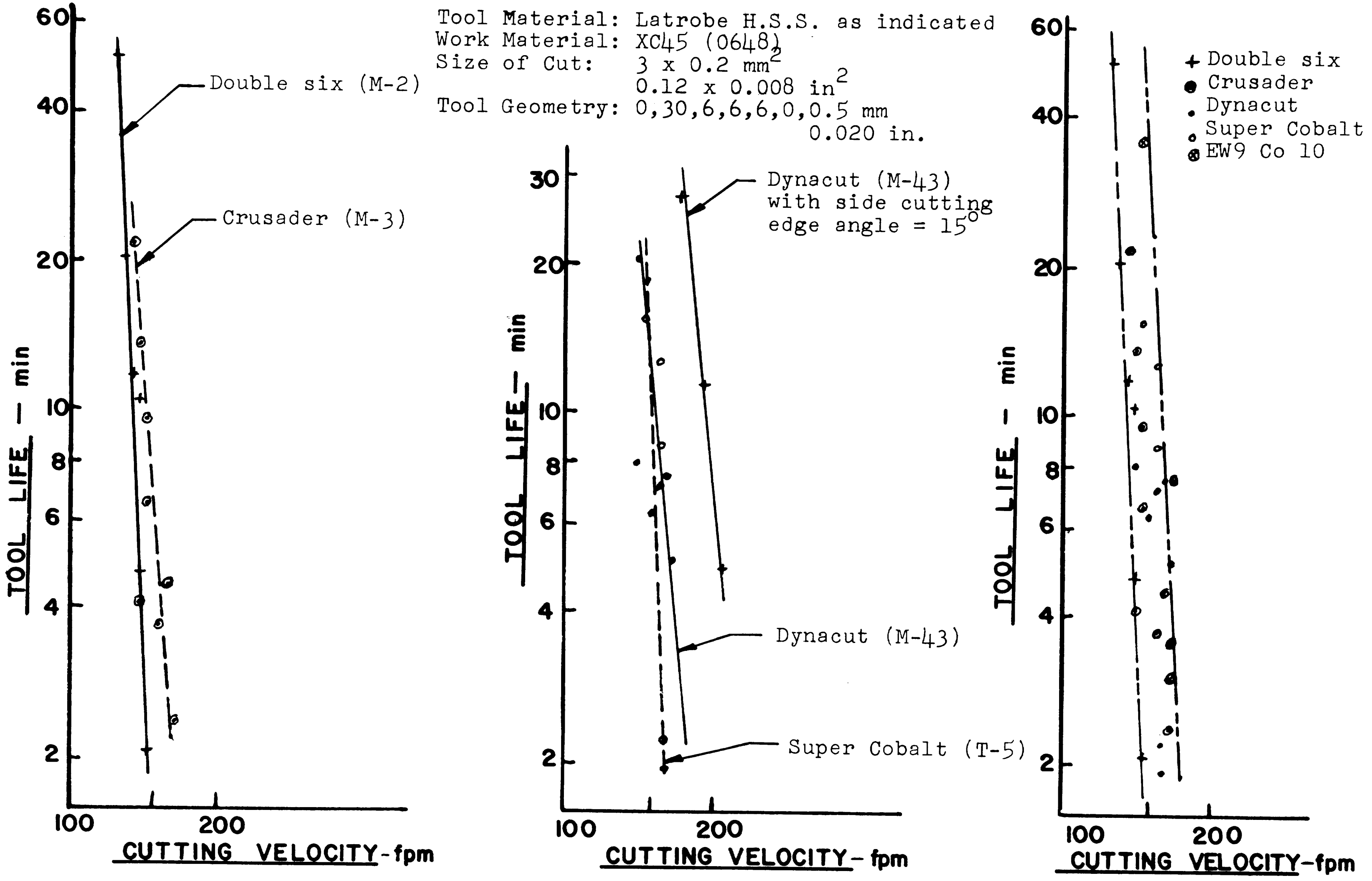

Tool Material: Latrobe H.S.S. as indicated
Work Material: XC45 (0648)
Size of Cut: 3 x 0.2 mm^2
0.12 x 0.008 in^2
Tool Geometry: 0,30,6,6,6,0,0.5 mm
0.020 in.

Figure 35. Results of tool life tests with American H.S.S. tools.

PART IV

ACCELERATED TESTS FOR RATING HIGH SPEED STEEL TOOLS

Almost without exception, the most useful machinability data which are currently available have come from long extended laboratory evaluations, or have resulted from long experience in the observation of on-the-job performance. The desirability of a short time test procedure which would provide a valid machinability evaluation is, therefore, self-evident.

Some preliminary studies of a short time technique were to have been included for high speed steel tools in this phase of the international co-operative research program, but the problems encountered in the high speed steel program in general made it advisable to postpone this series until the problems are resolved. However, the groundwork for the accelerated test program has been laid by previous investigations in Europe and The University of Michigan. Two techniques are described. Both involve a variation in cutting velocity, but one technique uses a stepped variation in geometric progression, while the other employs a continuously varying velocity.

I. GEOMETRICALLY STEPPED CUTTING SPEEDS

This technique is being used by Professor E. Bodart of the University of Liege. The following information is a translated version of his paper "Correlation des Resultats entre une Methode Rapide de Mesure de l'Usinabilite et les Essais de Longue Duree" (Correlation of Results Between a Rapid Method of Measuring Machinability and Tests of Long Duration) which appeared in CIRP-Annals of February, 1963 (Volume X).

A. INTRODUCTION

For given cutting conditions (tool material, tool geometry, work material, chip geometry) the durability of the cutting tool can be represented by V_{60}, the cutting speed for which the tool has a life of 60 min. The Taylor relation is $VT^n = C$. For given cutting conditions, tests are run at different cutting speeds, and the time to total tool failure is recorded. In this manner several tests, 7 or 8 for example, are run at different speeds. Tool lives fall, generally, between 8 to 80 min.

This classical method of determining V_{60} is very reliable, and is little influenced by local variations in work material characteristics; on the other hand, it is rather long and laborious, and it requires several tools and a fairly large quantity of steel. Several researchers have tried to find more rapid methods of measuring V_{60}. The method used here simulates the wear that the tool would have undergone in a normal test.

B. DESCRIPTION OF THE METHOD

The method consists of making cylindrical turnings with the same tool at cutting speeds increasing discontinuously following a geometric progression with a ratio 1:1.12; therefore, the cutting speeds are stepped according to a normal series (Renard series) with a ratio 1: $\sqrt[20]{10}$.

An initial cutting speed, V_o, definitely smaller than the cutting speed V_{60}, is selected. This cutting speed, V_o, is used for 0.2 min, then a cutting speed $V_1 = V_o \times 1.12$ is used for 0.2 min, and so on, up to a cutting speed $V_k = V_o \times (1.12)^k$, for which the tool fails in less than 0.2 min. Therefore, the tool fails after having been used for:

0.2 min at the cutting speed, V_o,
0.2 min at the cutting speed, V_1,
0.2 min at the cutting speed, V_2, and
T_k min at the cutting speed, V_k.

The deterioration (wear) of the tool during these different periods has to be taken into account. To this end, the following hypothesis is made: Let T_{k-1} be the cutting time which, for the cutting speed V_k would correspond to 0.2 min of cutting at the cutting speed V_{k-1} (respectively, the cutting time T_1, for the speed V_k, would correspond to 0.2 min of cutting at the speed V_1). Assuming that the relation $VT^n = C$ can be used, we have:

$$V_{k-1}\,(0.2)^n = V_k(T_{k-1})^n$$

$$V_1\,(0.2)^n = V_k(T_1)^n$$

for which

$$\frac{V_k}{1.12}\,(0.2)^n = V_k(T_{k-1})^n$$

$$\frac{V_k}{1.12^{(k-1)}}\,(0.2)^n = V_k(T_1)^n$$

Knowing the value of the exponent n (let n = 0.08), it is deduced that:

$$\begin{aligned} T_{k-1} &= 0.0475 \text{ min} \\ T_{k-2} &= 0.0113 \text{ min} \\ T_{k-3} &= \underline{0.0026 \text{ min}} \\ & 0.0614 \text{ min} \end{aligned}$$

Therefore, the calculated times [equivalent times at speed V_k] T_{k-1}, $T_{k-2}, \ldots,$ are added to the time T_k, which is found experimentally at the speed

V_k. Times smaller than .001 min are disregarded. It is sufficient to add 0.06 min to the time T_k, providing that tool failure occurs during the fourth period or a following period.

The first periods during which the tool is used correspond to very small equivalent times T_1, $T_2, \ldots$, that have little bearing on the value to be added to the experimentally determined time T_k. However, these first periods are rather important, it is during this time that the tool adapts itself to the cutting conditions. Therefore, an initial cutting speed must be chosen such that tool failure will occur after at least 9 or 10 speed increments. For certain grades of steel and certain machining conditions, V_{60} is known in advance within 15% margin of error; therefore a starting speed can be determined accurately to allow 10 steps to failure. The initial speed would be equal to 0.4 x V_{60}.

C. CONDITIONS OF TEST

The adopted criterion for tool life is V_{60} (cutting speed for which the tool has a life of 60 min). The tests have been run in dry turning at a depth of cut of 2 mm (0.080 in) and a feed of 0.2 mm/rev (0.008 ipr). The tool geometry is as follows:

α	γ	λ	χ	ϵ	r
8°	27°	0°	60°	90°	0.5 mm = 0.020"

The tool material is 18-4-1 high speed steel.

D. RESULTS

The method was first used on 83 steels of different grades and of several thermal and/or mechanical treatments. The 18-4-1 high speed steel tools were taken from the same heat (lot B_1) for which the values of V_{60} and $n (n = 0.08)$ had been determined by the classic long time test. These tests gave the following relationship between V_{60} classic and V_{60} rapid:

V_{60} classic = (V_{60} rapid + 1.0) x 1.029 with a standard error σ equal to ± 8.10% (see Figure 36)

The same rapid method was used on 7 steels with different machinabilities (V_{60} ranging from 35 m/min to 113 m/min). These were machined with 18-4-1 high speed steel tools from the same heat (lot B_2) for which the values of V_{60} and n $(n = 0.05)$ were known. These tests gave the following relationship:

V_{60} classic = (V_{60} rapid - 0.7) x 0.928 with a standard error σ equal to ± 3.20% (see Figure 37)

The rapid test was also used to determine the machinability of a C30 m steel. With n = 0.065, the V_{60} rapid is 3.9% smaller than V_{60} based upon long time tests; the standard error, σ, is ± 7.75%.

In order to run these rapid tests, the lathe must have stepped speeds in the ratio of 1:1.12, or must be equipped with a variable speed drive. Such lathes are not normally used in workships, but there are lathes in which spindle speed is graduated in a geometric progression with a ratio of 1:$\sqrt[10]{10}$ or 1:1.26.

A lathe with the 1:1.26 ratio was used with 6 of the 7 steels previously reported in Figure 37 for a ratio of 1:1.12. These were machined with the same lot of tools, and it is noted, in Figure 37 that similar results are achieved with either speed ratio.

E. CONCLUSIONS

There is generally good correlation between the classic long time method and the rapid method, but there are exceptions. However, it presents a definite practical interest for:

a. A rapid evaluation of machinability, allowing the most favorable cutting conditions,

b. a test of practical acceptance, and

c. the rapid examination of a large number of steels.

II. CONTINUOUSLY VARIABLE CUTTING SPEEDS

This particular technique probes into relationships between cylindrical turning, or the classic method of evaluation, and taper turning and facing. The following information is taken from work performed at The University of Michigan, including ASME paper 62-WA-281, "Tool Life for Cuts Wherein the Cutting Speed Varies During the Cut," by Professors L. V. Colwell and J. C. Mazur.

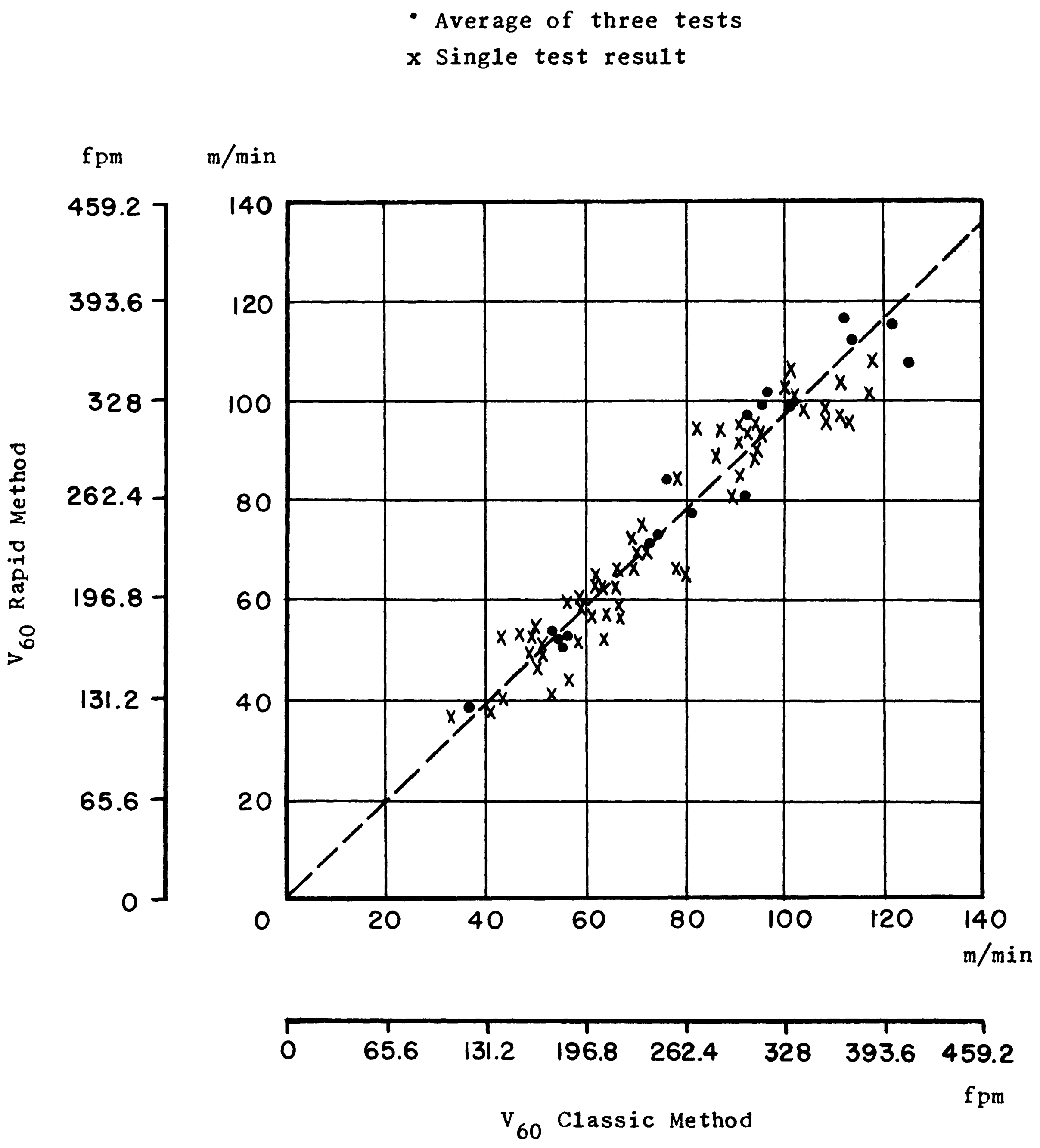


Figure 36. Correlation between rapid method and classic method of evaluation for 83 steels of different grades and of several thermal and/or mechanical treatments.

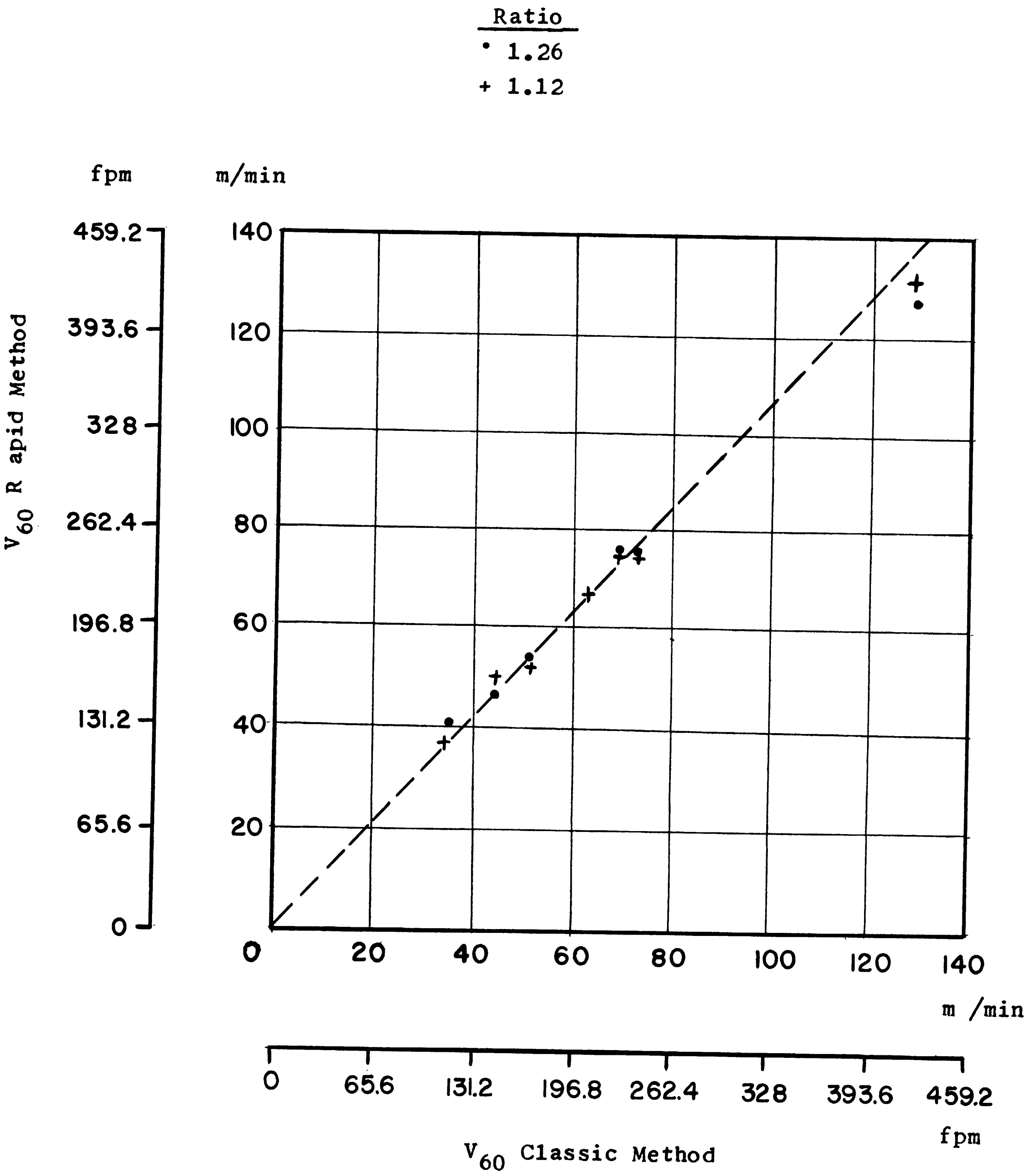


Figure 37. Correlation between rapid method and classic method of evaluation for seven steels using two incremental speed ratios.

A. THEORETICAL RELATIONSHIPS

The initial theoretical concept is based upon the assumption that the life of a cutting tool is dissipated linearly with cutting time. This implies, for example, that a tool could be used for say 50% of the tool life at a velocity of V_1, 25% of the tool life at a velocity V_2, and the tool would then fail after cutting for 25% of the tool life at another velocity V_3. Therefore,

$$\frac{\Delta T_1}{T_1} + \frac{\Delta T_2}{T_2} + \frac{\Delta T_3}{T_3} + \ldots\ldots = 1 \quad \text{or} \quad \sum \frac{\Delta_i}{T_i} = 1 \ .$$

When the velocity varies uniformly as in taper turning or facing at a constant RPM, the time intervals would be infinitely small and the relationship would be expressed as:

$$\int_o^{t_f} \frac{dt}{T} = 1 \qquad (1)$$

where

dt = differential of elapsed time during cutting

T = total tool life corresponding to cylindrical turning

t_f = actual elapsed cutting time to total tool failure

From Taylors equation, $VT^n = C$,

$$T = \frac{C}{V}^{\frac{1}{n}} = \frac{C}{2\pi RN}^{\frac{1}{n}} \qquad (2)$$

For taper turning,

$$t = \frac{12\ (R-R_o)\ \cot \theta}{Nf}$$

and

$$dt = \frac{12 \cot \theta\ dR}{Nf} \qquad (3)$$

where

R = radius of workpiece at certain interval, ft

R_o= radius at beginning of cut, ft

N = spindle RPM

f = feed rate, ipr

θ = 1/2 included taper angle

t = cutting time at given point.

After substitution of Eqs. (2) and (3), integration of Eq. (1) from R_o to R_f, the radius at failure, yields the following derived expression for taper turning:

$$NR_f^{\frac{1+n}{1-n}} = \left[\frac{Cf^n}{2\pi}\left(\frac{1+n}{12n \cot \theta}\right)^{n}\right]^{\frac{1}{1-n}} \qquad (4)$$

Equation (4) applies to facing when $\cot \theta = 1$. [Note: R_o does not appear in the final equation because in the integration the term $R_o \exp (n+1/n)$ is $\ll R_f \exp (n+1/n)$ and can be neglected.]

B. LABORATORY EVALUATION

To evaluate the concepts of the preceding section, tool life tests in cylindrical turning, taper turning, and facing were performed at the following conditions:

work material: 1045 H.R. steel
tool material: T-1 H.S.S.
tool geometry: 0, 22, 6, 6, 6, 0, 0.020 in.
feed : 0.0115 ipr
depth of cut : 0.040 in.

In each case, tools were run to complete failure in a continuous cut. Facing started from a hole diameter of 1.25 in. Tapers were 3 in./ft, with initial diameters as low as 1 in. Maximum work diameter was 8 in.

C. TEST RESULTS

The average values of as many as 10 tool life tests at each spindle speed are plotted on logarithmic coordinates in Figure 38 for both taper turning and facing. It is seen that the results can be represented by an equation of the form

$$NR_f^{m} = K_t \qquad (5)$$

where "m" is the absolute slope of the line.

Equation (5) and Eq. (4) have the same format. Therefore, for taper turning,

$$m = \frac{1+n}{1-n}$$

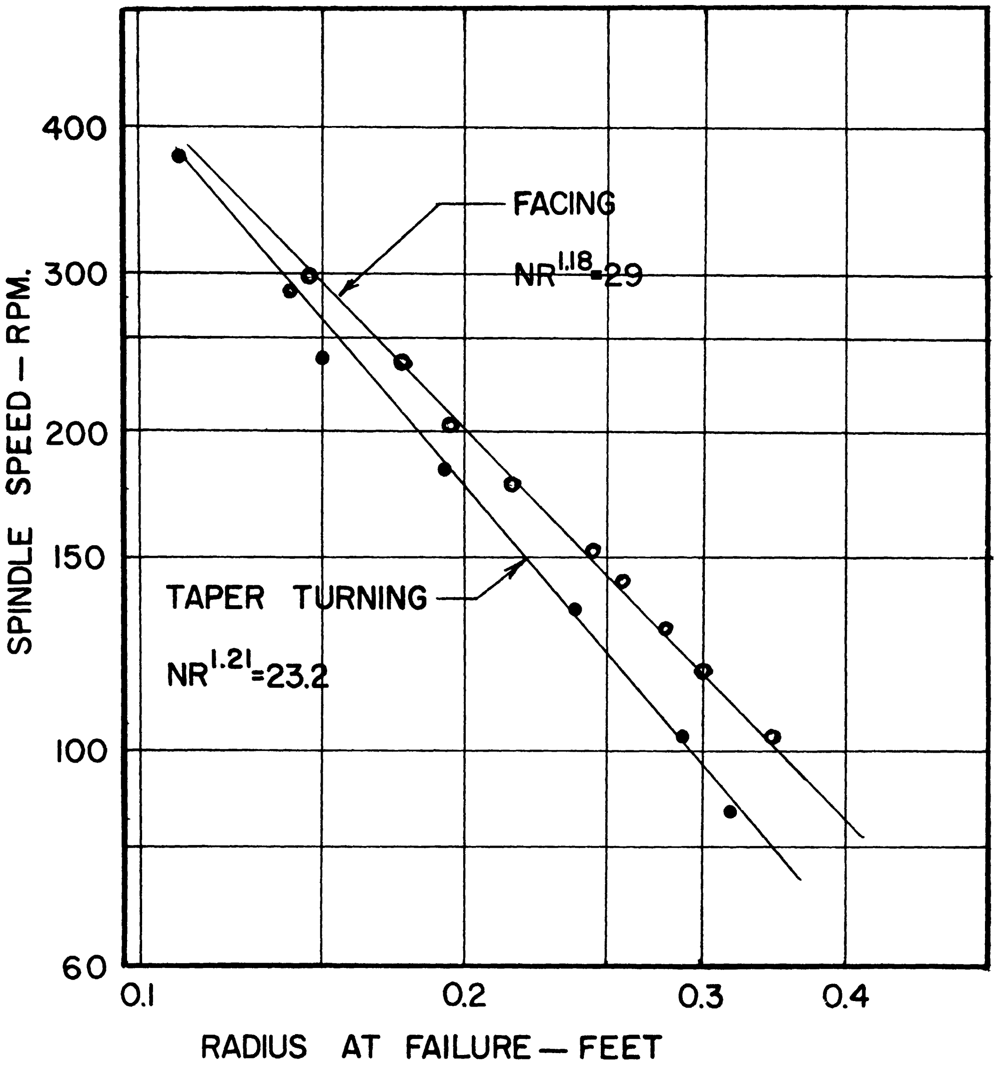


Figure 38. Taper turning and facing results under test conditions. Points are averages of a number of tests. Taper 3 in/ft.

and $$K_t = \left[\frac{Cf^n}{2\pi}\left(\frac{1+n}{12n \cot \theta}\right)^n\right]^{\frac{1}{1-n}}$$

Consequently, it is possible to predict "m" and "K_t" for taper turning if "n" and "C" are known from Taylors equation for cylindrical turning; or, Taylor's expression can be derived if the taper turning equation is known. The same holds true for facing as well. Table VI shows the comparison between actual results determined by experiment, and the corresponding equation for each operation as predicted from the results of the other two.

TABLE VI. COMPARISON OF ACTUAL VS. PREDICTED TOOL LIFE EQUATIONS WHEN CYLINDRICAL TURNING, TAPER TURNING, AND FACING 1045 H.R. STEEL AT TEST CONDITIONS

Operation	Directly from Experiment	Equations as Predicted from Results of:		
		Cylindrical Turning	Taper Turning	Facing
Cylindrical Turning	$VT^{0.10}=205$		$VT^{0.095}=204$	$VT^{0.083}=198$
Taper Turning	$NR^{1.21}=23$	$NR^{1.22}=23$		$NR^{1.18}=24$
Facing	$NR^{1.18}=29$	$NR^{1.22}=29$	$NR^{1.21}=29$	

Undoubtedly, within the range of cutting conditions used, the correlation between actual and predicted values is very good. Other tests indicate that the correlation holds for wide feed ranges and for several other materials which were available. However, additional studies are required to evaluate the technique as a short time test.

D. CONCLUSIONS

a. Cutting behavior is predictable wherein the velocity varies during the cut.

b. Theoretical equations based upon the assumption that tool life is dissipated linearly with time appear to give good correlation among cylindrical turning, taper turning, and facing results.

c. The results indicate common dependency of all three types of operations on the same differential equation.

III. PROPOSED TESTS

The accelerated test program is set up to be carried out on a LeBlond tape-turn lathe. The unique capability of a numerically controlled lathe adds convenience and versatility to the various techniques.

The increasing velocity techniques will be used in the formal program, but it is also desirable to know whether the temperature increase associated with progressively increasing feed rates at constant speed will accomplish the same result. It is feasible that this approach might yield confident evaluation in substantially shorter time than the conventional Taylor tool life test. The increments of feed rate are small enough to produce a smoother transition of temperature during a test cycle, in contrast to the somewhat coarser steps of cutting speed reported by the European laboratories.

One disadvantage of using taper turning and facing for continuously varying cutting velocity is that both operations become less accurate as the diameters of the workpieces decrease. Consequently, the unique capability of a numerically controlled lathe for programming increasing spindle speeds and increasing feed rates offers a facility for overcoming the problems peculiar to both techniques. Preliminary tests have given repeatable information.

PART V

SUMMARY OF HISTORY AND RESULTS OF INTERNATIONAL COOPERATIVE RESEARCH IN METAL CUTTING

I. INTRODUCTION

This project constitutes a segment of participation on the part of the United States in an international cooperative research program in metal cutting. The program has the political support of the Organization for Economic Cooperation and Development (OECD), and is under the technical guidance and direction of a committee of "experts" from the International Institution for Production Engineering Research (CIRP). It has been underway for approximately four years and has developed a significant body of information on the machining of normalized plain carbon steel.

The CIRP believes that scientific explanations can be found for operator skills and proposes to find them so as to relieve mankind of the need to relearn the same skills with each succeeding generation. Further, it believes that a scientifically based technology such as can be developed from finding these explanations is the only means through which modern high speed digital computers, numerical control, and adaptive control can achieve their full potential for increasing needed productivity. This is its objective.

Eleven of the twenty-two member countries of the OECD are engaged in various phases of study including surface finish, forces and energy, mechanics of cutting, cutting temperatures, and tool wear in addition to detailed analyses of the work and tool material. The OECD/CIRP activity is expected to continue for an extended period, and will cover several work materials and several processes.

This particular contract was set up essentially to participate in that part of the OECD/CIRP program devoted to the wear of sintered carbide and high speed steel cutting tools in turning. It covers substantially only European tools and a European source of normalized 1045 steel as the work material. However, several commercial grades of American H.S.S. and carbide tools have been introduced to provide a link with the main body of information being developed by the international program, and to investigate laboratory techniques and analytical procedures for producing technological information of use to American industry.

In addition to the substantial support provided by the United States Air Force through the medium of this contract, the Latrobe Steel Company and Kennamental, Inc. are cooperating by providing cutting tools, technical assistance, and the analytical capabilities of their own laboratories. The Micrometrical Division of Bendix Corporation supplied use of a Proficorder for tool wear measurements. It is only through such voluntary cooperation within each country that the OECD hopes to broaden and extend the total program to a successful conclusion.

II. INTERNATIONAL COOPERATIVE RESEARCH PROGRAM ON TOOL WEAR

A. SPECIFIC OBJECTIVES AND APPROACH OF THE OECD

The planners of the overall program recognized that the same problems which beset early attempts at international cooperation in chemistry, physics, metallurgy, electronics, and other branches of science would also have to be overcome in this venture. They realized also that no plan can successfully anticipate the nature of all the results to be expected from a thoroughly fundamental research program. Consequently, the initial stages of the plan consisted of a simple and cautious beginning.

It was decided to start with a simple, common work material and conventional tool materials in simple lathe turning. The guiding objective was a high degree of uniformity. Therefore, the tools and the work material were to be acquired from single sources and evaluated as to uniformity. Further, the test protocol or analytical procedure was specified in substantial detail.

The laboratory program was divided into two parts, the Standard Program and the Main Program. The Standard Program was to be carried out by all laboratories so as to get an indication of the dispersion that still persisted among laboratories despite rigid standardization of materials and practices. It was intended also as a means toward correction of unusual or unexpectedly large deviations from a common average. The Main Program was to be shared cooperatively, but with sufficient duplication for a check on results.

The initial plan was scheduled in three phases:

Phase 0. Procurement and standardization
Phase 1. Comparative study of one steel by all participating laboratories to test and correct the proposed analytical and experimental methods in order to assure agreement among laboratories
Phase 2. Study of steels of different microstructures and properties.

Phase 0 of the program was carried out during 1961 and 1962. This involved the selection, manufacture and evaluation of the initial work and tool materials, the development of standard test methods, the comparison of tool dynamometer calibrations, and the development of a detailed program of the tests and studies to be conducted by each laboratory. Phase 1 was initiated early in 1963 when the work and tool materials were ready for delivery. Phase 2 materials are in preparation.

A very important part of the cooperative effort has been the semiannual meeting of the OECD/CIRP coordinating committee. The oral discussions have helped to discover unusual or unexpected results which otherwise might not be reported and yet which may constitute new and rewarding directions for further research. Thus in the initial phases and in subsequent phases yet unplanned, the OECD/CIRP program can be expected not only to yield useful technological information but also to:

1. discover new directions for basic research
2. develop better analytical techniques and equipment and
3. make significant progress toward universally dependable procedures and standards which can be applied internationally.

B. WORK MATERIAL

The work material selected is a normalized XC45 plain carbon steel, which corresponds to an AISI 1045. It was electric furnace melted and continuously cast in 100 mm (4 in.) diameter bars by the French firm, "Societe des Aciers Fins de l'Est." The compositions of two heats cast for the OECD/CIRP studies are as follows:

Heat No.	C	Si	Mn	S	P	Ni	Cr	Mo	Co
Z0648	0.445	0.35	0.73	0.008	0.015	0.09	0.09	Trace	0.043
Z0656	0.440	0.41	0.71	0.010	0.015	0.09	0.08	-----	0.046

The bars were sprayed with aluminum to protect them from excessive oxidation and decarburization during heat treatment. They were heat treated in an automatic oil furnace for 45 min at a temperature of 870°C, furnace cooled to 800°C, then further cooled by moving air to 50°C in another 45 min. Typical strength properties are:

Heat No.	Ultimate Strength, kg/mm^2(psi)	Yield Strength, kg/mm^2(psi)	Elongation, %	Average Hardness Vickers
Z0648	74.3 (105,300)	47.2 (67,000)	20	195
Z0656	73.7 (104,500)	48.2 (68,500)	19.5	205

Extensive macro-and microanalyses of the structures showed Heat No. Z0648 to have a slightly more banded and coarser structure than Heat No. Z0656. However, the structures were fairly uniform and the differences were very small. On the basis of these analyses, it was determined that a "clean-up" cut of no less than 1 mm (0.040 in.) depth be taken to remove surface variations, and that cutting be stopped at a bar diameter of approximately 2 in. to stay within a uniform structure.

Studies of plasticity and related properties of both heats are being carried out at the Chalmers Technical University in Goteborg, Sweden. Figure 39 shows the location of test specimens used to determine the true stresses and strains plotted in Figure 40. Professor Olav Svahn concludes that:

1. The material in the center zone, 1, is harder than the rest.
2. Zones 2, 3, and 4 correspond fairly well.
3. Zone 4 has the least scatter while zone 3 has the largest scatter, probably due to the history of the material.
4. The curves have approximately the same slope and are parallel.

The results from both heats are in excellent agreement. These results will become part of a larger body of information on these and other materials and will be analyzed for any possible correlation between material properties and tool wear behavior.

C. CUTTING TOOLS

1. European Carbide Tools

The carbide tools selected for the OECD/CIRP study were ISO grades P10 and P30. These have the following nominal chemical compositions:

ISO Grade	Source	Source Grade	Composition, %			
			WC	TiC	TaC - CbC	Co
P10	Soderfors	N-16	71	12	12.5	4.5
P30	Widia	TT 30	82		8	10

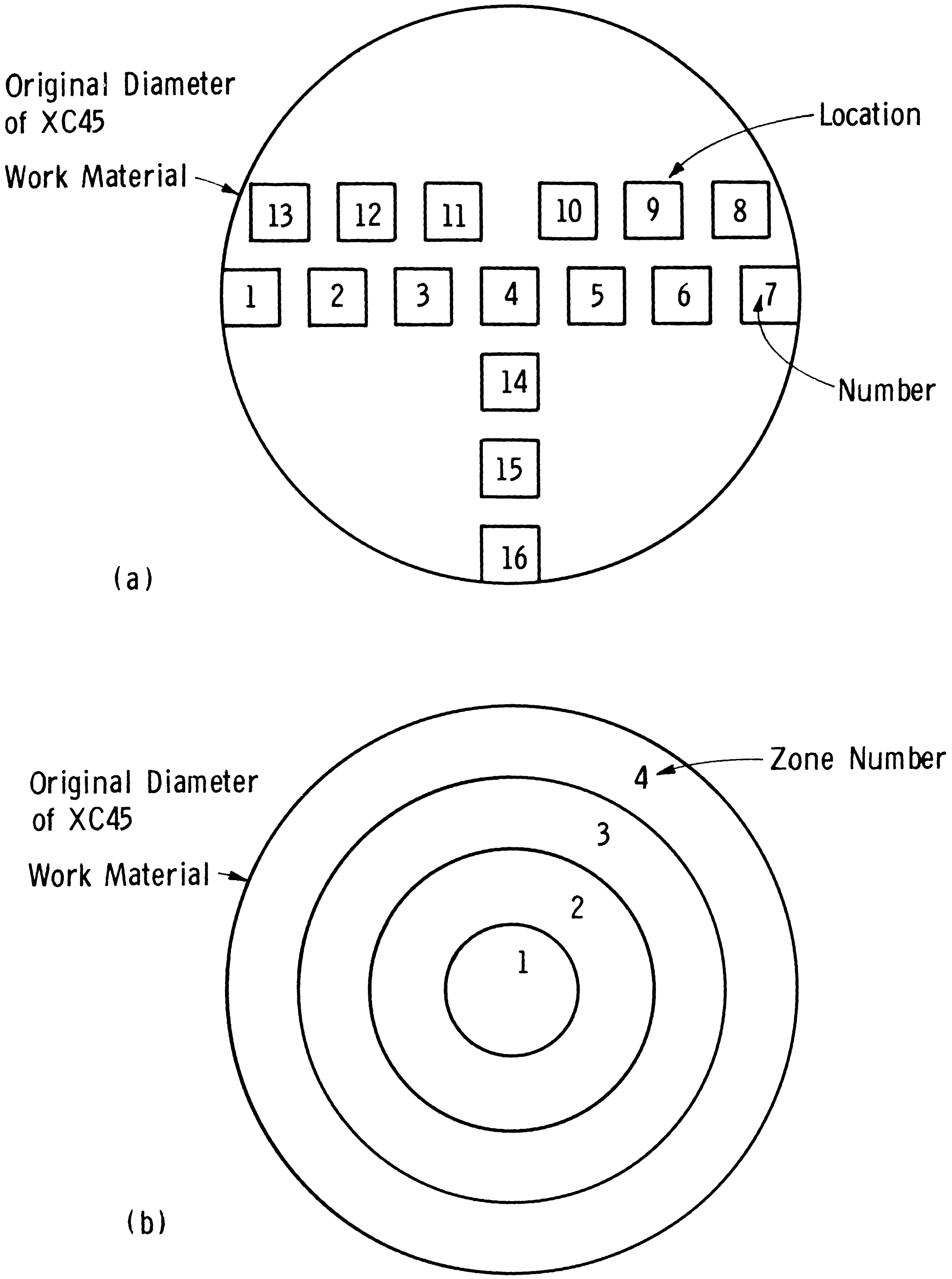


Figure 39. Locations from which both compression and tension specimens were taken for plasticity studies of XC45 work material.

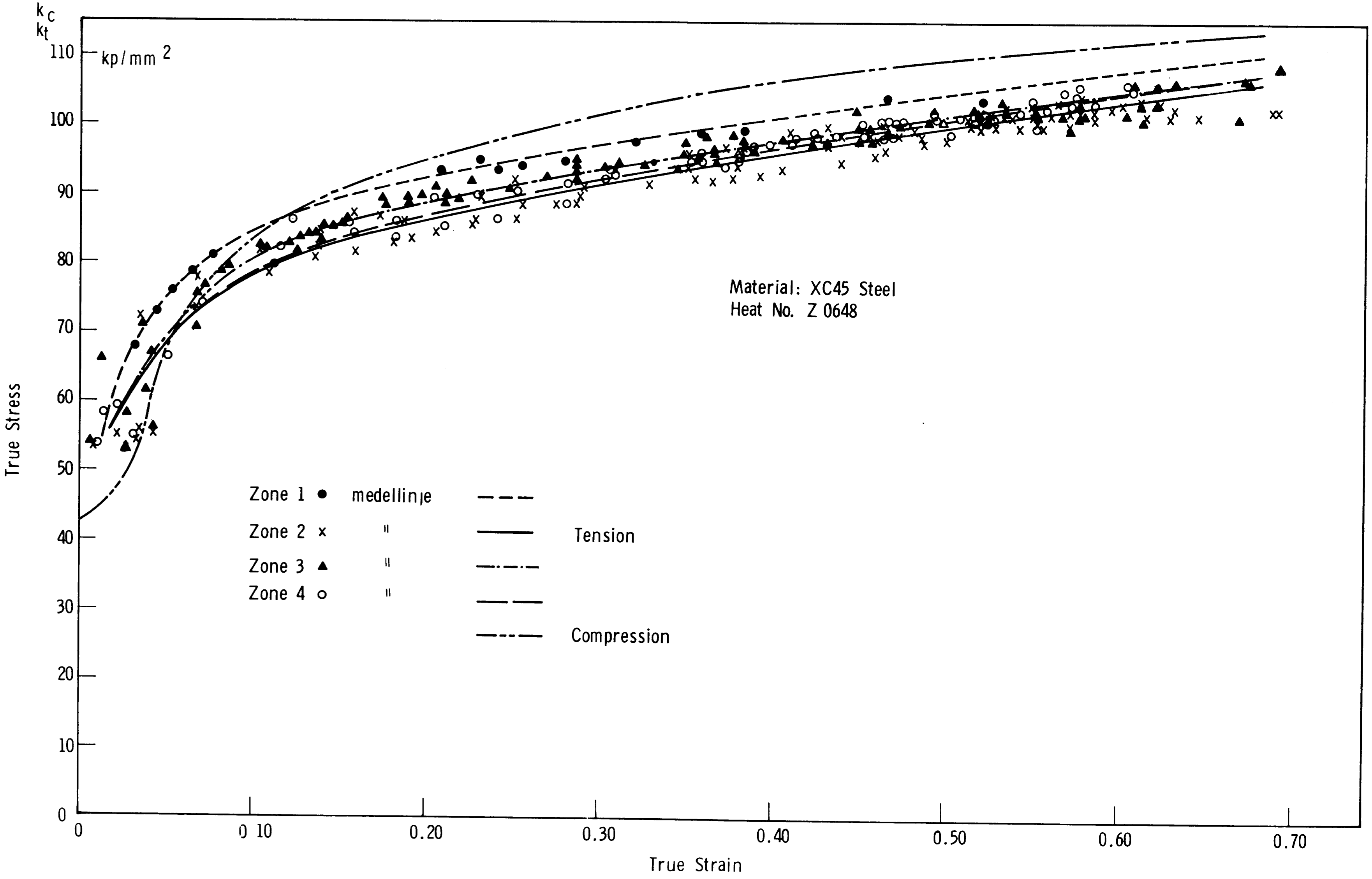


Figure 40. Results of true stress-true strain behavior of XC45 steel.

The tools were 1/2 in. square by 3/16 in. thick by 1/32 in. nose radius indexible or throw-away tips, precision ground on all surfaces for both 6° positive and 6° negative rake tool holders.

Each tool was assigned an identification number, and each tool was checked for hardness and for density to determine the degree of uniformity. The results of tests carried out at the Technical University in Aachen, Germany on the initial order of 1144 tools, Figures 41 through 44, indicate that the tools are uniform with little scatter or dispersion for either hardness or density. Evaluations performed at The University of Michigan on additional tools agreed very favorably. The Rockwell A hardness scale was selected over the Vickers test after consideration of results and various advantages and dis-advantages of both methods.

Five tool tips from each grade were selected on a sampling basis (guided however, by the extremes and averages for both hardness and density) for electron microscope investigation of microstructure. It was found that the microstructures of both carbide P10 and carbide P30 are substantially uniform, although within individual tool tips there are occasional tungsten carbide grains as large as 5.0 μ. The average grain diameter varies between 1.5 and 2.0 μ in the P10 grade, while carbide P30 has a slightly smaller average grain size ranging from 1.2 to 1.5 μ. All tools with especially high densities were shown to exhibit larger structural and hardness differences. These tips were removed from the study program.

2. European High Speed Steel Tools

The original high speed selected for the cooperative program is a high cobalt composition known as EW9Co10. It was made by the Jessop-Saville Works in Sheffield, England and processed by the Rohn Works in Sassenheim, Netherlands. It has the following composition:

Grade	Chemical Composition, %										
	C	Mn	Si	S	P	Ni	Cr	W	V	Co	Mo
EW9Co10	1.3	0.33	0.30	0.009	0.014	0.16	4.54	9.65	3.58	10.10	4.00

Rockwell C hardness is 64-65

The tools themselves are a nominal 1 in. square by 6 in. long. The first tools had approximately a 1.5 in. length of high speed steel but welded to a regular steel shank. Later tools were solid high speed steel.

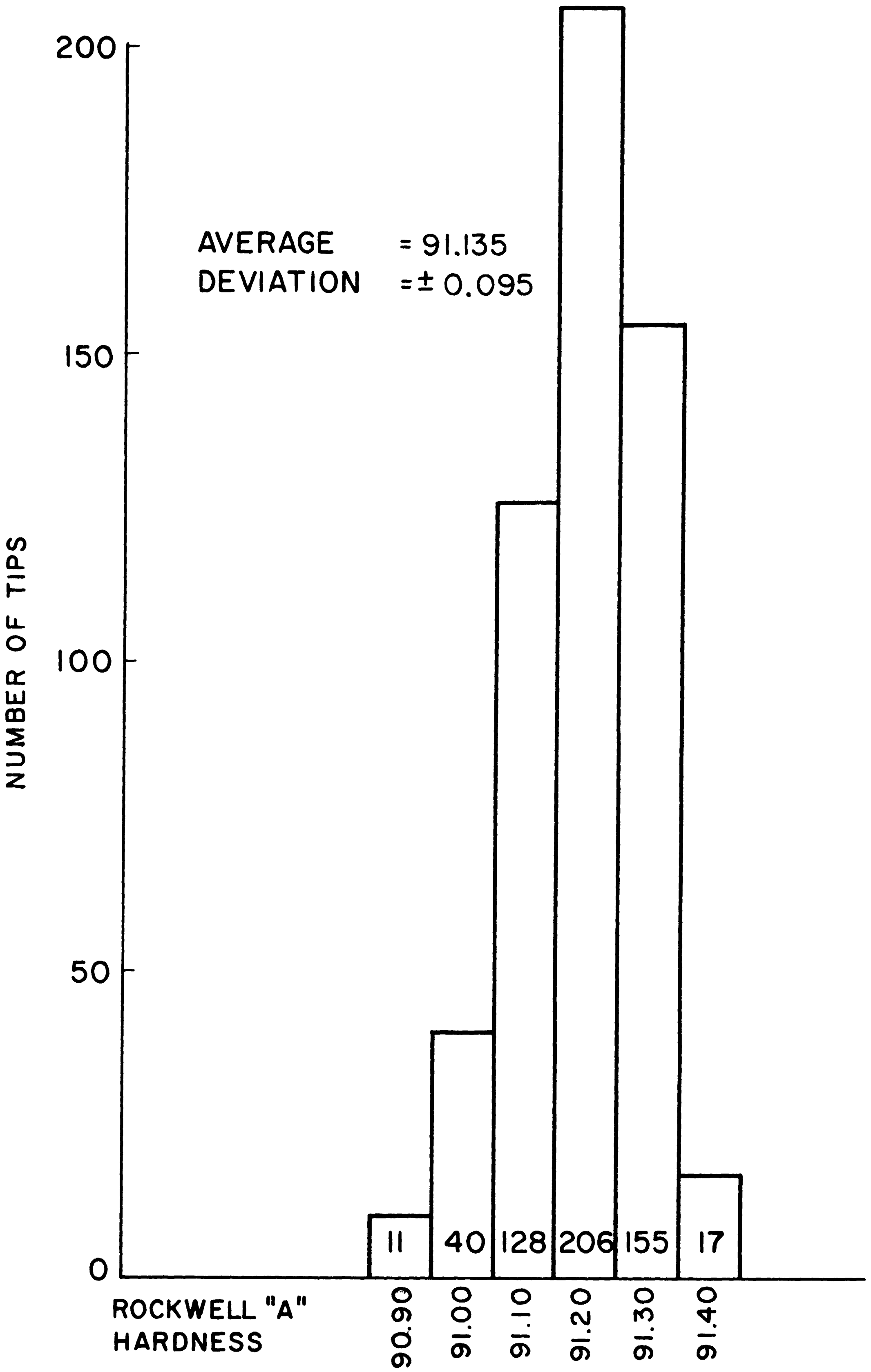


Figure 41. Rockwell A hardness—Carbide P10.

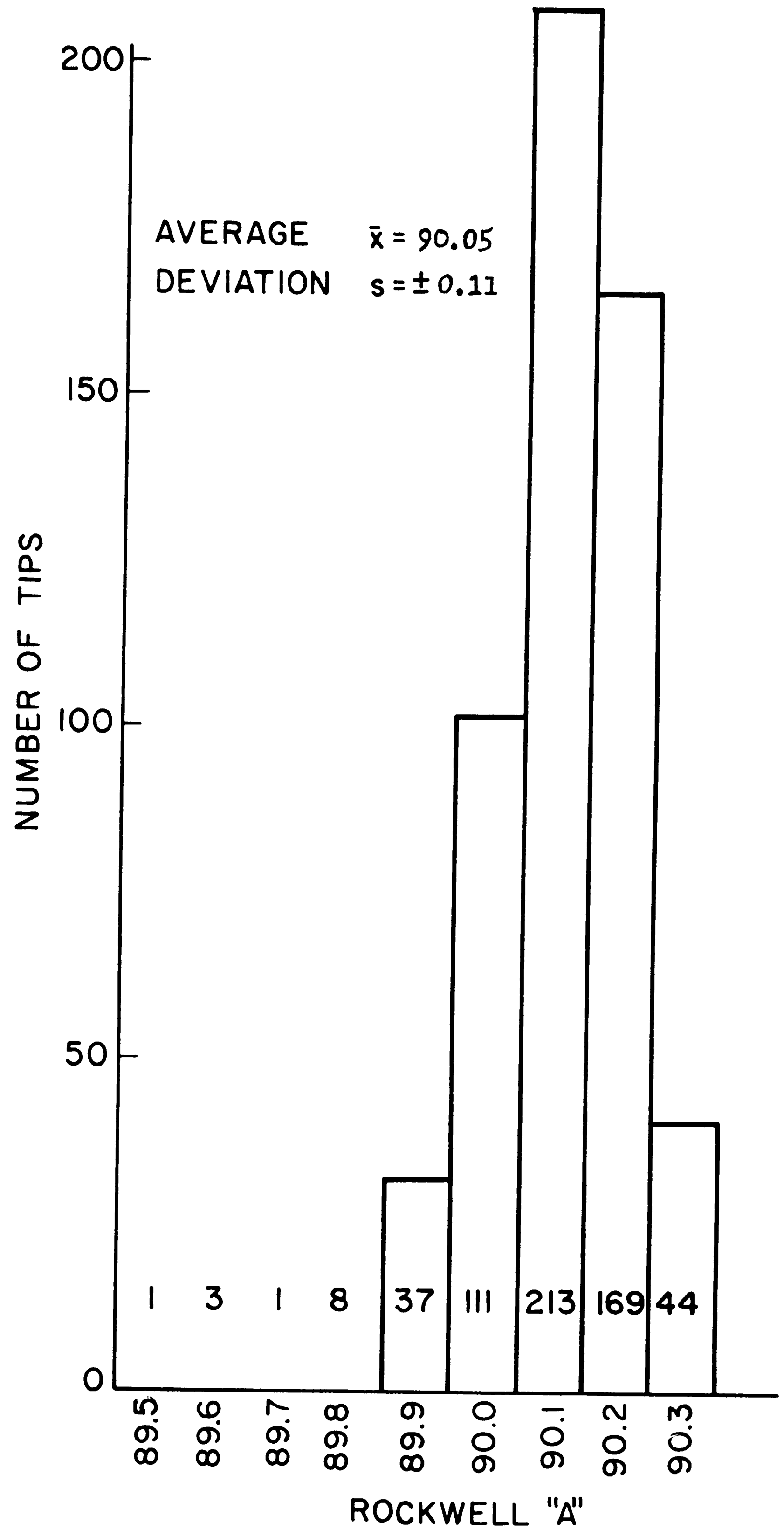


Figure 42. Rockwell A hardness—Carbide P30.

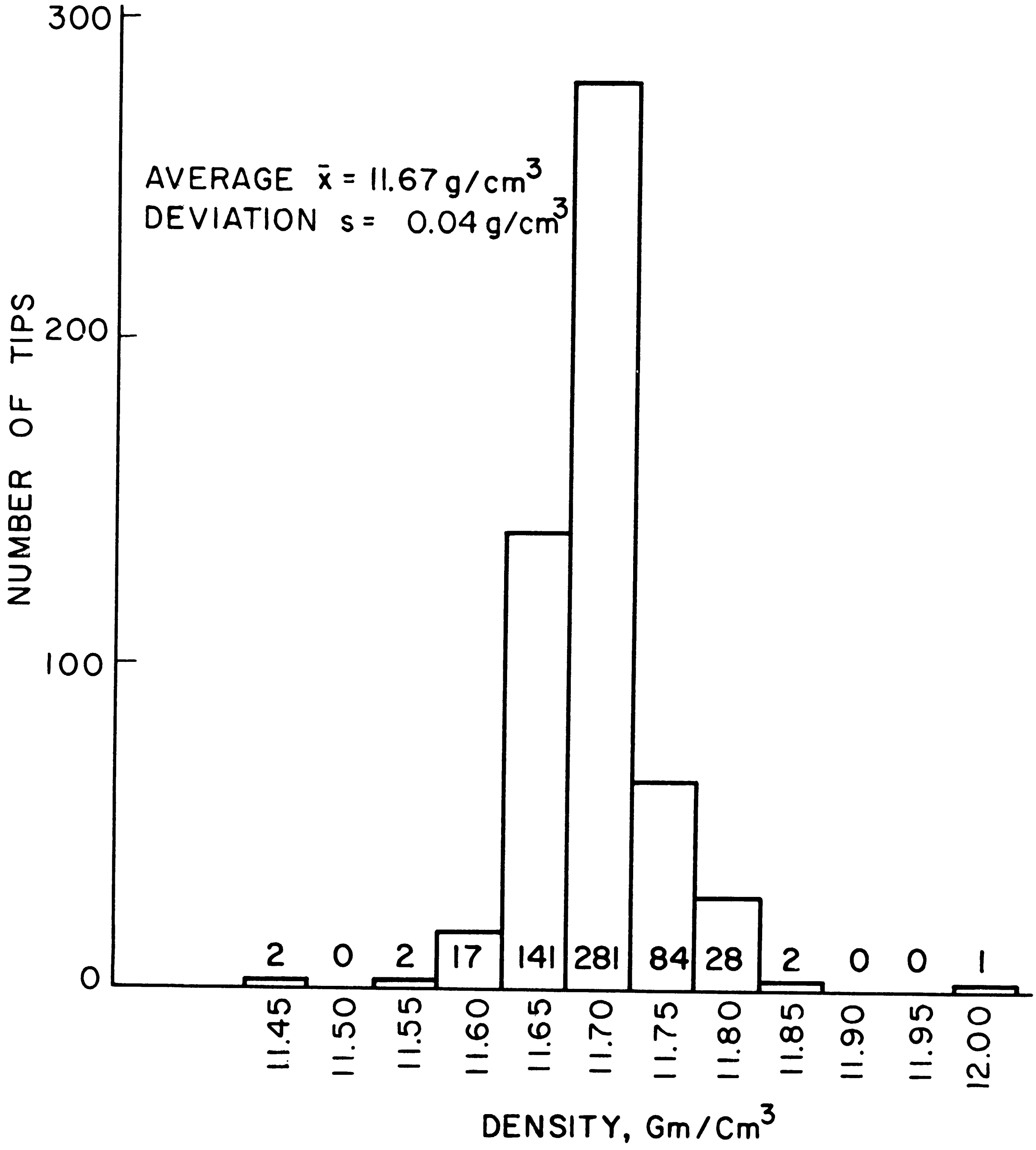


Figure 43. Density—Carbide P10.

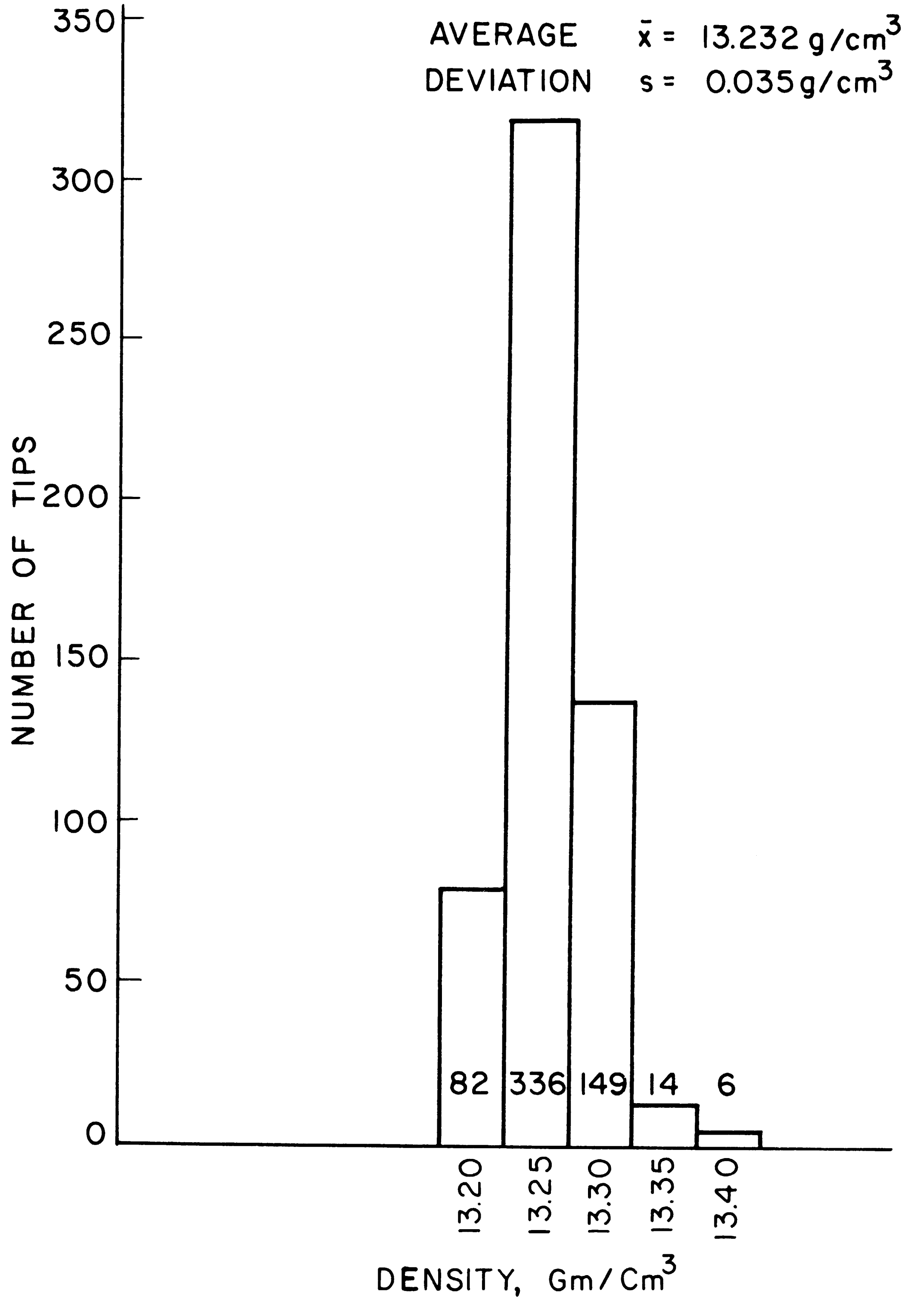


Figure 44. Density—Carbide P30.

Although cutting tools were made only from those bars which fulfilled all of the requirements with respect to inclusions, grain size, and carbide distribution, the high speed steel phase of the cooperative program has been plagued by large discrepancies in results. Resolving these differences may require some program changes.

3. American Cutting Tools

Investigations with American cutting tool materials have been exploratory or introductory in nature in this phase of the cooperative program. A number of different materials grades will be evaluated before more extensive studies get underway.

The carbide cutting tools were provided by Kennametal, Inc. in all commercial grades for positive and negative rake angles. The following grades were on hand for this study:

Rake Angle	Kennametal Carbide Grade K2S	K5H	K6	K21	K68
Negative	X		X	X	X
Positive		X		X	

The shape and size are identical to the European grades.

High speed steel tools were provided by the Latrobe Steel Company in standard 1/2 in. square tool bits in four grades:

Latrobe Grade	AISI Type	Hardness, Rc
Electrite Double Six XL	M-2	64-66
Electrite Crusader	M-3	65-67
Electrite Dynacut	M-43	68-70
Electrite Super Cobalt	T-5	64-66

In every grade, the tools on hand represent the product of a single bar of steel to minimize the influence of minor variations in chemistry or mill processing.

D. EXPERIMENTAL PROGRAM

Details of the paln for the experimental program on wear of carbide tools were issued by Dr. Opitz of the Technical University of Aachen, Germany in January, 1963. A very similar plan governing the conduct of high speed steel tool life tests was published by Professor Bodart of the University of Liege, Belgium in February, 1963. The purpose of both plans is to provide a base for all tests to guarantee and prove conformance of all participating laboratories in measuring wear and conducting the metal cutting tests uniformly.

Every phase of the program is spelled out in a rigorous format. Each combination of tool material, tool geometry, and size of cut is specified by a test number, and definite cutting velocities are specified for each test. Other details of the program range from the proper identification of tools and cutting edges, as in Figure 45, and the proper method of machining a test bar, as illustrated in Figure 46, to proper recording procedures and wear measuring techniques to yield the data indicated on the typical test data sheet shown in Figure 47. The various symbols and dimensional units used in the program are identified in Table VII. Tool angles are identified in Figure 48.

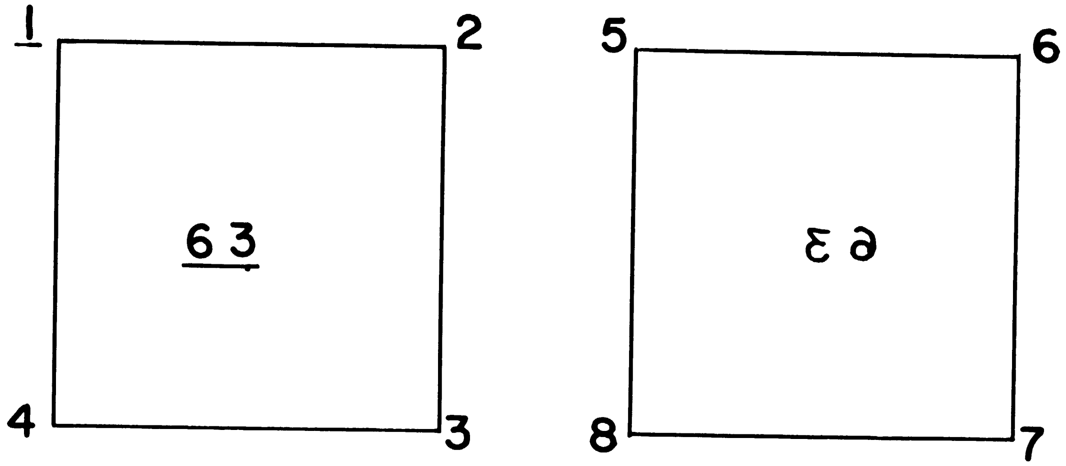


Figure 45. Method of identifying cutting edges of indexable carbide tool bits.

The total program consists of two parts, the Standard Program and the Main Program. The Standard Program (Table VIII) was to be conducted by all participating laboratories so that data from different sources could be compared and evaluated for scatter, reproducibility and proper application of techniques, and instrumentation. These evaluations served as a basis for discussing and setting up the Main Program which was an extension of the format in Table VIII. In reality, the Standard Program served as a clearing house to trouble shoot various problems which arose during the exchange of information among the various laboratories. Once reliability was established, the Main Program was shared among the participants.

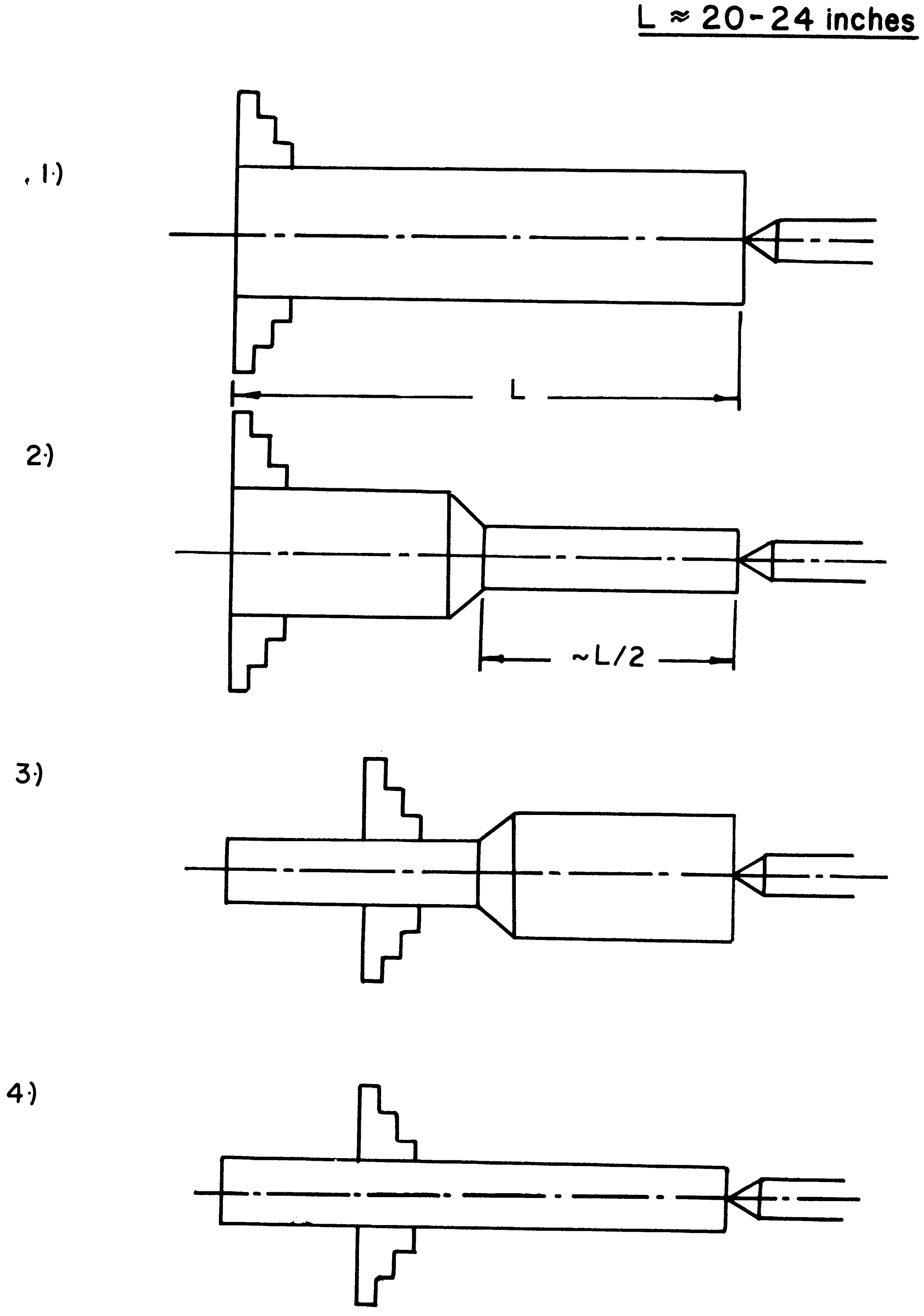
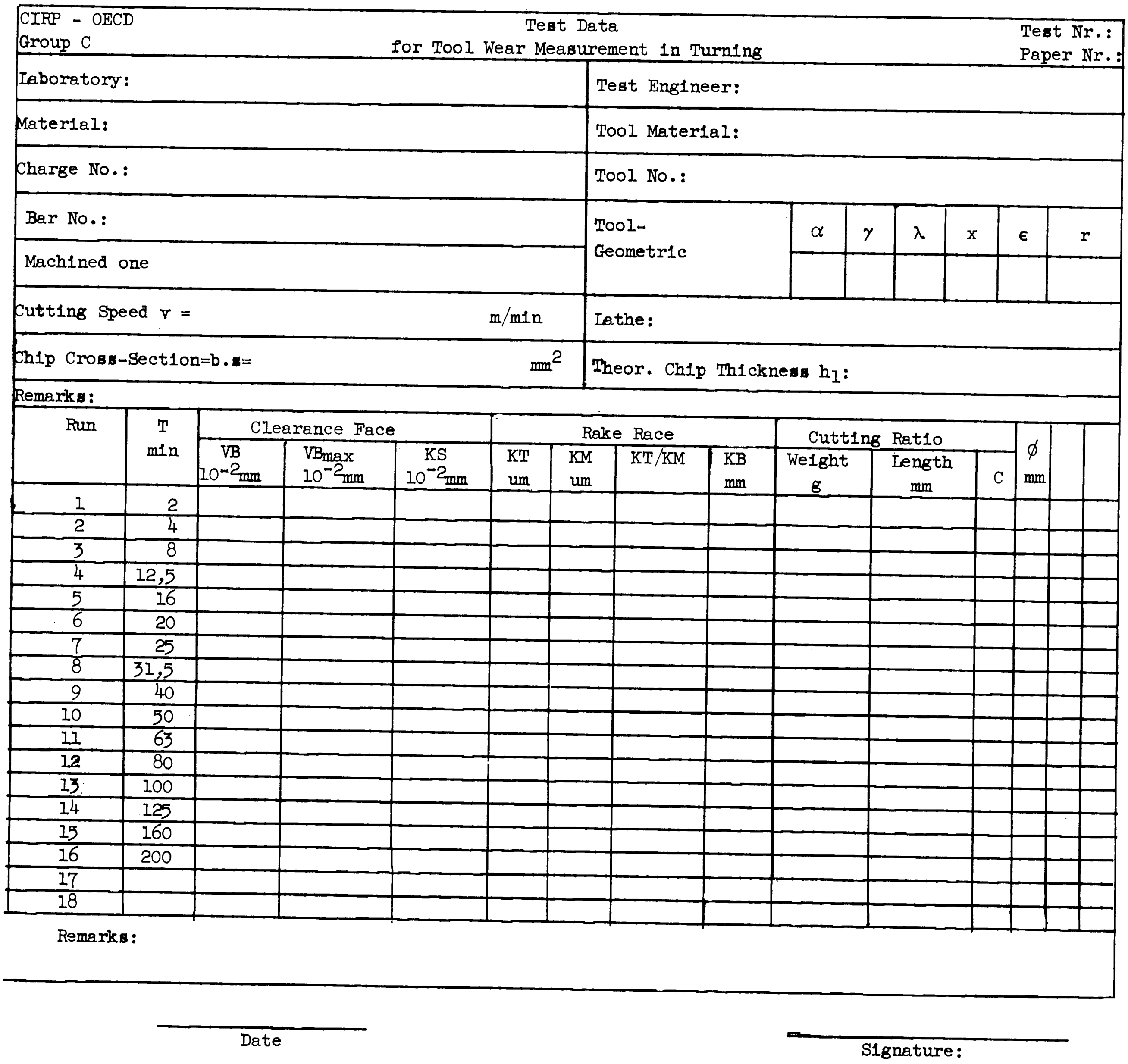


Figure 46. Method of machining test bar.



CIRP - OECD
Group C

Test Data
for Tool Wear Measurement in Turning

Test Nr.:
Paper Nr.:

Laboratory:	Test Engineer:
Material:	Tool Material:
Charge No.:	Tool No.:
Bar No.:	Tool-Geometric
Machined one	
Cutting Speed v = m/min	Lathe:
Chip Cross-Section=b.s= mm^2	Theor. Chip Thickness h_1:

α	γ	λ	x	ε	r

Remarks:

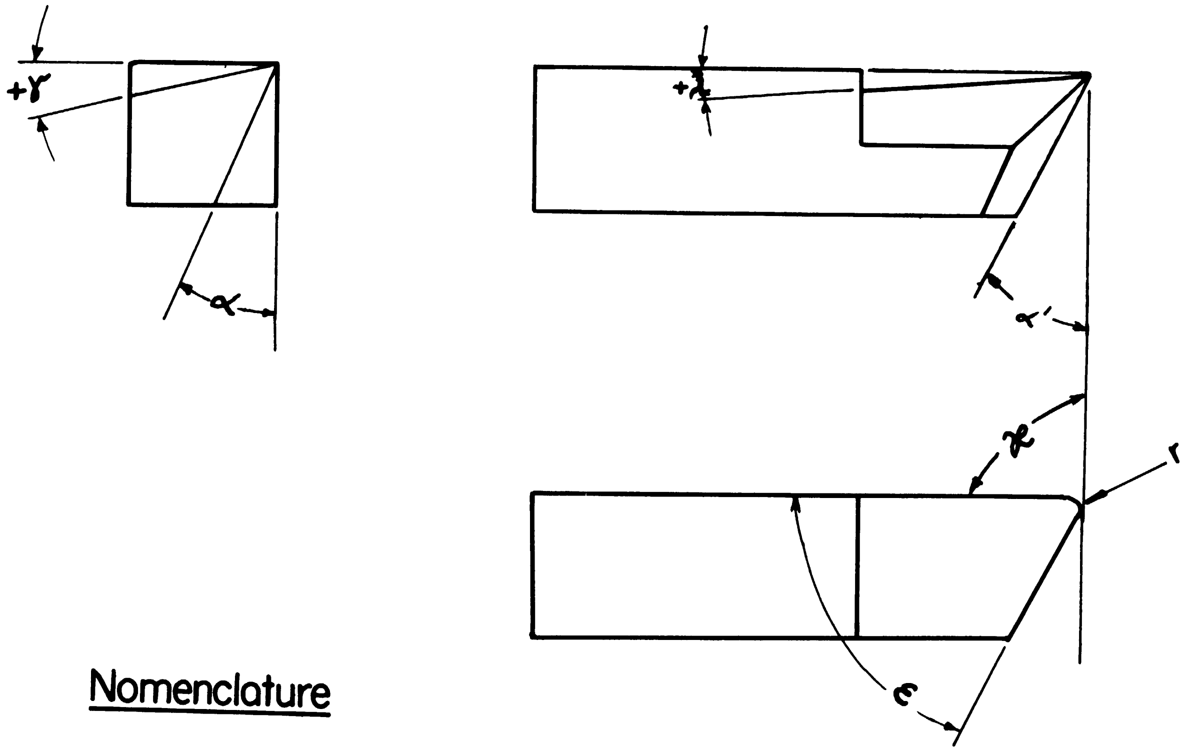
Run	T min	Clearance Face			Rake Race				Cutting Ratio			∅		
		VB 10^{-2}mm	VBmax 10^{-2}mm	KS 10^{-2}mm	KT um	KM um	KT/KM	KB mm	Weight g	Length mm	C	mm		
1	2													
2	4													
3	8													
4	12,5													
5	16													
6	20													
7	25													
8	31,5													
9	40													
10	50													
11	63													
12	80													
13	100													
14	125													
15	160													
16	200													
17														
18														

Remarks:

Date

Signature:

Figure 47. Typical test data sheet.



Nomenclature

rake angle	γ
inclination angle	λ
relief angle	α
end relief angle	α'
side cutting edge angle	$\varkappa$
nose angle	ε
nose radius	r

Figure 48. Angles of a cutting tool.

TABLE VII. SYMBOLS AND DIMENSIONAL UNITS

Specification	Symbol	Dimension
width of wearland	VB	mm
depth of crater	KT	µm
width of crater	KB	mm
shift of cutting edge	KS	µm
distance between cutting edge and deepest point of crater	KM	µm
width of crater lip	KL	µm
feed	s	mm/r
depth of cut	b	mm
cutting speed	v	m/min
revolutions per minute	n	1/min
diameter	d	mm
cutting ratio	c	--
nose radius	r	mm
radius of cutting edge	r_i	µm
roughness	R_t; R_a; CLA	µm

TABLE VIII. OUTLINE OF STANDARD TEST PROGRAM

Test No.	Tool Material	Tool Geometry						Cutting Conditions		
		α	γ	λ	χ	ϵ	r, mm	Feed, mm/r	Depth of Cut, mm	Cutting Speed, m/min
2.1	P30	6°	6°	0°	70°	90°	0,8	0,25	3	63-80-100-125-160-200
2.2	P30	6°	6°	0°	70°	90°	0,8	0,5	3	80-125-160
7.1	P30	6°	-6°	-6°	70°	90°	0,8	0,25	3	80-125
6.2	P30	6°	6°	0°	70°	90°	0,8	0,25	3	100-160-200*
10.1	P10	6°	6°	0°	70°	90°	0,8	0.25	3	100-160-200-250
10.2	P10	6°	6°	0°	70°	90°	0,8	0,5	3	125-200
15.1	P10	6°	-6°	-6°	70°	90°	0,8	0.25	3	125-200
14.2	P10	6°	6°	0°	70°	90°	0,8	0,25	3	125-200*

*With chipbreaker.

Most of the format outlined in the test program fulfills the requisites of any good test procedure. However, wear measurements and tool life criteria differ substantially from those in common use in the United States. American practice is to rely almost exclusively on flank wear as a criterion of failure on carbide tools, and total failure on high speed steel tools. Crater wear is often observed, but not formally considered. The international cooperative program on tool wear employs both flank and crater wear to evaluate tool behavior. The important measurements are identified in Figure 49.

1. Wear Measurements

Use of the crater as a criterion of failure requires that a trace be made of the crater profile, from which the deepest part of the crater, KT, and the distance from this deepest part to the existing cutting edge at the time, KM, can be determined. The ratio of KT/KM is a measure of effective crater wear. A Tukon hardness indentation outside of the expected wear band serves as a reference and assures that the trace can be made through the same point with little error. The following recommended criteria represent tool failure:

$$VB = 0.2 \text{ mm } (.008 \text{ in.}) \text{ and } K = 0.2$$

or

$$VB = 0.4 \text{ mm } (.016 \text{ in.}) \text{ and } K = 0.1$$

where VB = flank wear and K = crater ratio, KT/KM.

The two sets of criteria reflect situations when either flank wear or crater wear predominates.

Methods used to measure the crater include both tracer and optical techniques. Table IX lists the various laboratories which participated in formal attempts to determine the degree of reliability or repeatability of tool wear measurements with various instruments. In general, the repeatability is good. However, practically every laboratory showed excessive deviation from the mean in at least one of the measurements indicated in Figure 49. It is estimated that some of the dispersion is due to human judgment. The rest is due to the equipment itself. A tentative conclusion is that equipment using physical contact with diamonds or similar devices may be responsible for some of the larger deviations. Burrs and other hazards are more easily recognized by optical means. Included angles of styli also tend to mask boundaries such as cutting edges or crater edges. Care is required in interpretation of the measurement.

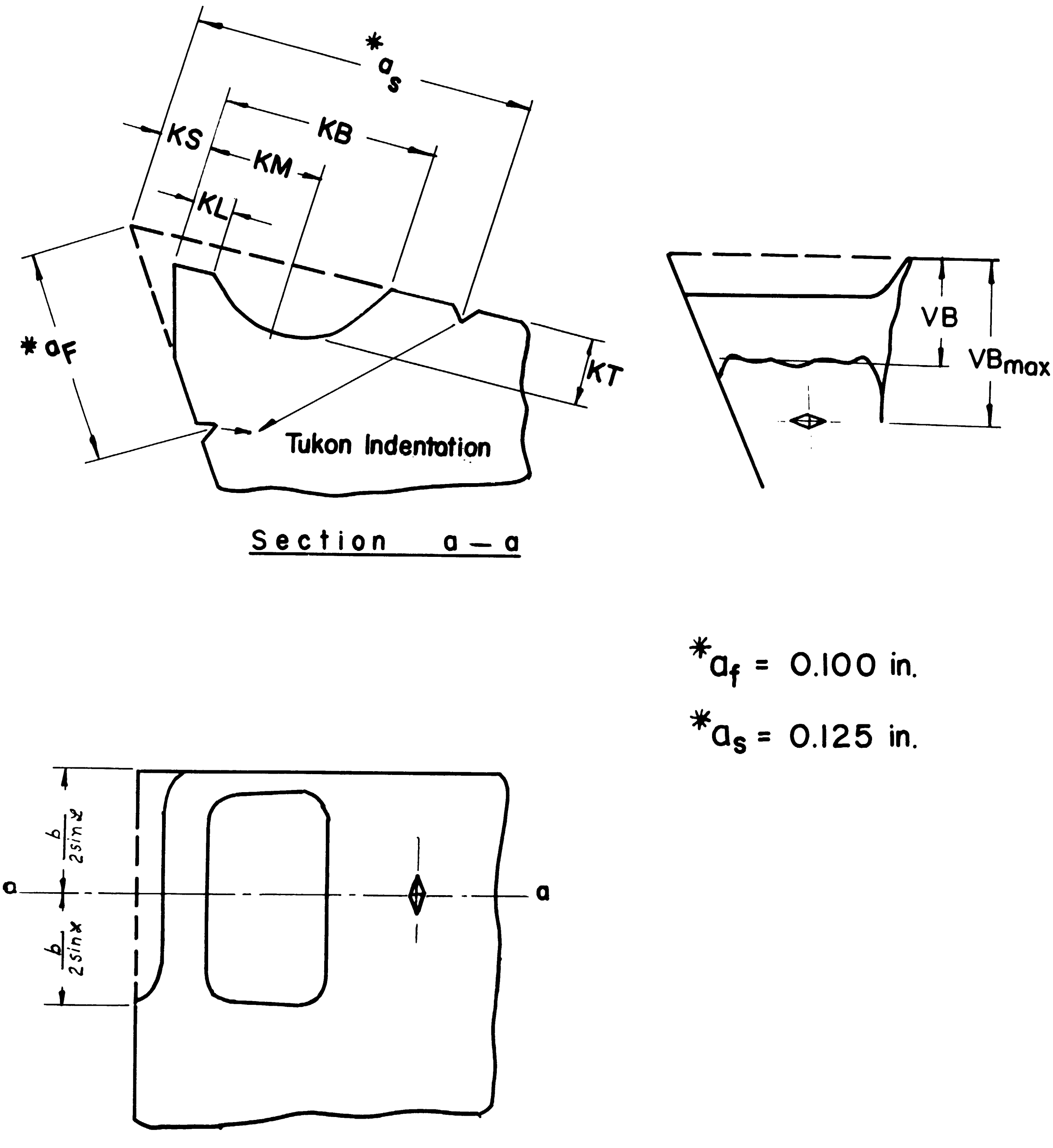


Figure 49. Identification of tool wear.

TABLE IX.

PARTICIPATING LABORATORIES AND EQUIPMENT USED

Tool No.	Laboratory	Equipment
1	Delft (Netherlands)	A, B, VB', KB, KL: toolmakers' microscope amplification 30x KM, KT; Talysurf amplification: vertical 200x; horizontal 20x
2a	Aachen (Germany)	A, B, VG', KB, KL: toolmakers' microscope A, KB, KM, KL, KT: Leitz-Forster
2b	London	First reading
2c	London	One day later
3a	Kapfenberg (Austria)	KT: Leitz-Forster all other sizes: Stereo microscope with ocular micrometer magnification rx and for KL 100x
3b	Aachen	Same as 2b
4	Zurich	Schmaltz-lightsection microscope on a SIP universal measuring machine MU 214 B
5a	Chippendale (Austria)	Light section microscope of own design
5b	Chippendale	Profile projection method
7	Goteborg (Sweden)	Talysurf and toolmakers' microscope
8	Leige	A, B, VB', KB, KL: toolmakers' microscope KT: Forster-Leitz
9a	Manchester (England)	Microscope
9b	Manchester	Talysurf
9c	Manchester	Talysurf and microscope, readings one month later
10	Saint-Ouen	B, VB': SIP measuring machine MU 214 B other sizes: Perthometer
11a	Arcueil (France)	SIP measuring machine MU 214 B
11b	Arcueil	A, B, VB', KB, KL: toolmakers' microscope magnification 13x; KT, KM: Schmaltz light section microscope
12a	Torino (Italy)	SIP measuring machine MU 214 B
12b	(Torino	A, B: optical comparator Microtechnica magnification 50x; VB', KB, KM, KL, KT: optical micrometer (Galileo) magnification 50x
12c	Michigan (U of M)	Toolmakers' microscope
12d	Michigan	Proficorder
15	Kapfenberg	Same as 3
16a	Delft	Same as 1
16b	Pittsburgh (Carnegie Tech.)	Profile recorder and measuring microscope

E. TOOL WEAR RESULTS

1. Carbide Tools

a. Effect of Cutting Velocity

Figures 50, 51, and 52 are concerned directly with the typical wear criteria upon which tool life determinations are based. They show the orderliness of flank wear, crater depth, and crater ratio as wear parameters. The large asterisk at the end of four of the five plots indicates that the tool was unusable for further testing.

Typical tool life-cutting speed plots from the flank wear and crater ratio determinations are shown in Figures 53 through 60. Figure 53 is a tool life plot based upon total tool travel or rubbing distance rather than cutting time. It shows a typical difference between the two curves, which implies that some cutting conditions will encounter catastrophic failure due to crater wear while others will be due to flank wear. However, Figure 54 shows that the difference in tool life as a result of using either flank wear or crater wear as the criterion of failure are somewhat arbitrary depending upon the actual limiting values selected in each case. One set of curves representing the higher cutting speeds and longer tool lives is based upon a flank wear of 0.3 mm (0.012 in.) and a crater ratio of 0.2. The other set at lower cutting speed is based upon a flank wear of 0.2 mm (0.008 in.) and a crater ratio of 0.1. In both cases, the results are nearly equal, but the crater wear becomes dominant at higher cutting speeds. Appropriate values of both these criteria differ among work materials and vary with the type of operation. Consequently, it seems appropriate to reserve judgment on the proper limiting value until more information of this type is available.

Another interesting comparison in the use of either flank wear or crater ratio as the criterion of tool failure is shown in Figures 55 and 56, which represent the results of tool life tests on the two heats of XC45 work material prepared for the international study. Figure 55, based upon a limiting flank wear of 0.2 mm (0.008 in.), shows no significant difference between the two heats. However, there is an appreciable difference when the crater wear characteristics are compared, as in Figure 56. The reasons for the differences in sensitivity of these parameters are not adequately understood at this time and will require further study.

Comparisons of results among participating laboratories are summarized in Figures 57 through 60. It is evident that there is scatter of the order of at least two to one in most of the data, but it is also evident that crater wear gives more consistent results than flank wear particularly on the P10 carbide material. This is especially true of the results found at The University of Michigan as covered in Part II of this report. Figure 61 shows that

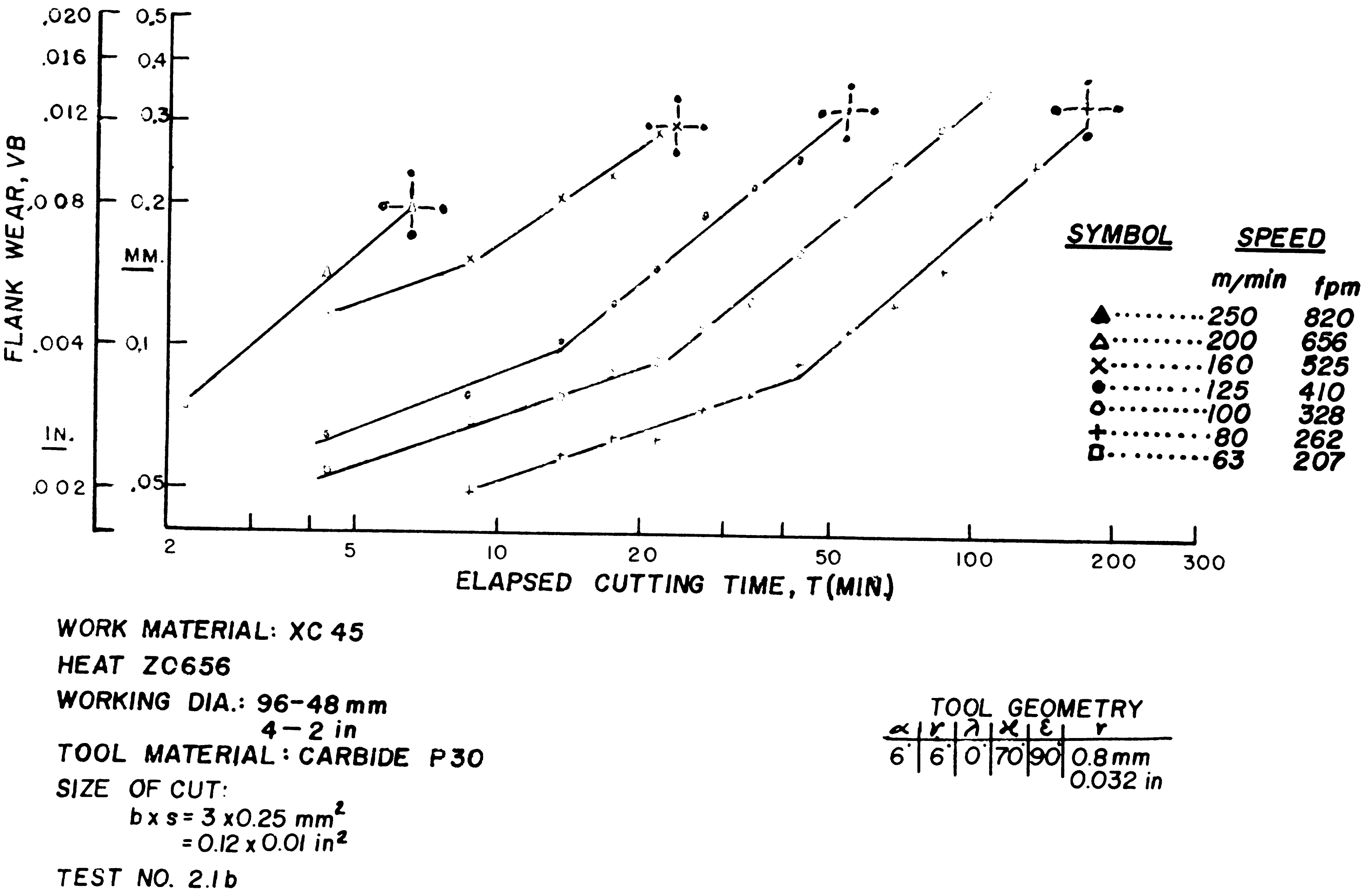
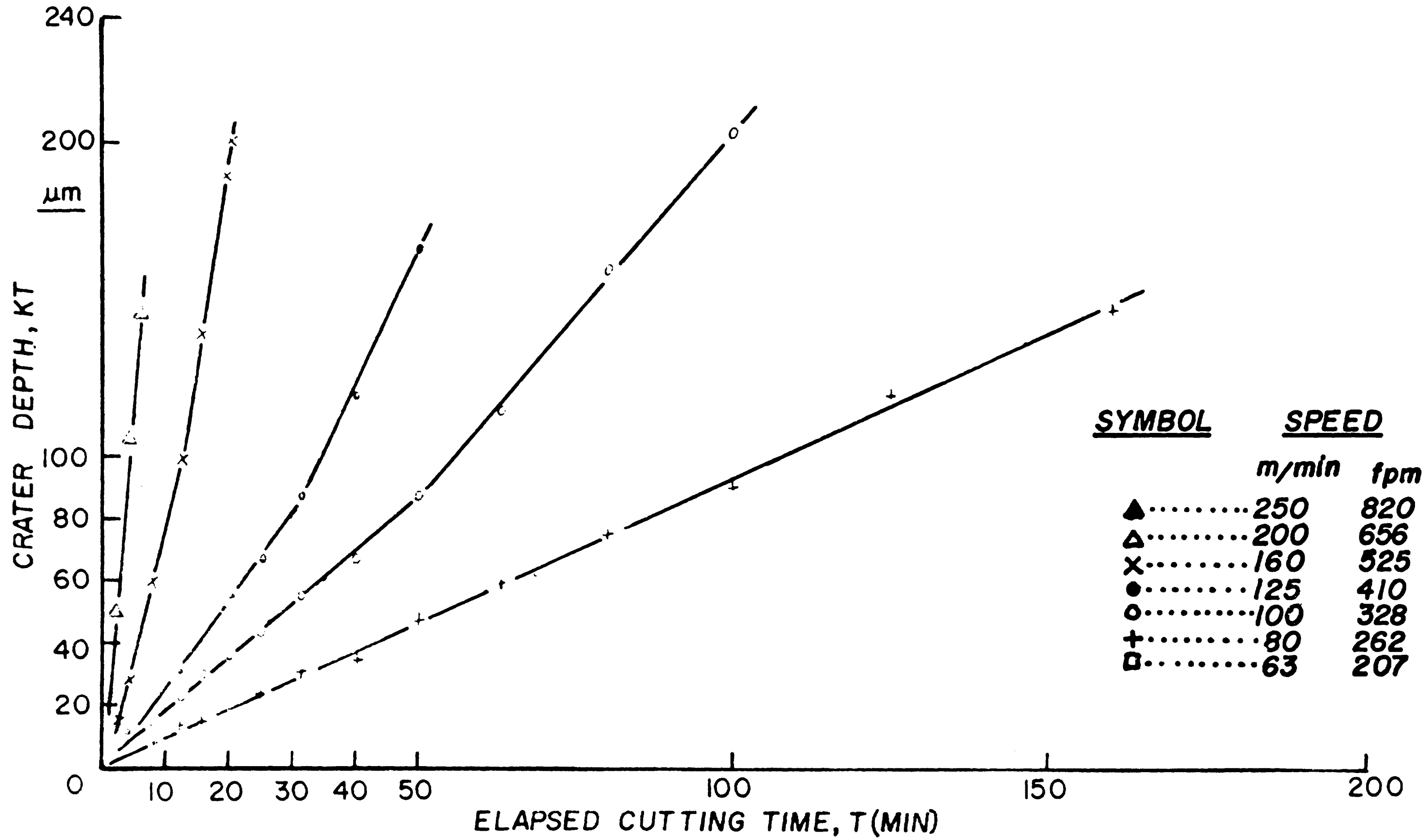


Figure 50. Typical plot of flank wear versus cutting time. The large asterisk at end of curve indicates that tool was unsuitable for further testing.



WORK MATERIAL: XC 45

HEAT: Z0656

WORKING DIAMETERS: 96-48 mm 2-4 in

TOOL MATERIAL: CARBIDE P 30

TEST NO. 2.1b

SIZE OF CUT: 3 x .25 mm^2, 0.12 x 0.01 in^2

TOOL GEOMETRY

α	γ	λ	χ	ϵ	r
6	6	0	70	90	08 mm 0.032 in

Figure 51. Typical plots of crater depth versus elapsed cutting time. The depth represents a maximum depth along a prescribed path normal to the cutting edge.

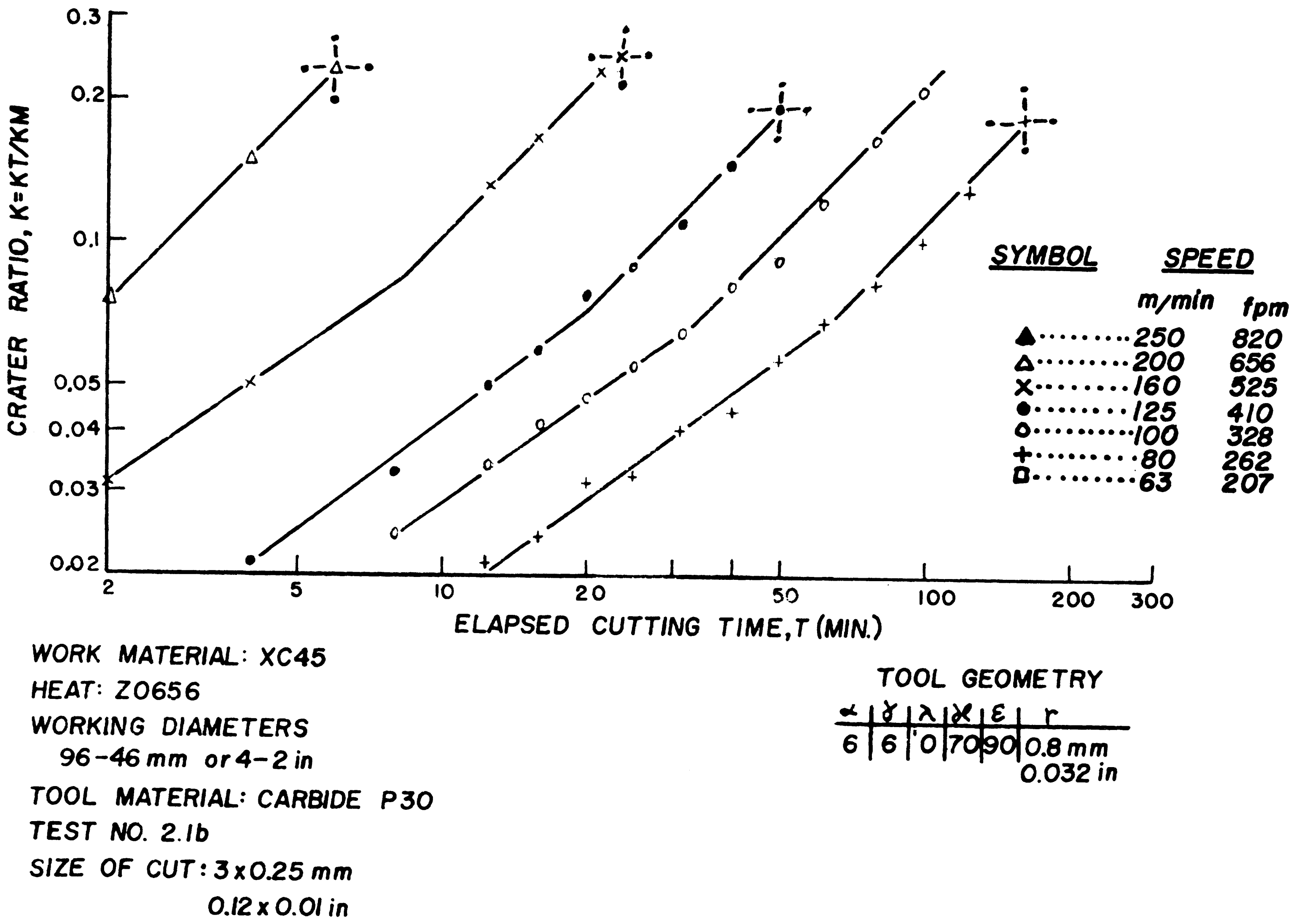
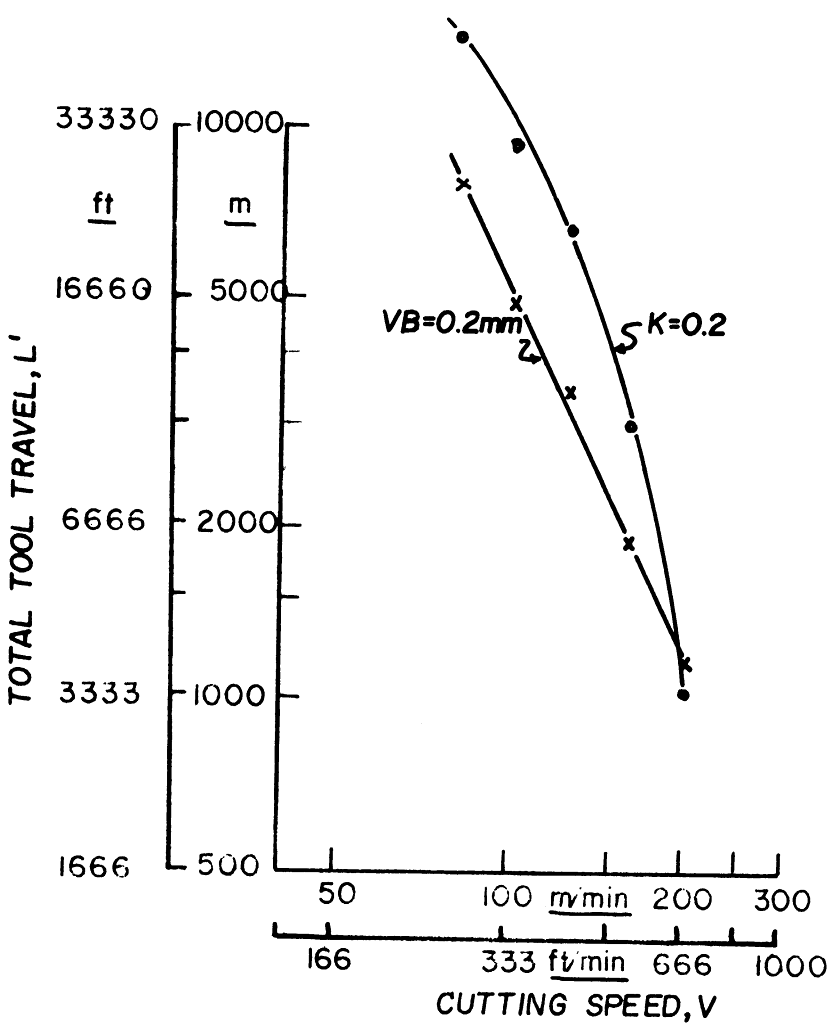


Figure 52. Typical plots of crater ratio versus cutting time. Values of 0.1 or 0.2 serve as tool failure criteria.

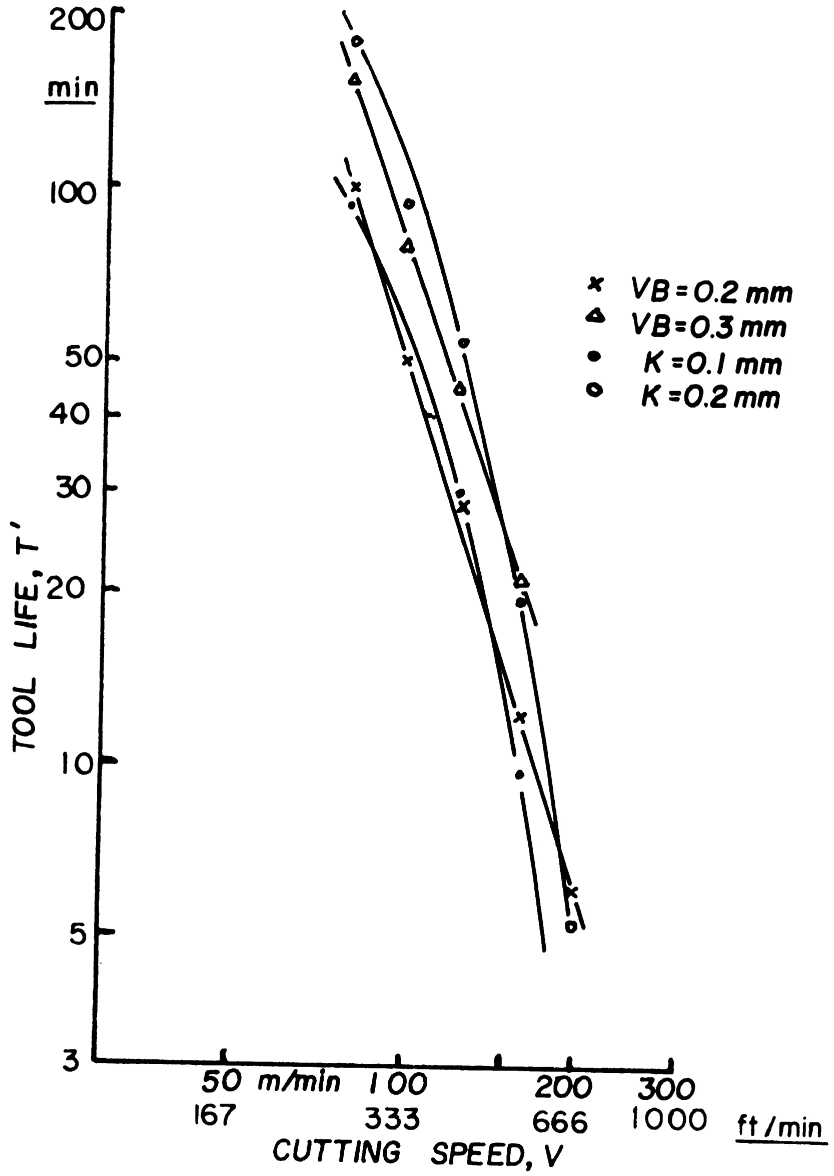


TOOL MATERIAL: CARBIDE P30
HEAT: Z0656
WORKING DIAMETER:
96-48 mm or 4-2 in
WORK MATERIAL: XC45
TEST NO. 2.1b
SIZE OF CUT: 3 x .25 mm^2
0.12 x 0.01 in^2

TOOL GEOMETRY

α	γ	λ	$\varkappa$	ε	r
6	6	0	70	90	0.8 mm 0.032 in

Figure 53. Tool life plot based upon total tool travel or rubbing distance to reach a flank wear of 0.2 mm or a crater ratio of 0.2 at various velocities.

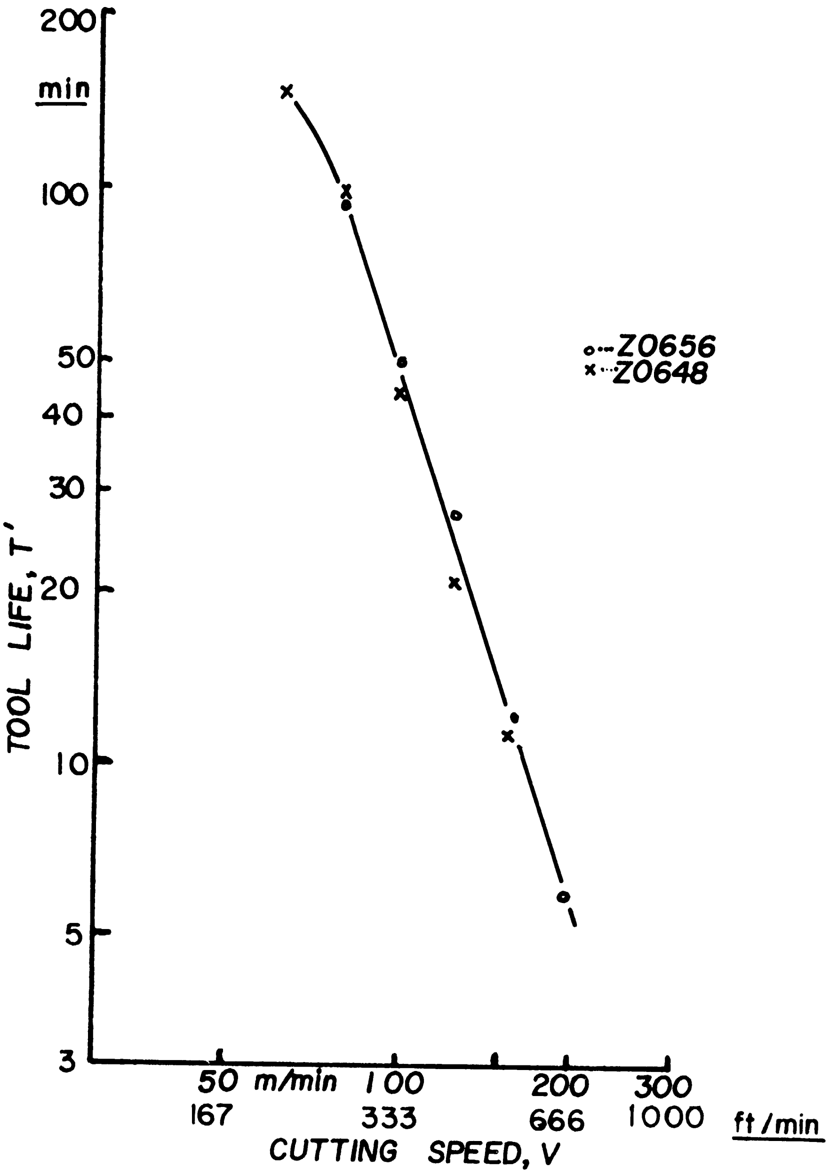


WORK MATERIAL: XC 45
HEAT: Z0656
WORKING DIAMETER
96–48 mm or 4–2 in
TOOL MATERIAL: CARBIDE P 30
TEST NO 2.1b
SIZE OF CUT: $3 \times 0.25 \text{ mm}^2$
$= 0.120 \times 0.010 \text{ in}^2$

TOOL GEOMETRY

α	γ	λ	χ	ε	r
6	6	0	70	90	0.8 mm 0.032 in

Figure 54. Tool life versus cutting velocity based upon different values of flank wear and crater ratio.

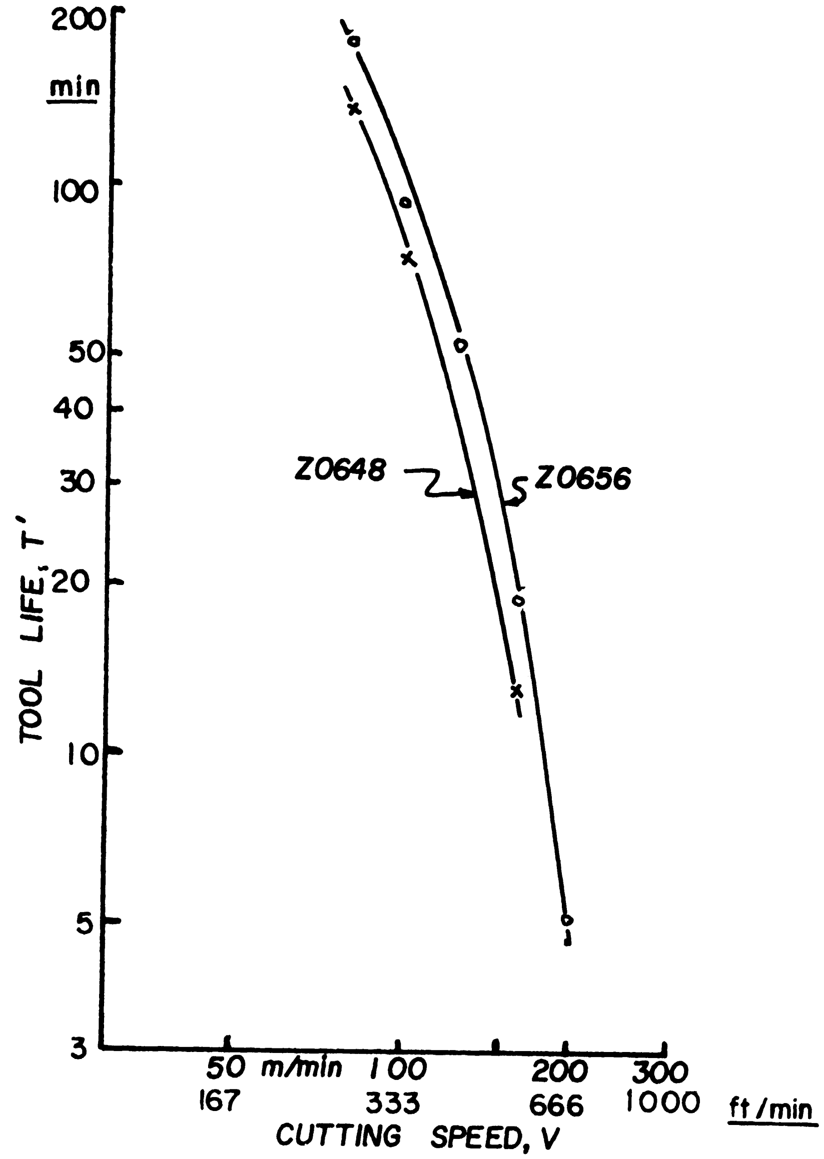


WORK MATERIAL: XC 45
HEAT: Z0648/Z0656
WORKING DIAMETER
96–48 mm or 4–2 in
TOOL MATERIAL: CARBIDE P 30
TEST NO 2.1 a/b
SIZE OF CUT: 3x0.25 mm^2 ·
= 0·120 x 0·010 in^2

TOOL GEOMETRY

α	γ	λ	χ	ε	r
6	6	0	70	90	0.8 mm 0.032 in

Figure 55. Tool life versus cutting velocity for two heats of XC45 steel. Tool failure based upon flank wear of 0.2 mm.



WORK MATERIAL: XC 45
HEAT: Z0648/Z0656
WORKING DIAMETER
96–48 mm or 4–2 in
TOOL MATERIAL: CARBIDE P 30
TEST NO 2.1 a/b
SIZE OF CUT: 3x0.25 mm^2
=0.120 x 0.010 in^2

TOOL GEOMETRY

α	γ	λ	$\varkappa$	ε	r
6	6	0	70	90	0.8 mm 0.032 in

Figure 56. Tool life versus cutting velocity for same two heats of XC45 steel of Fig. 55 but tool failure based upon crater ratio of 0.2. Difference between the two heats of steel are more pronounced.

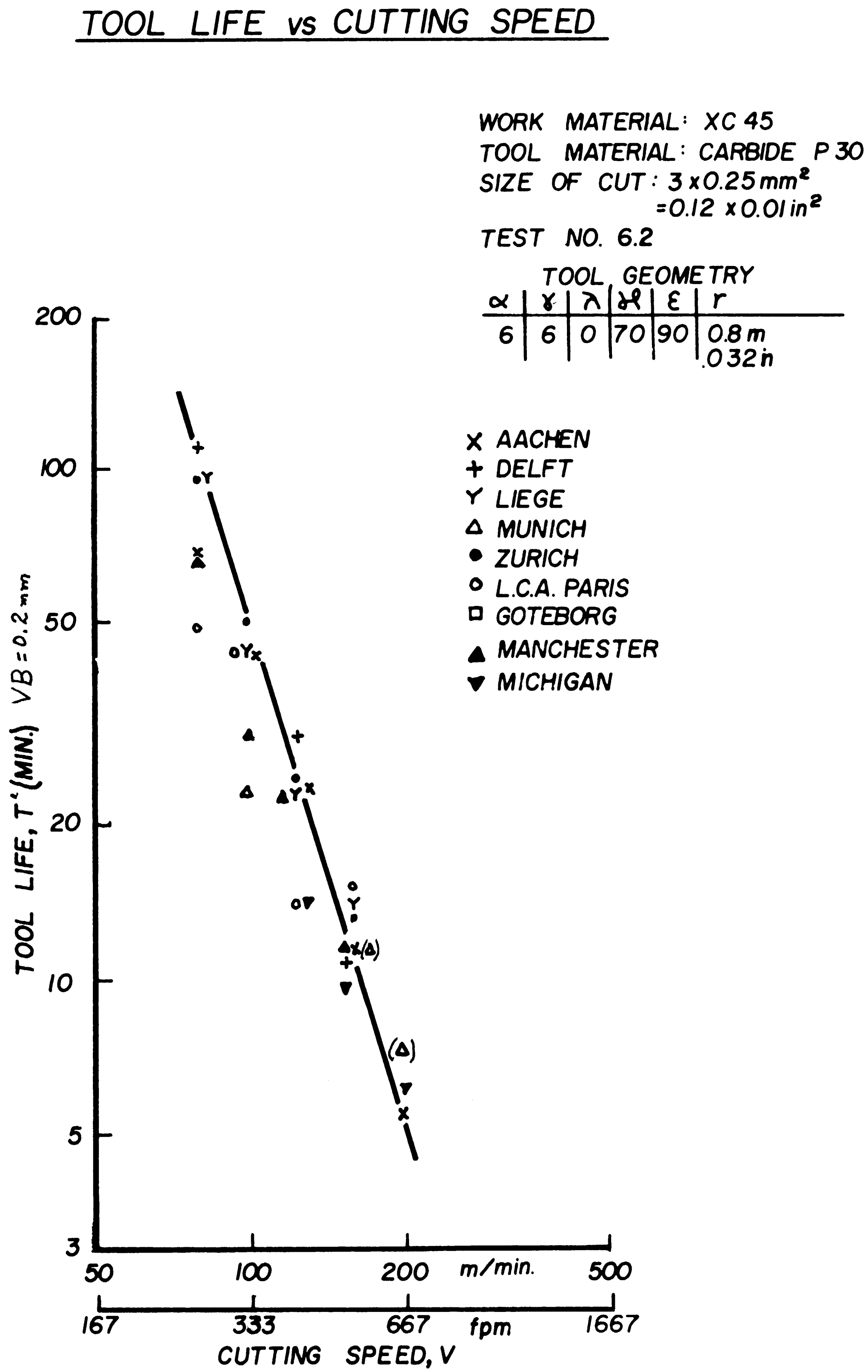


Figure 57. Comparison of tool life results among nine laboratories when based upon flank wear of 0.2 mm with P30 carbide.

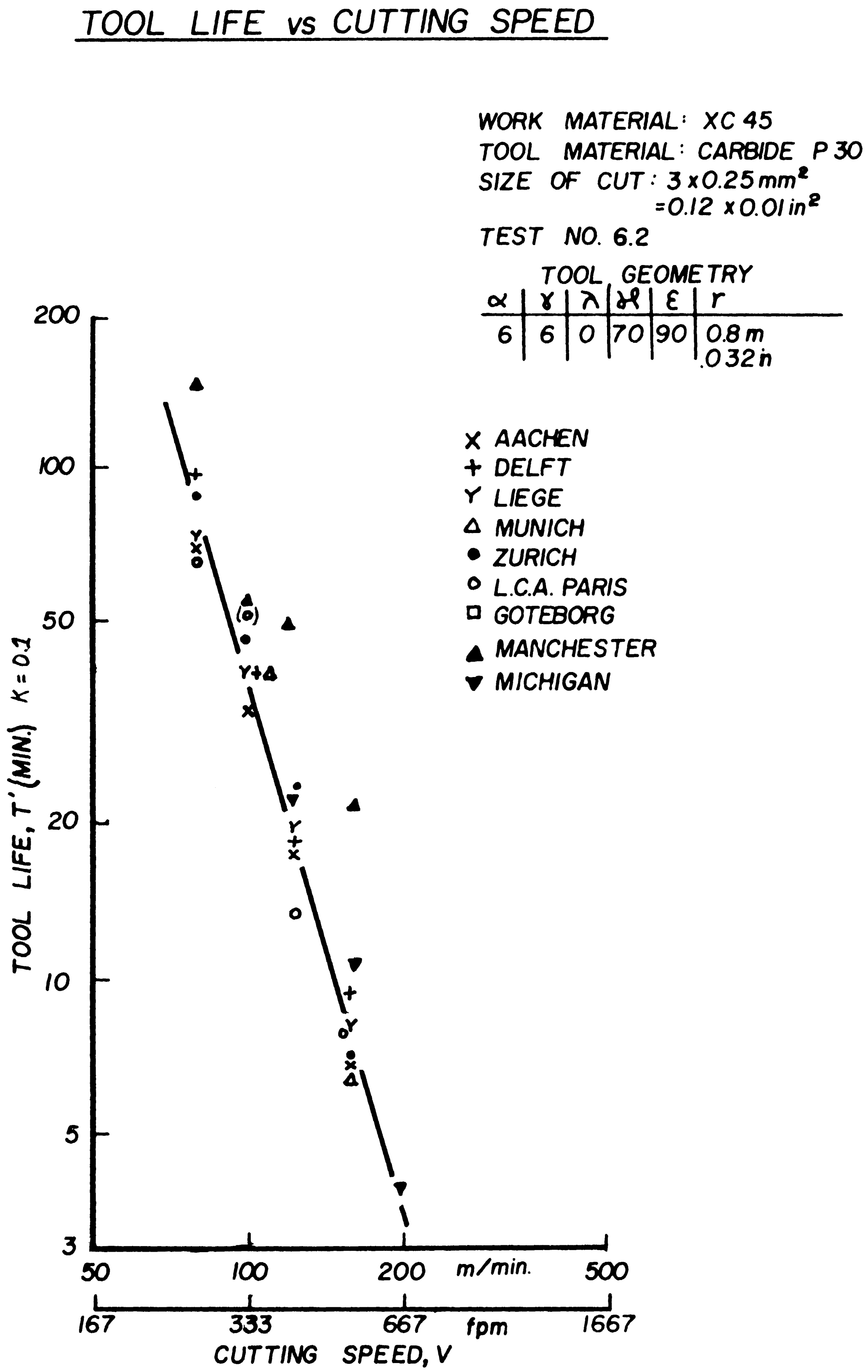


Figure 58. Comparison of tool life results among nine laboratories when based upon a crater ratio of 0.1 with P30 carbide.

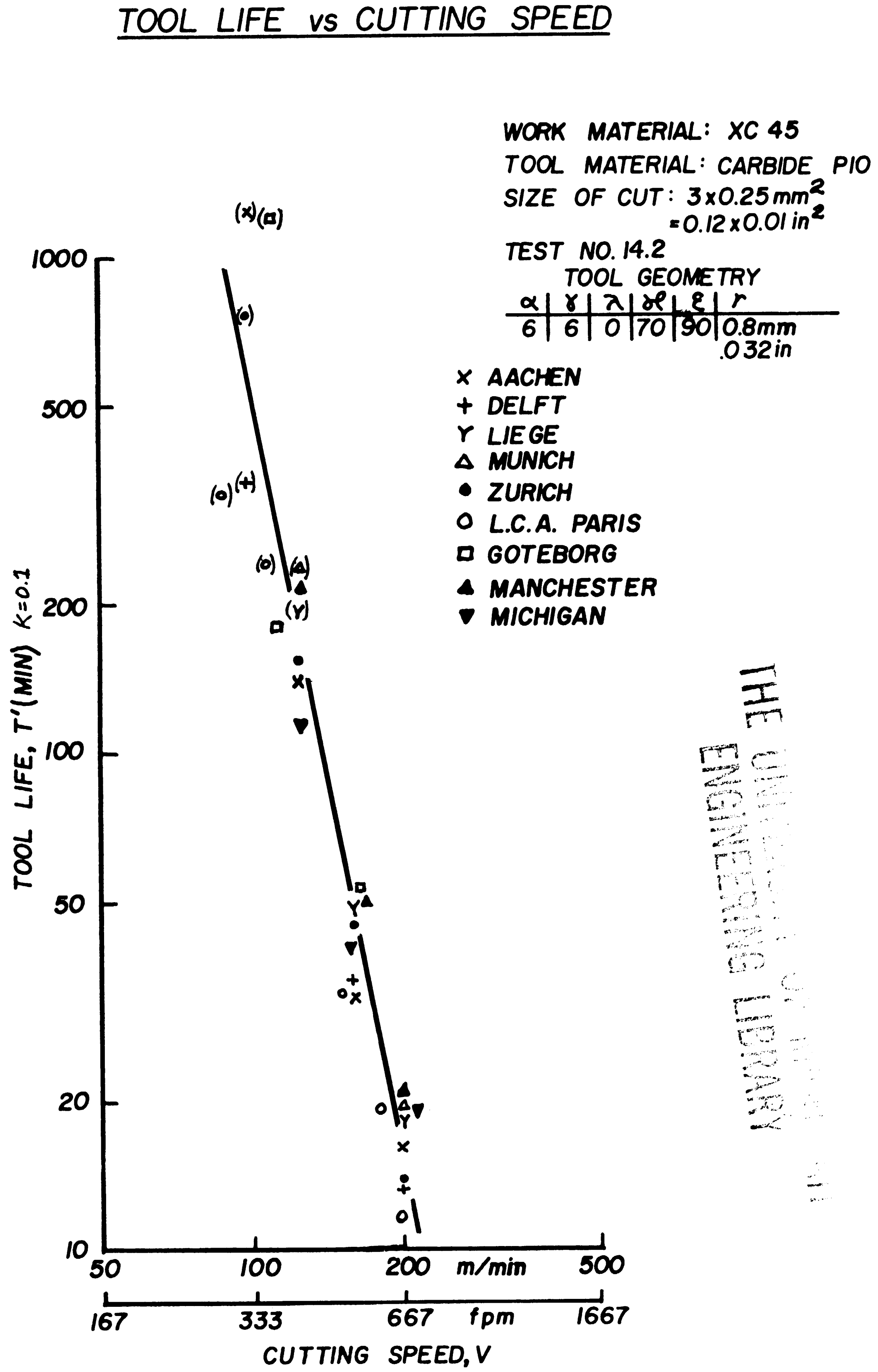


Figure 59. Comparison of tool life results among nine laboratories when based upon a crater ratio of 0.1 with P10 carbide.

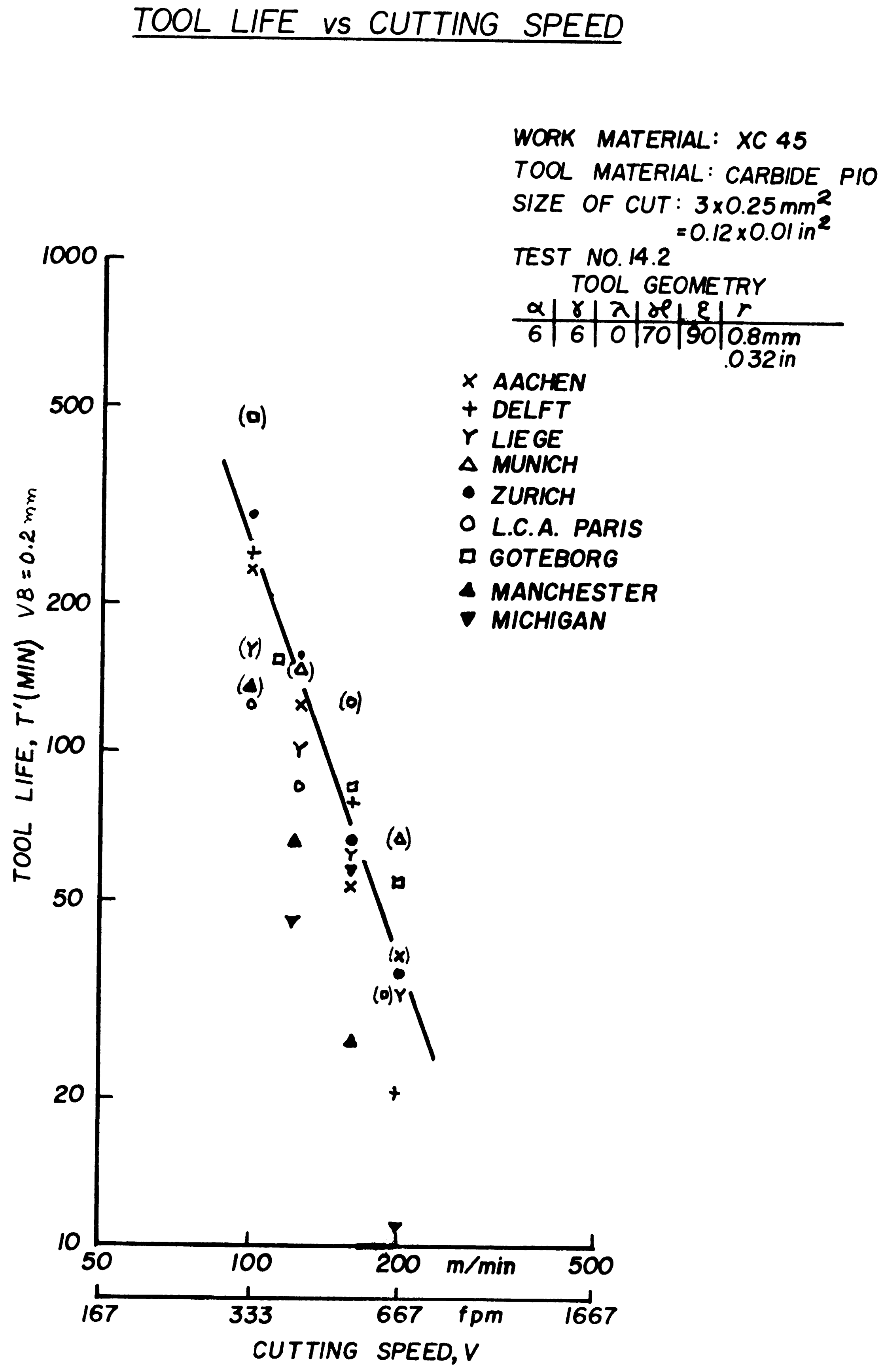


Figure 60. Comparison of tool life results among nine laboratories when based upon flank wear of 0.2 mm with P10 carbide.

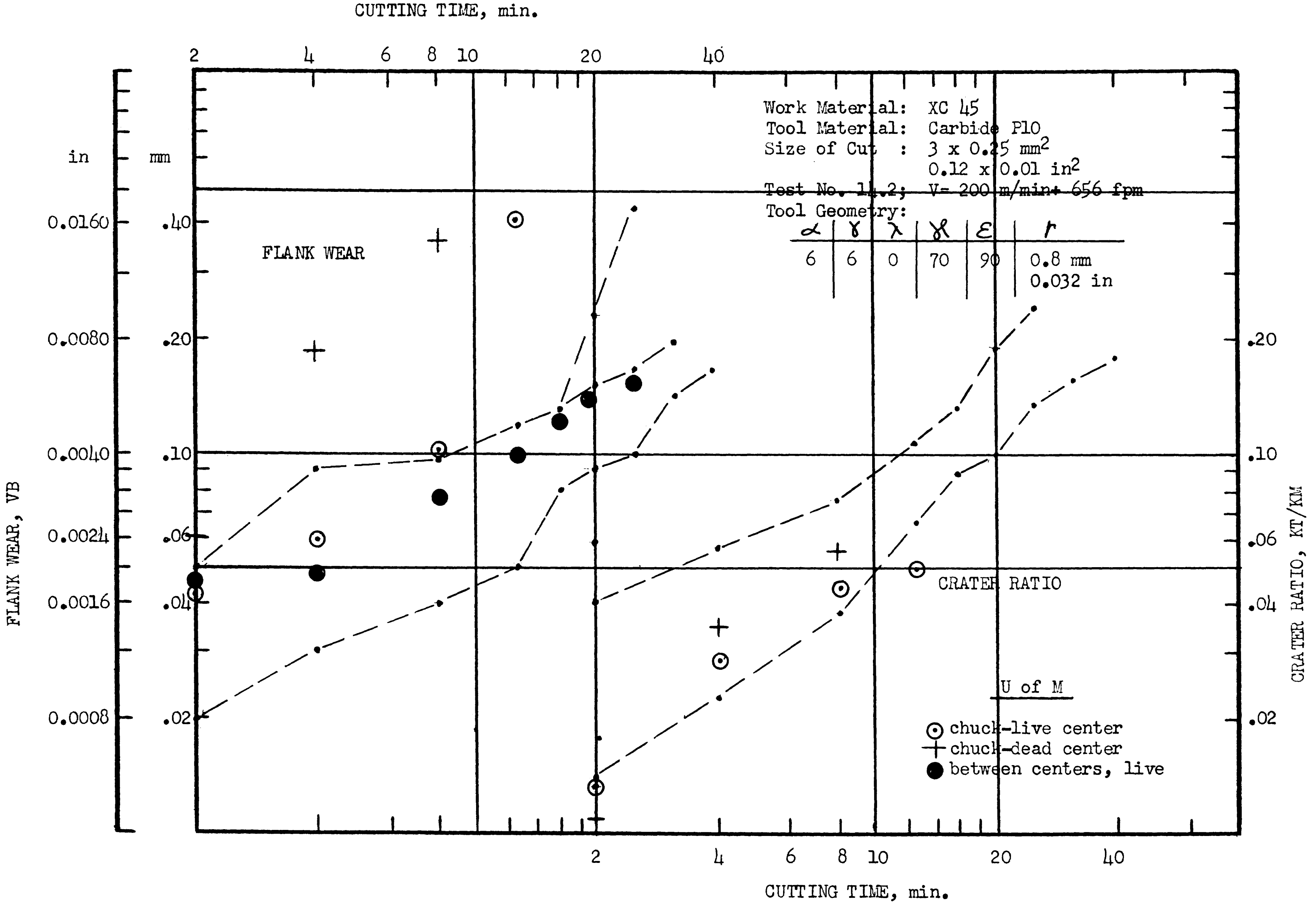


Figure 61. Tests at The University of Michigan indicate that the method of holding and driving the workpiece has an influence on tool life criteria. The effect is greater upon flank wear than upon crater ratio.

the method of holding and driving the workpiece had a great influence on flank wear, but seemed to have little effect on crater wear, or at least, on crater ratio. Some of the observations made at the University indicate that a given crater ratio is not always indicative of the actual size of the crater.

b. Effect of Tool Geometry and Feed

Figures 62 and 63 demonstrate typical opposite trends with regard to optimum or best normal rake angle, γ, and best side cutting edge angle, χ, depending upon whether flank wear or crater wear is used as the criterion for the end of useful tool life. The results are for the P30 carbide, but similar results were noted for the P10 material.

The data are significant, for they indicate that tool geometry may be a more important factor in carbide tool wear than is generally understood. Obviously the presence of such contradictary guide lines requires more research not only to provide a broader base for making proper selections of tool shape, but for determining the causes. Cutting temperature distributions, development of crater and flank profiles, and shape of the cross section of the chips would provide valuable contributions if documented and analyzed during the entire useful life of the cutting tools.

c. Nose and Groove Wear

Wear along the cutting edge and nose of turning tools is an important factor in the determination of surface quality; particularly in finish operations. The University of Delft, under the direction of Professor Pekelharing, has specialized in studying the problems of finish machining, and has developed special techniques in which the consequences of nose wear and groove wear may be adequately observed. The progression of wear with time can be studied from a single picture made by superimposing a series of photographs from consecutive time intervals one upon the other as illustrated in Figure 64. Nose wear and groove wear are defined as N and G, respectively.

Professor Pekelharing's technique makes no attempt to explain the causes of nose and groove wear, but it does provide an interesting study of the effect of tool wear upon the surface roughness of the workpiece and the interaction of this resulting roughness pattern on the tool configuration.

Results with carbide tools indicate that nose wear increases continuously with time, as would be expected. However, groove wear can actually decrease during longer cutting times after reaching a peak value in earlier stages. It was found that the grooves have a pitch equal to the feed.

d. American Carbides

The tests with American carbide tool materials are covered in Part II of this report. The initial emphasis has been placed on extensive description

V vs S

α	γ	λ	χ	ε	r
6		0	70	90	0.8mm 0.032 in

WORK MATERIAL: XC 45
TOOL MATERIAL: CARBIDE P30
SIZE OF CUT: 3 x (Var mm^2
=0.12 x 0.01 in^2
TEST NO 2.1,2,3 3.1,2

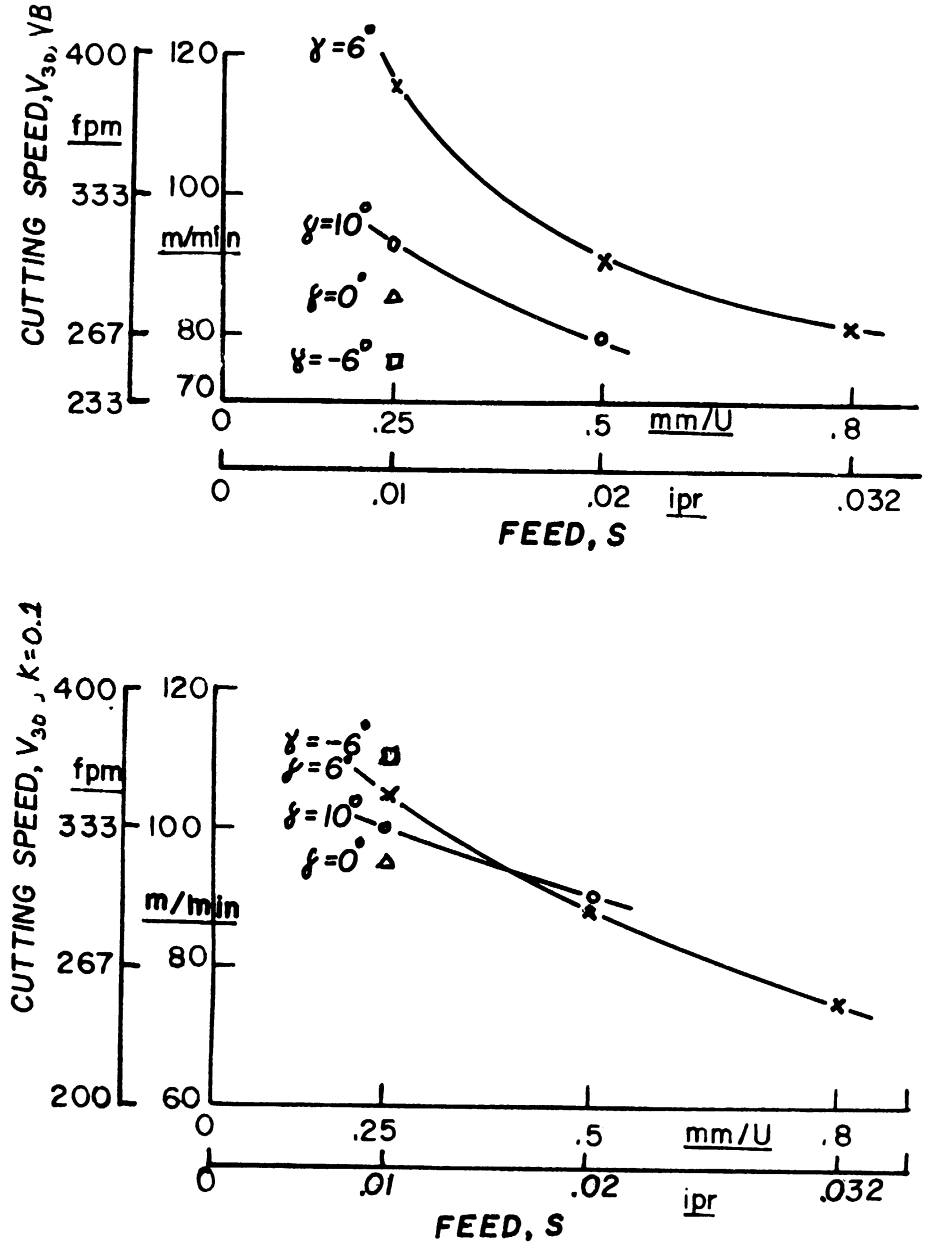


Figure 62. Variations in normal rake angle shown contradictory trends when V_{30} is based upon flank wear or crater ratio as failure criteria.

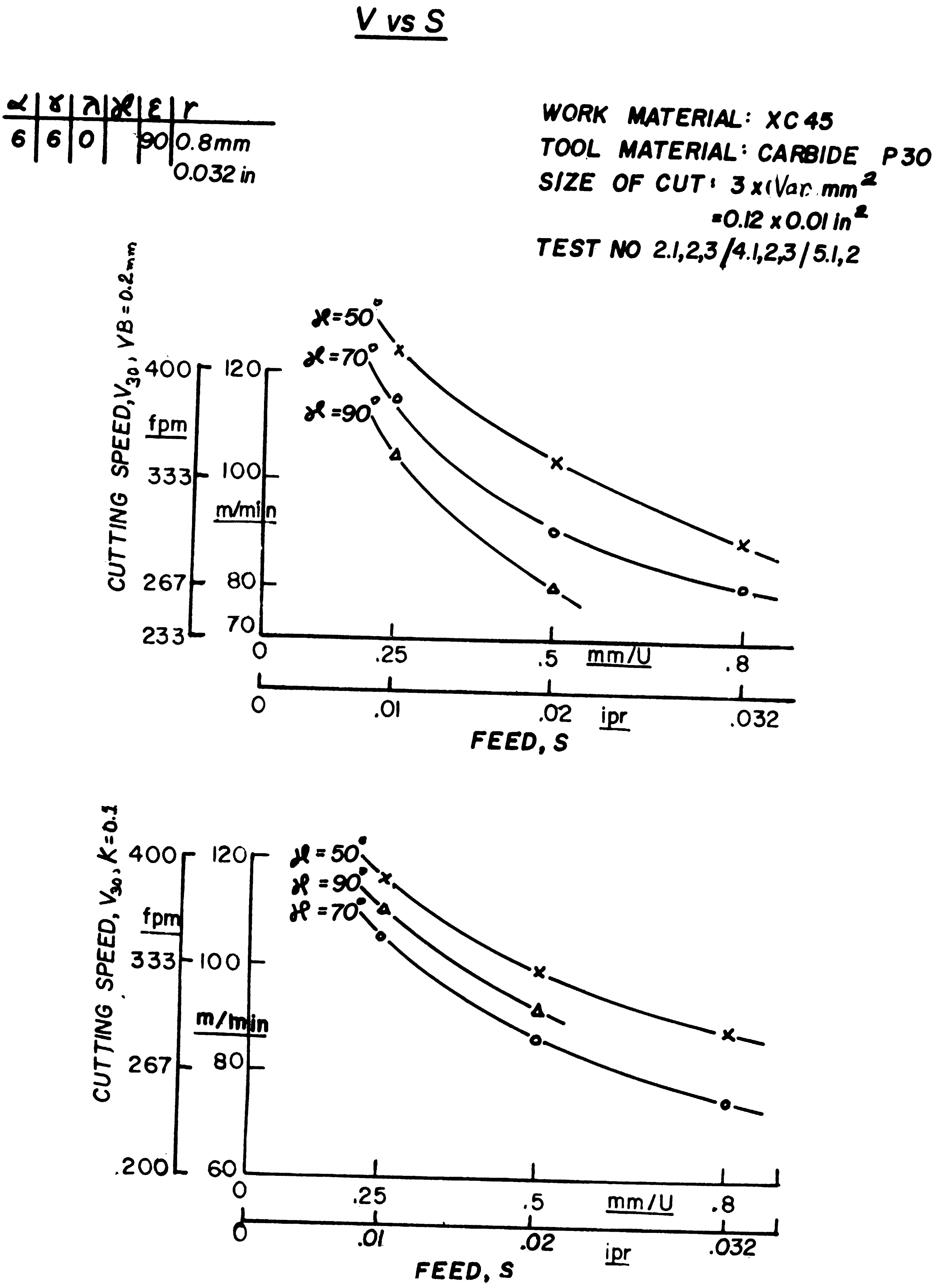


Figure 63. Optimum side cutting edge angle is also influenced by form of failure criterion, flank wear or crater ratio.

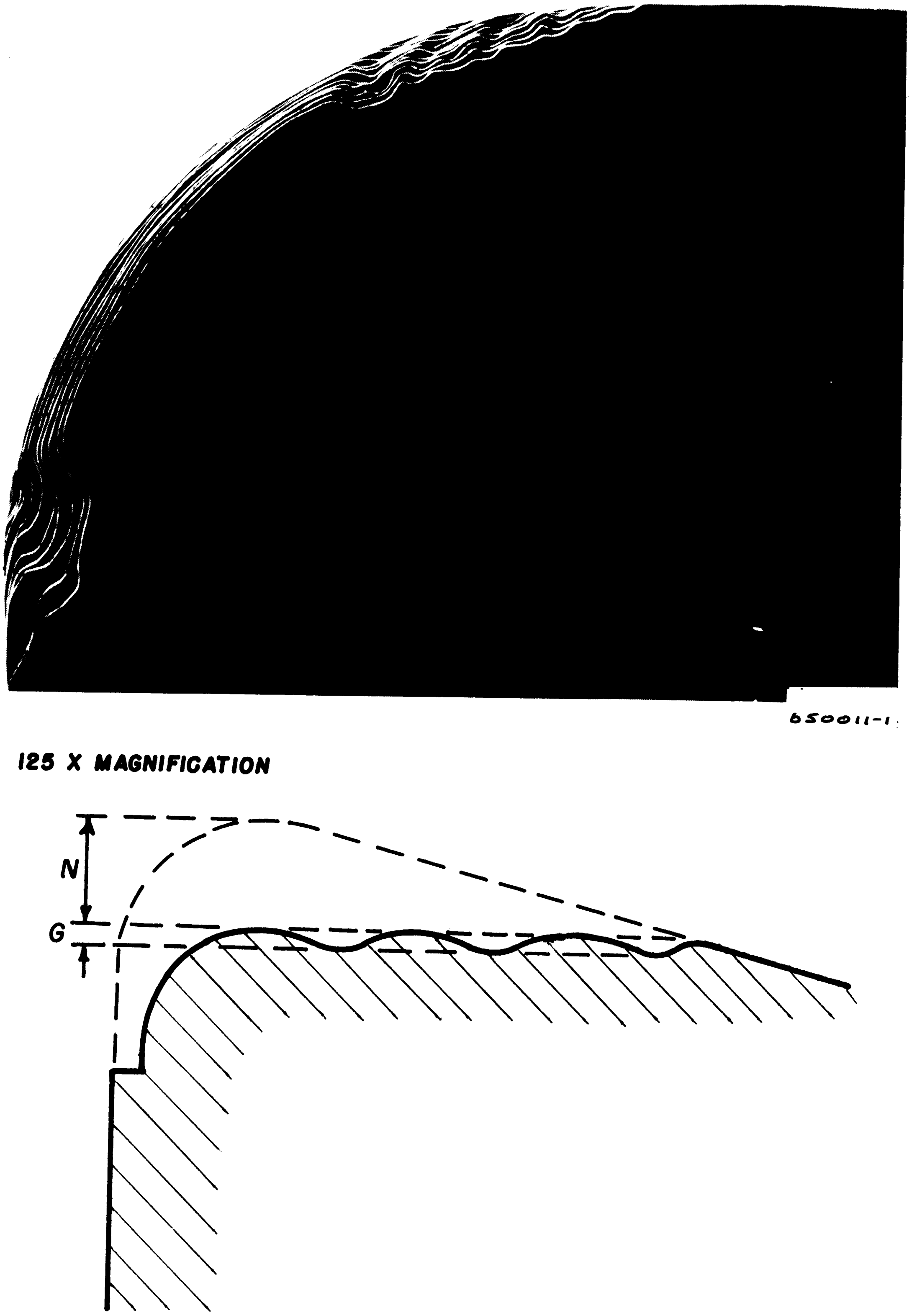


Figure 64. Photograph and schematic of tool wear in finish machining.

of crater wear. Entire craters are traced at given time intervals, and the results are plotted to give crater profiles as in Figures 65 and 66. As these figures indicate, this has been found to provide a very sensitive indication of differences among carbide grades. It is contemplated that this technique will be extended to cover all carbide grades for at least short time intervals at the OECD/CIRP cutting conditions. This will provide not only an indication of differences among the grades, but will establish a "tie-in" with the wealth of information available from the main program.

2. High Speed Steel Tools

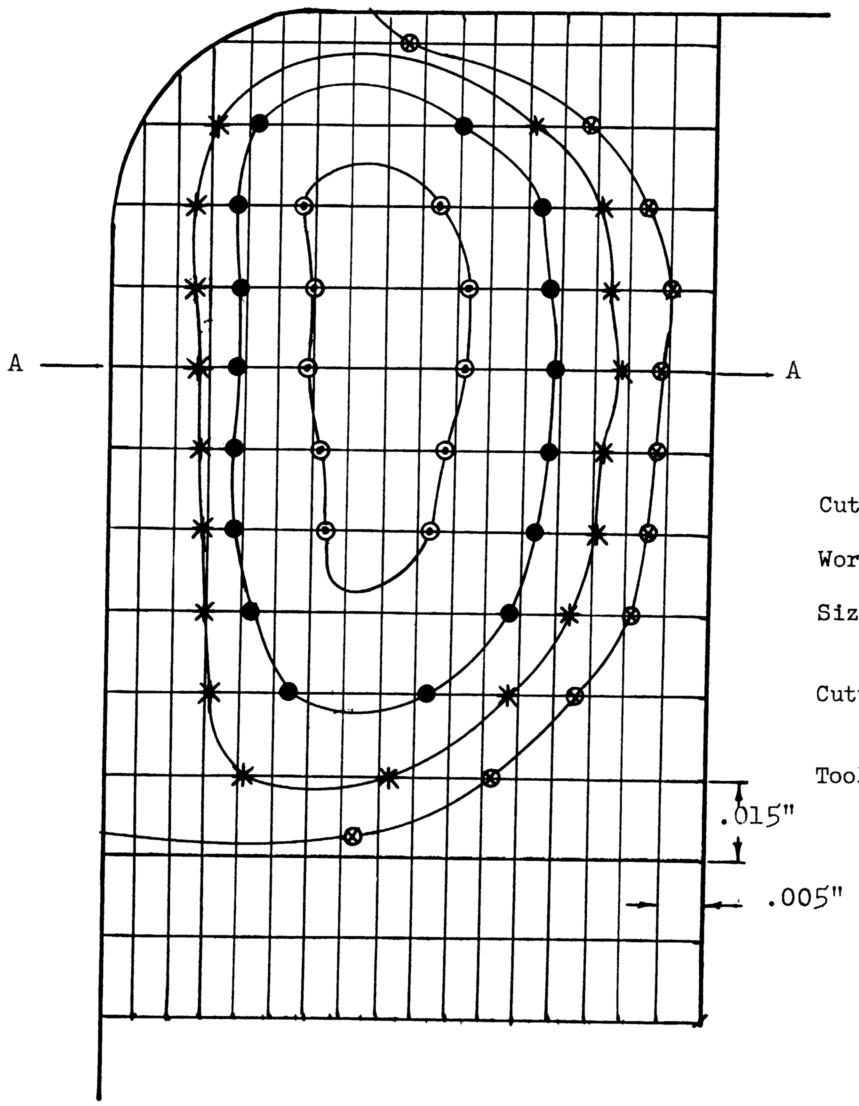
The high speed steel program with the European EW9Co10 tool material has been plagued by extreme dispersion reported by virtually all participating laboratories. The problem has not yet been resolved to full satisfaction. Opinions of various investigators have focused attention on tool composition, heat treatment, grinding practice, and standardized cutting conditions. On the basis of tests at The University of Michigan with carefully prepared tools, there is evidence to support the claim that the high cobalt content of the EW9-Co10 steel is a possible cause of difficulties both in grinding and in relation to the OECD/CIRP test conditions.

Figure 67 gives the tool life results (based on total failure) on four American grades and the European grade of high speed steel. It is noted that the greatest dispersion in results among the American tools occurred with the two grades which have high cobalt contents (~ 8%). On the other hand, these same tools were capable of slightly higher velocities for given tool lives. Excessive dispersion of results was not experienced with the EW9Co10 grade, but in fairness to European results, only a limited number of tests were made. It compared very favorably with the best of the four American grades.

The high speed steel program is covered in more detail in Part III of this report.

III. ADDITIONAL OECD/CIRP RESEARCH IN METAL CUTTING

Although the tool wear program has received the greatest participation, there are a number of laboratories including those at the Carnegie Institute of Technology and the Cincinnati Milling Machine Company that are engaged in other phases of activity—Mechanics of Cutting and Cutting Forces, Machined Surfaces, Metallurgical Properties of Machined Steel, and Statistical Programming among others. When available, many of the reports covering the results of work accomplished have been included either in close association with the tool wear results or as separate sections.



CRATER DEPTH

⊗ - 0.0 µ in. 0 µm
✱ - 1,600 µ in. 40 µm
● - 3,200 µ in. 80 µm
⊙ - 4,800 µ in. 120 µm

Cutting Time: 2 min.

Work Material: XC 45 (0656)

Size of Cut: 3 x 0.25 mm^2
0.12 x 0.01 in^2

Cutting Velocity: 160 m/min = 525 fpm.

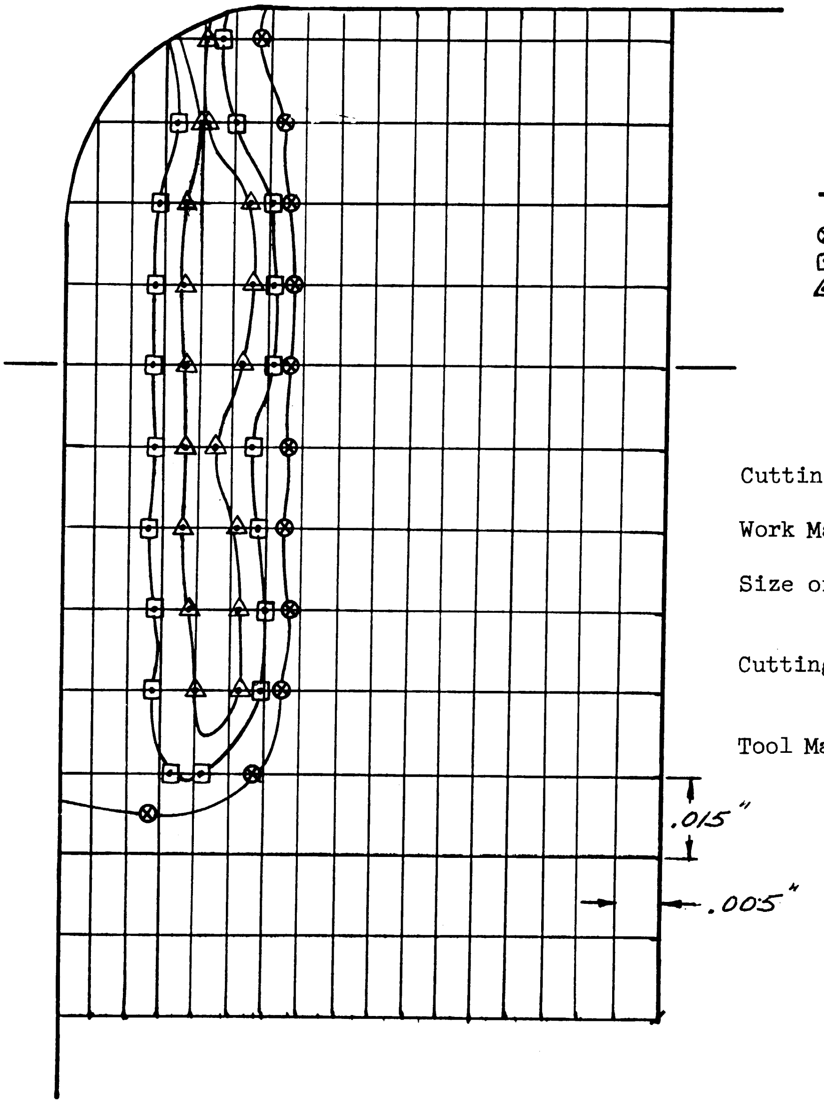
Tool Material: K68 Carbide

TOOL GEOMETRY

α	γ	λ	$\varkappa$	ε	r
6	-6	-6	70	90	0.8mm 0.032in

SCALE 50:1

Figure 65. Crater on face of K68 carbide grade tool with negative rake at cutting time of 2 min under conditions listed. Differences in behavior of carbide grades are emphasized when results are compared with corresponding crater on K21 grade under identical conditions.



CRATER DEPTH

⊗- 0.0 μin. 0μm
⊡- 100 μin. 2.5μm
△- 200 μin. 5μm

Cutting Time: 2 min.

Work Material: XC 45 (0656)

Size of Cut: 3 x 0.25 mm^2
0.12 x 0.01 in^2

Cutting Velocity: 160 m/min. = 525 fpm.

Tool Material: K21 Carbide

TOOL GEOMETRY

α	γ	λ	χ	ε	r
6	-6	-6	70	90	.8mm .032i

SCALE 50:1

Figure 66. Crater on face of K21 grade carbide is much smaller and shallower than crater of K68 grade under identical conditions as shown in Fig. 65.

Tool Material: Latrobe H.S.S. as indicated
Work Material: XC45 (0648)
Size of Cut: 3 x 0.2 mm^2
0.12 x 0.008 in^2
Tool Geometry: 0,30,6,6,6,0,0.5 mm
0.020 in.

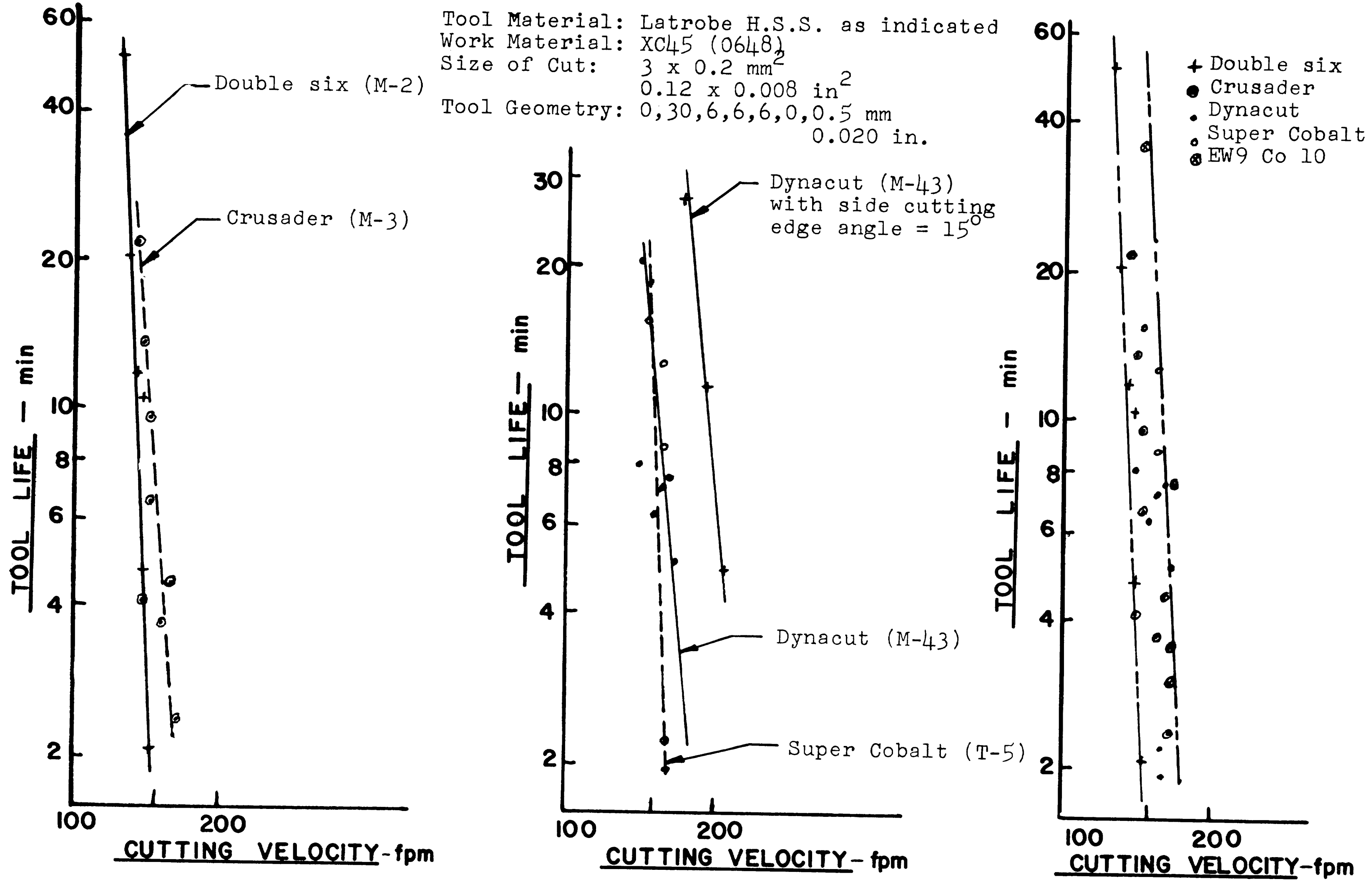


Figure 67. Results of tool life tests with American H.S.S. tools.

Part I of this report presents a summary of work completed on forces and shear zone mechanics as compiled by Mr. Eugene of the French Central Armament Laboratories (LCA), chairman of the subgroup on "Mechanics of Cutting and Cutting Forces." Some interesting work has also been performed by Professor Pekelharing at the University of Delft in which he investigates the effect of built-up edge (BUE) on surface finish in an attempt to determine the cutting conditions for obtaining the best possible surface finish on the XC45 work material. Professor Pekelharing concludes that the best cutting condition is one in which the cutting speed is high enough to eliminate BUE, and that this cutting speed decreases as feed increases. It is affected, however, by work material and tool material properties. More complete information on surface quality will soon be available from other laboratories as well.

One important aspect of the overall cooperative research program is that with proper guidance, proper distribution of work activity, and free and complete exchange of information through reports and scheduled group meetings, the quantity and quality of work done cannot be achieved by any other means. The future of metal cutting research promises to take on more meaning after the first phase of the OECD/CIRP program.

IV. CONCLUSIONS AND RECOMMENDATIONS

Based upon the work done in The University of Michigan laboratories, and the exchange of information among all laboratories, the following conclusions are those of the authors of this report and not necessarily those of the OECD/CIRP committee:

1. It is possible to obtain reasonable agreement across international boundaries as to the machining characteristics of tools and work materials when both are adequately defined and analytical procedures are specified and controlled and test equipment is carefully compared.

2. The international cooperative research approach will:

   a. discover new directions for basic research;
   b. develop better analytical techniques and equipment, and;
   c. make significant progress toward universally depenable procedures and standards which can be applied internationally.

3. The American practice of basing the life of carbide tools only upon flank wear is suspect for many applications.

4. Tool geometry may be a more important factor in influencing the wear of cutting tools than is generally understood. The combined use of flank wear and crater wear to study causes and effects of metal cutting behavior has considerable merit.

For these and other reasons that can be drawn from the results of this study, it is recommended;

1. that the cooperative program be extended to cover other work materials and microstructures as is contemplated in Phase II;

2. that efforts be made to explore a broader range of tool properties and tool shapes;

3. that more exhaustive and correlated analyses be made of the effects of cutting time upon: (a) flank wear, (b) crater wear, (c) cutting forces, (d) cutting temperatures and their distribution, (e) cutting ratio, (f) shape of chip cross section, (g) shape of the crater, and (h) degree and frequency of chips segmentation.

There is a pronounced lack of information of this type which could help to evaluate performance in adaptive control systems, and which could guide metallurgists in developing better tool materials for unique combinations of workpiece composition and microstructure.

APPENDIX

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II. Structural Analysis of XC45 Work Material

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II. Repeatibility of Wear Measurements Between Laboratories
III. Influence of Speed and Feed on Forces, Finish, and Built-Up Edge
IV. A New Method for Studying Tool Wear in Finish Machining
V. Plasticity Study of XC45 Work Material

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13. ABSTRACT

This is the fourth and final report of the series under this contract. It includes coverage of forces and shear zone mechanics, wear of American and European carbide and high speed steel cutting tools, and accelerated tests for evaluating cutting performance. In addition, the report summarizes the objectives, experimental procedures, and related activities of the OECD/CIRP international cooperative research program in metal cutting as detailed in Interim Reports 1, 2, and 3.

The program has shown that it is possible to work successfully among various laboratories and across international boundaries to achieve specific goals. The exchange of information has proved to be not only a valuable check upon the repeatability and validity of results, but has led to improvements in measuring techniques and associated instrumentation for more reliable and more consistent interpretations.

The results have helped to identify those areas which need more intensive studies for evaluation of causes and effects of metal cutting behavior. Phase II, a study of steels of different microstructures and properties, is an important next step in the expansion of the OECD/CIRP program.

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