AN INTERPRETIVE REVIEW

OF

20TH CENTURY US MACHINING

AND GRINDING RESEARCH

An e-Monograph on a Notable Chapter in the Lore of Machining Process Technology

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PREFACE

This e-monograph had its beginning in a grant from the National Science Foundation in 1991 (Grant No. DDM-9196034), administered by its Division of Design, Manufacture and Industrial Innovation of the Engineering Directorate. The intent in preparing such a review was to serve the needs of those in this country, including NSF personnel, who fund, plan, guide or perform research in this field of manufacturing, by reviewing the essence of this country's past contributions to such research. The value of such a review to the research community lies in the fact that, as has often been said, those who have been denied a sense of history are condemned to repeat it. The effectiveness with which we in this country move forward with research in this field will rely on our ability to set the right priorities and directions as a function of where we have been.

In keeping with that fact, it was initially envisioned that the book would be a comprehensive review. However, it became evident by the close of the first phases of this project that the need for such a review had, by that time, already been satisfied. This circumstance was brought about by the production by Professor Ranga Komanduri, of Oklahoma State University, of just such a review in 1993 (1-2). That was presented in a special issue of Applied Mechanics Reviews, titled US Machining and Grinding Research in the 20th Century. His detailed exposition and description of the eventful course of such research provides excellent overall documentation of such.

In light of this development, it was felt that, instead of writing the book initially envisioned for this project, it would serve a much more useful purpose if the effort were directed at providing a unique supplement to Komanduri's masterful detailed review, in the form of a more general monograph on the subject. Such a monograph would be one that would provide an interpretation of how and why the progress of the research detailed by Komanduri took the course that it did. The principal author was in a unique position to create such an interpretation because of his over 60 years of having been immersed in and directly exposed to the main stream of the course of 20th century research in machining and grinding. According to the plan that was then developed, that experience would be supplemented by first-hand, roundtable-type interviews with key still-living researchers who had made major contributions to this field, together with telephone interviews with other influential researchers, plus a questionnaire sent to still others doing research in this field. Therefore the proposed book evolved into a monograph giving a concise interpretative review of such research and centered about a selection of some of the most influential events in that research, while still serving the original intent stated above. A first draft of the monograph was completed in 1995 and a copy of that was sent to all the still-living researchers whose work was cited in it (as well as to NSF) asking for their corrections and comments. Some 13 responses were received.

Meanwhile, possibilities for publishing the monograph were explored, but no appropriate ones materialized, so the document was not put in final form at that time. However, the possibility of publishing it as a free online e-document on TechSolve's website recently became available, so it was then put in final form for such publication. We are happy to be thus able to make it available to all interested parties in academia, industry, government or elsewhere, as an aid to guidance and enrichment of machining and grinding research conducted there. We hope you may find it helpful and useful.

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CHAPTER 1

INTRODUCTION

– The Beginnings

Purpose

As indicated in the Preface, the purpose of this monograph is to serve the needs of those in this country who fund, plan, guide or perform research in the field of machining and grinding, by interpreting the essence of this country's past contributions to such research. Its objective is to accomplish this by providing an interpretive historical review of the most significant research on the technology of the machining and grinding of metals done in the United States during the period beginning with the pioneering research of F.W. Taylor (1-1)#, reported on by him in 1907, and extending into the 1980's. This period has been chosen because the research that was done during it produced and tested the machining and grinding technologies that are considered to be the basis for the engineering of those processes today.

The Technology - Its Nature, Early History and Current Importance

The industrial production of useful parts and objects by the removal of material, for the purpose of producing a desired shape, is today almost exclusively carried out by the processes known as machining and grinding. Here, the metal is removed by sharp-edged cutting tools, or by abrasive grinding wheels, propelled and guided by precise machines termed machine tools. Thus, the technology of the machining and grinding of metal is primarily concerned with the characteristics and performance of three main players; namely, the cutting tool, the machine tool and the material being cut or ground.

Machining, as a machine-performed process suitable for utilization to produce products on an industrialized basis, came into being in 1775 with the invention by Wilkinson, in England, of a boring machine capable of boring a cylinder true “within the thickness of a worn shilling”, making it possible for Isaac Watt to manufacture his previously invented, but then un-producible, steam engine. With such a process in existence, a number of machine tools were developed between 1840 and 1850 in a form similar to today’s. As a result, a few intrepid investigators in France, Germany, Russia and Britain tried their hand at probing the technological mysteries of the process, but without much attention being paid to their findings, especially in this country. Further, their findings and conclusions were often far from being in agreement with one another, resulting in confusion and disinterest on the part of industry in general, as well as in a lack of any coherent basis for engineering of the machining process. Not until Taylor, starting in 1881, carried out his 26-year program of research on the engineering characteristics of the machining process did that situation change, ushering in an era in which a coherent basis for engineering the industrial application of that process began to unfold. A description of Taylor’s pioneering efforts in this field follows in Chapter 2.

Today, the machining and grinding of metals is by far the most widely used machine-performed process in the production of mechanical products by the manufacturing industry of the United States (and of other industrialized nations as well). As such, its economic impact is tremendous. These facts can be illustrated, for example, by means of data derived from the

"14th American Machinist Inventory" of machine tools installed in metalworking plants in the United States, published by American Machinist Magazine in 1989 (1-3). That inventory revealed that, as of 1989, almost 1,900,000 metal cutting and grinding machines were installed in the American metalworking manufacturing industry. (Of these, approximately seventy-five percent were machines for cutting metal and twenty-five percent were grinding machines.) Even using the most conservative values for the direct labor and the overhead costs incurred in the operation of these machines, one could calculate that the total cost of labor plus overhead for the operation of such was approximately $136 billion annually. This cost could then be compared with the value of the portion of the U.S. gross domestic product produced by the entire U.S. manufacturing industry at that time. That amounted to roughly $900 billion in 1989. Thus, the cost of machining and grinding in the U.S., even conservatively estimated, amounted to approximately fifteen percent of the value of all products produced by the manufacturing industry in this country at that time! Making the same calculation over the years, using each year's values for the various quantities, has revealed that this approximate percentage value has remained virtually unchanged. Thus the importance to the economic well being of this nation of continuing excellence in research to develop new and ever more productive machining and grinding technology for the engineering of these processes is evident.

Scope of the Review

As stated at the beginning of this introduction, the period covered by this review is that from the time of F.W. Taylor's pioneering research on machining of metals up to the 1980's. The review focuses almost entirely on research conducted in this country. Overseas research is mentioned only to the degree that it may have significantly influenced U.S. research. Further, the review is concentrated wholly on the two most extensively used material removal processes, namely material removal with edged cutting tools and with grinding wheels, i.e., machining and grinding. The so-called non-conventional material removal processes, such as electrical discharge machining (EDM), electro-chemical machining (ECM), water jet cutting and laser cutting are not included. This is done primarily because of their lesser use in industry. This choice of coverage also avoids complicating the research picture by inclusion of removal type processes that are very different from machining and grinding in their nature and thus in much of their technology and origin.

The procedure used in gathering the information for this review of research was somewhat unusual in that, in addition to the usual searching of the literature, it employed a large component of information-gathering from first-hand sources; i.e., those living persons who actually performed or had first-hand knowledge of the most significant portions of that research. Since a description of the specific details of that procedure is rather lengthy, that is presented separately in Appendix 1.

REFERENCES

Chapter 1

1-1 Taylor, F.W. 1906. On The Art of Cutting Metals, Transactions, American Society of Mechanical Engineers, Vol. 28, pp. 70-350.

1-2 Komanduri, R, 1993. Machining and Grinding: A Historical Review of the Classical Papers, Applied Mechanics Reviews, Vol. 46, pp. 80-132.

1-3 The 14th Inventory of Metalworking Equipment, American Machinist, 1989. Vol. 133, pp. 91-110.

CHAPTER 2

THE EARLY YEARS - AN AGE OF EMPIRICISM

The Beginnings into the 1940s

A Time of Engineering Ignorance

The invention of an industrially practical boring machine by Wilkinson in Britain in 1775 made it possible for James Watt to actually produce the steam engine that he had earlier invented. However, it was not until about 1840-1850 that a number of machine tools of industrially practical form, corresponding to what is now considered traditional, were developed and began to be manufactured in significant numbers. As a result, as indicated in Chapter 1, in the section on Scope of the Review, a few pioneering researchers in France, Germany, Russia, and Britain began to try to understand the mysteries of the machining process. As described by Ernst (2-1) in 1951 and elaborated on by Finnie (2-2) in a 1955 review of early metal cutting analyses, these investigators conducted experimental studies of the processes involved in chip formation in machining, and developed rudimentary theoretical analyses relating to the forces and power required in such, beginning as early as about 1850. (Chapter 3 includes brief details of this early research carried out in Europe). However, as Ernst points out (2-1), the findings of these pioneering researchers appear to have been passed by almost without notice by later workers.

There appear to be at least two important reasons for this lack of attention to developing any fundamental understanding of the principles underlying this important manufacturing process.

First is the fact that, to most utilizers of the machining process, it appeared to be a simple, straightforward, "brute-force" type of methodology, amenable to ordinary "common-sense" type approaches. Second, and more importantly, the primary need at this stage, for those who were "engineering-minded" enough to recognize it, was to try to find an engineering basis for determining proper machining parameters (such as cutting speed, feed rate, and cutting tool characteristics) for obtaining predictable and high productivity in applying the machining process in practice, rather than to try to develop a fundamental understanding of the process.

The principal process variable controlling productivity in machining is tool life — the elapsed time until an originally sharp tool becomes so worn ("dull") that it no longer can be depended upon to produce an acceptable machined part. Such more readily quantifiable machining variables as forces and power, while important, are of secondary importance to machining productivity, compared to tool life. However, tool life is, as could be expected, a direct function of the rate of wear of the cutting tool under given machining conditions — a highly elusive quantity from the point of view of establishing a sound theoretical basis for predicting it. Thus, the only alternative for establishing engineering equations for calculating tool life as a function of machining conditions was to develop them by empirical means, using extensive controlled experiments.

As can be appreciated, such a research undertaking is no small task, and one made almost insurmountable in the absence, in those early days, of significant sources of funding or of facilities, academic or industrial, devoted to manufacturing research. Add to that the general lack of understanding or appreciation of not only the need for such engineering research but also of the nature of the engineering problem to be solved, given the prevalence of the "brute-force," common-sense" view among utilizers of the processes.

Fortunately, an individual emerged who understood both the need and the problem, and who was also able to help the company that employed him to understand that supporting the research needed to develop the basic engineering "building blocks" could give them a major competitive advantage. That man was Frederick W. Taylor, and the company was the Midvale Steel Works, which he joined in 1878.

Eric Thomsen (2-3), Emeritus Professor of Mechanical Engineering at the University of California-Berkeley, presented a paper to the ASME Production Engineering Division in 1982 titled "F. W. Taylor — A Historical Perspective." In this, Thomsen both reviewed and critiqued Taylor's contributions, and also described them. This has served as a valuable source to us, along with Taylor's own publication of his work, previously cited as reference 1-1, in the discussion of Taylor and his background that follows.

Fig. 2.1 F.W. Taylor, 1856-1915

A Young Engineer Faces Up to the Challenge

Frederick Winslow Taylor was born March 20, 1856, in Germantown, Pennsylvania. At the age of 18, although he was prepared to enter Harvard University, he was advised to give this up because of apparent problems with his eyesight. Instead, he entered an apprenticeship and pursued a four year journeyman's course that trained him as a patternmaker and machinist. Upon completing that in 1878, he started work with Midvale Steel Works, but as a laborer, not a machinist, due to the depressed economy of the time. However, he proceeded to earn a degree in mechanical engineering in a three-year night course, while advancing through various departments at Midvale. Six years after starting there, Frederick Taylor had advanced to the position of chief engineer. In 1880, when he was made foreman of Midvale's machine shop, he began a series of metal cutting experiments that eventually resulted in an increase of 200-300 percent in the productivity of the machines and an increase of 25-100 percent in the pay of its machinists!

This came about as follows. Beginning with his work as a shop clerk in charge of the tool room, Taylor noted that the machinists each had only their own judgment and experience to guide them in the selection of cutting tools, grinding them to shape (which they did individually), and selecting the cutting speed, feed, and depth of cut to be used in machining each given part. It seemed evident to him that, because of this situation (which was standard practice in all mechanical shops at that time) the machinists were, on average, accomplishing less than half of what they should be capable of doing. When he was promoted to foreman of the machine shop, he began an effort to get the machinists to increase their output by encouraging them to use what he considered to be more appropriate cutting speeds, feeds, and depths of cut. He found, however, that his knowledge of just what combination of these three would do the work in the shortest time, for each different job, was even less accurate, on average, than that of the machinists. Further, there was no body of knowledge, mathematical relationships, or even data, in existence to guide him. In other words, there were no engineering tools or methodologies in existence to answer the three questions, which, in

Taylor's own words, "must be answered each day in every machine shop by every machinist who is running a metal cutting machine" -- namely:

1. What tool shall I use?
2. What cutting speed shall I use?
3. What feed shall I use?

However, Taylor’s conviction that the machinists were producing half as much output as they should be able to was so strong that he obtained the permission of the management to carry out a series of experiments to investigate the "laws" of the cutting of metals, with a view to establishing the needed body of knowledge. He expected that these experiments would take not longer than six months. Instead, they went on for 26 years!

The fact that Taylor was able to obtain permission to run these experiments so readily, and to continue to experience support for them as they went on and on, was due to the fact that William Sellers, who was well known to be one of the most patient and broad-minded experimenters of the day, was president of Midvale at that time. It was Sellers who, in spite of protests that were made against continuing the project, allowed the experiments to proceed; even, at first, at a very considerable inconvenience and loss of production in the shop. The extent of that inconvenience is well described in Taylor's own words, to quote Reference 1-1:

> "…we were using a 66-inch diameter vertical boring mill, belt-driven by the usual cone

> pulleys, and, in order to regulate the exact cutting speed of the tool, it was necessary to slow down the speed of the engine that drove all of the shafting in the shop; a special adjustable engine governor having been bought for this purpose. For over two years the whole shop was inconvenienced in this way, by having the speed of its main line of shafting greatly varied, not only from day to day, but also from hour to hour. Before the two years had elapsed, however, the writer had obtained such valuable and unexpected results from the experiments as to much more than justify all of the annoyance and expenditure, and soon after that he readily obtained permission to employ a young technical graduate to devote his whole time to the continuation of this work."

Taylor's efforts to establish empirical "laws" (so-called) describing the relationships between the engineering variables governing the performance of the machining process then gathered momentum. Still, he encountered a long period of frustration before he was able to obtain valid data on which to base these "laws." He was aware from his experience in the machine shop that the principal factor controlling how quickly a part could be economically machined with a given tool was the effect of cutting speed on tool life. The higher the cutting speed that could be used to obtain a given, economical tool life in machining a part, the faster that part could be machined. Taylor therefore concentrated on establishing the relationship between cutting speed and tool life for various values of feed, depth of cut, and other cutting conditions. The problem he encountered was that when he ran cutting tests at speeds resulting in very short tool lives, the resulting tool life data was quite consistent, but each test consumed an enormous amount of work material and took a very long time. It took him eight years to find that a cutting speed giving a tool life of twenty minutes was the only practical one to use in the testing, in the face of this problem, since it provided dependable data without consuming an inordinate amount of work material. To quote Reference 1-1,Taylor said:

> "It was only after about 14 years' work that we found that the best measure for the value of a tool lay in the exact cutting speed at which it was completely ruined at the end of 20 minutes. In the meantime, we had made one set of experiments after another as we successively found the errors due to our earlier standards, and realized and remedied the defects in our apparatus and methods; and we have now arrived at the interesting though rather humiliating conclusion that with our present knowledge of methods and apparatus, it would be entirely practicable to obtain through four or five years of experimenting all of the information which we have spent 26 years in getting."

A Team Is Formed

It was probably such frustrations as this that soon brought Taylor to the realization that carrying out an engineering project of such scope as this one required a variety of knowledge and experience going well beyond his own. His answer to this need was to bring on board a team of people having, collectively, the breadth of knowledge and experience required to competently handle the scope of the undertaking. (This is certainly reminiscent of today's highly effective multi-disciplinary team approach to the carrying out of engineering projects.) The members of this team were:

Mr. H. L. Gantt, a graduate of Stevens Institute of Technology, who, being a talented manager, managed the experimental program

Mr. Maunsel White, also a graduate of Stevens Institute of Technology, who was an accomplished metallurgist

Mr. Carl G. Barth, a graduate of the Technical School of Horten, Norway, who was a talented mathematician.

This team, headed by Taylor, worked actively on this project throughout the remainder of the 26 years, as reported on by him in his historic ASME paper of 1906 (cited previously as reference 1-1). The team left Midvale Steel Works in 1889, 11 years after Taylor joined that company. However, they continued to carry on the investigations in one plant after another, funded by various companies. Taylor acknowledges being especially indebted to Cramp's Shipbuilding Company, Messrs. William Sellers (former president of Midvale and Company), Link-Belt Engineering Company; Messrs. Dodge and Day, and most of all, to Bethlehem Steel Company.

During the course of the 26 years, ten machine tools had been fitted with special drives and other needed equipment for running the experiments. All those used after 1894 were equipped with electric motor drives to make it possible to operate at any desired cutting speed. During the 26 years, using these machines, between 30,000 and 50,000 recorded experiments were made and more than 400 tons of steel and iron were cut into chips. The entire program of experiments was devoted to the taking of roughing cuts on castings and forgings, since light or finishing cuts were not of interest to the particular firms supporting the investigation. However, the empirical rules and principles that were developed from the research by Taylor and his team have, in large part, been found to apply, in principle at least, to machining with lighter cuts as well.

The one result of this extensive research project that is still well known to, and used by, all manufacturing engineers is the establishment of the basic empirical relationship, known as Taylor's Law, between cutting speed and tool life in machining. The formula is:

$$VT^n = C \tag{2.1}$$

where V = cutting speed, ft/min

T = tool life, minutes

C = a constant, incorporating the effects of all the cutting conditions, such as feed and depth of cut, on tool life

n = approximately 1/8 for steel

This is used to calculate cutting speeds to be used to obtain desired tool lives under a given set of cutting conditions, when the tool life obtainable at one particular cutting speed is known. It has been found to correlate well with experimental results, almost universally, though the value C, and to a lesser extent n, of course varies considerably from one type of machining application to another.

Impressive Accomplishments Achieved

Yet, the years of research and experimentation produced, of course, far more comprehensive results than this. Taylor summarized the broad accomplishments of those years as follows, quoting Reference 1-1:

1. "The determination by a series of experiments of the important facts or laws connected with the art of cutting metals."
2. "The finding of mathematical expressions for these laws which are so simple as to be suited to daily use."
3. "The investigation of the limitations and possibilities of metal cutting machines."
4. "The development of an instrument (a slide rule) which embodies, on the one hand, the laws of cutting metals, and on the other, the possibilities and limitations of the particular lathe or planer, etc. to which it applies and which can be used by a machinist without mathematical training to quickly indicate in each case the speed and feed which will do the work quickest and best."

As the first milestone in the progress through this set of accomplishments, Taylor identified, by means of the experiments, those variables which have the most significant effects on the choice of an appropriate set of cutting conditions for machining a given part in the shortest time, by turning. The variables so identified were as follows:

1. The quality of the metal to be cut.
2. The diameter of the workpiece.
3. The depth of cut.
4. The feed per revolution of the workpiece.
5. The elasticity of the work or tool.
6. The shape or contour of the cutting edge of the tool, together with its clearance and rake angles.

7. The chemical composition of the steel from which the tool is made, and the heat treatment of the tool.
8. Whether or not a copious stream of water, or other cooling medium, is applied to the tool.
9. The duration of the cut; i.e., the time during which a tool is actually cutting metal before it needs to be reground (normally termed "tool life").
10. The force exerted on the tool by the cut.
11. The value of speeds and feeds available on the lathe.
12. The maximum power, torque, and tool feeding force available on the lathe.

Taylor and his team identified these by varying only one of all possible variables (including the above) at a time, while holding all the other possible variables as nearly constant as possible. The magnitude of the effect which each had (if any) on the cutting speed that would yield a desired given tool life was thereby determined. (Taylor selected 20 minutes as the desired tool life in these tests.) The resulting mass of data on the way in which cutting speeds for 20 minutes of tool life varied with each of the 12 significant variables was studied to try to identify facts and empirical laws governing the behavior of this tool life under the influence of each variable, and combinations of them, and to develop mathematical expressions for such. The hope was that these expressions would indeed be simple enough for daily use by machinists, but unfortunately, with few exceptions, this was not the case. As a representative example of the complexity of these expressions, the all-important general relationship for calculating the cutting speed for a 20-minute tool life in the turning of steel was expressed by the following empirical equation:

$$V_{20} = \frac{\text{Constant}\left(1 - \frac{8}{7(32r)^2}\right)}{\left\{\text{f exp.}\left(\frac{2}{5} + \frac{2.12}{5+32\text{r}}\right)\right\}\left\{\frac{48d}{32r}\text{exp.}\left(\frac{2}{5} + 0.06\sqrt{32\text{r}} + \frac{0.8(32\text{r})}{6(32\text{r}) = 48\text{d}}\right)\right\}} \text{--} \qquad (2.2)$$

where V_{20} = cutting speed for a 20 minute tool life, ft/min.

r = tool nose radius, in.

f = feed per revolution, in.

d = depth of cut, in.

Attempts were then made to provide tables of data that could be used by machinists to select an appropriate set of cutting conditions for machining a given part in the shortest time on a given machine. However, in the words of Taylor, "This method was…so exceedingly slow and laborious as to make it far from generally useful." The approach that finally proved successful was to develop slide rules. Barth, Gantt, and Taylor, working as a team, with Barth taking the lead, carried out this work. Concerning this latter fact, Taylor stated, "Mr. Barth is a better mathematician than either Mr. Gantt or the writer and it is very largely due to his long continued work, both on the slide rules and in revising the expressions for the laws, that the present solution of the problem is due." The three patented the basic slide rule jointly. The slide rules provided a practical solution to the mathematical problem of applying the empirical laws that had been found to govern the effect of the 12 variables described above on what Taylor had called the three great questions:

1. What depth of cut shall be used?
2. What feed shall be used?
3. What cutting speed shall be used?

An example of the slide rules, this one being titled by Taylor "Slide Rule Embodying the Important Laws Deduced by Us," is shown in Figure 2.2.

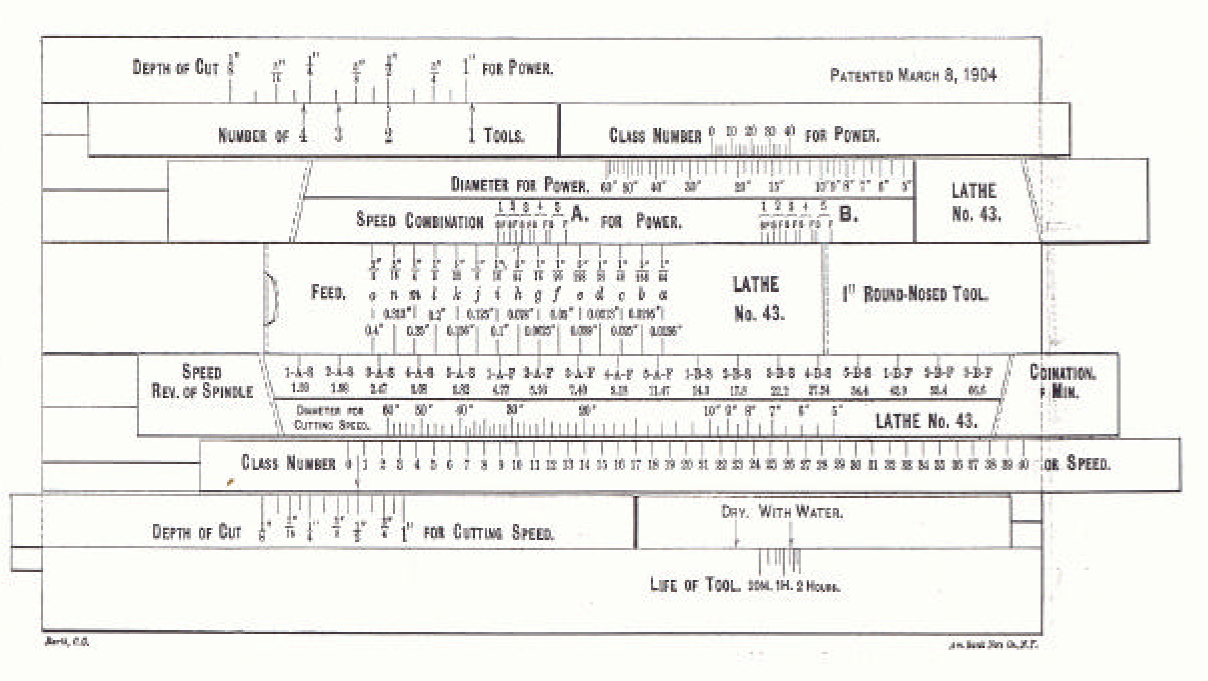

Fig. 2.2 Example of the slide rules developed by the team

The development of the empirical relations and of the slide rules were not the only significant accomplishments of the 26 years of effort by Taylor and his team. Taylor presented a chronological listing of 18 items that he considered to be "some of our more important steps." A selection of those that seem to illustrate the evolution of the team's thinking and understanding, or to have proven to be of particular significance to later developments, stated in abbreviated form and more or less in Taylor's own words, is as follows, quoting Reference 1-1:

1. In 1881, the discovery that a round-nosed tool could be run under given conditions at a much higher cutting speed, and therefore turns out much more work, than the old-fashioned diamond-pointed tool.
2. In 1881, the demonstration that, broadly speaking, the use of coarse feeds accompanied by their necessarily low cutting speeds would do more work than would the use of fine feeds with their accompanying high speeds.
3. In 1883, the discovery that a heavy stream of water poured directly upon the chip at the point where it is being removed from the steel forging by the tool would permit an increase in cutting speed, and therefore in the amount of work done, of from 30 to 40 percent.
4. In 1883, the completion of a set of experiments with round-nosed tools: first, with varying values of feed rate while the depth of the cut was maintained constant; and secondly, with varying depths of cut while the feed remained constant, to determine the effect of each of these elements on the cutting speed.
5. In 1883, the demonstration of the fact that the longer a tool is called upon to cut before failure, the slower must be the cutting speed, and the exact determination of the effect of the duration of the cut before tool failure upon the cutting speed.
6. In 1883, the development of the mathematical expression of the foregoing relationship between cutting speed and tool life. (See Equation 2.1.) Fortunately, this formula, and

those that were subsequently developed, turned out to be of exponential form, greatly facilitating the eventual development of the slide rules.

7. In 1883, the experimental determination of the force on the tool involved in taking cuts at various depths and feeds.
8. In 1884, the design of an automatic grinder for grinding tools in lots and the construction of a tool room for storing and issuing ready-ground tools to the men.
9. From 1885 to 1889, the making of a series of practical tables for a number of machines in the shops of the Midvale Steel Company, by the aid of which it was possible to assign precisely defined tasks each day to the machinists who were running machines, resulting in a great increase in their output.
10. In 1886, the demonstration that the thickness of the chip or layer of metal removed by the tool has a much greater effect upon the cutting speed for a given tool life than does any other element.
11. In 1894 and 1895, the discovery that a greater proportional gain could be made in cutting soft metals through the use of tools made from self-hardening (air hardening) steels than tempered tools in cutting hard metals. The gain in cutting speed for a given tool life made by the use of self-hardening tools over tempered tools in cutting soft cast iron was almost 90 percent, whereas the gain in cutting hard steels or hard cast iron was only about 45 percent. This experiment resulted in substituting self-hardening tools for tempered tools for all "roughing work" throughout the machine shop.
12. In 1894 and 1895, the discovery that in cutting wrought iron or steel, a heavy stream of water thrown on the chip at the nose of the tool produced a gain in the cutting speed of self-hardening tools of about 33 percent. Up to this time, the makers of self-hardening

steel had warned users never to use water on the tools.

13. From 1898 to 1900, the discovery and development of the Taylor-White process of treating tools; namely, the discovery that tools made from chromium-tungsten steels, treated by heating to the melting point, would increase production rates from two-to-four times compared to other tools. This was the discovery of modern high-speed tool steel.
14. In 1899-1902, the development of our slide rules, which were so simple that they enabled an ordinary workman to make practical and rapid everyday use in the shop of all the laws and formulae deduced from our experiments.

15. In 1906, the discovery that by adding a small quantity of vanadium to tool steel to be used for making modern high-speed chromium-tungsten tools treated by heating to near the melting point, the red hardness and endurance of tools, as well as their cutting speeds for a given tool life, materially improved.

Looking at Taylor's 26-year research project in retrospect, one must, first of all, conclude that Taylor was, and remains, one of the world's great engineers. He created a monumental body of engineering knowledge and understanding of the machining process — a process of major importance to the economic well being of industrialized nations — where before an almost total vacuum had existed. That knowledge and understanding has remained fundamental to the practice of manufacturing engineering as it has evolved throughout the years, and remains so even today.

A Lesson Goes Unlearned

Despite this fact, Taylor is little known for his groundbreaking research on machining, except among manufacturing engineers. He is, however, quite widely known, and justifiably so, for his thinking and classic work on factory management, since this reached the non-engineering component of industry as well as its engineering component. Taylor expressed disappointment that the results of his pioneering research on machining, when published, attracted so much more attention than did his publications on factory management (since he considered the latter to be of greater importance to industry). However, that situation was in time reversed, in part because what was thought to be his management philosophy became so controversial.

But his philosophy was misunderstood. He was thought to have been a principal advocate of the concept of the division of labor in manufacturing. However, his principal concept, instead, favored increased cooperation and teamwork in manufacturing. His acceptance of the concept of division of labor was secondary, necessitated by the relatively low, unsophisticated level of the education of factory workers of his day. As noted earlier in this chapter, he quite early recognized the distinct benefit of carrying out an engineering project (such as his research project on machining) by means of a multi-disciplinary team. Further, that concept did not stop there. That is well illustrated by one of the closing two paragraphs of Part 1 of his historic ASME paper presenting the results of his 26 years of research on machining:

> "In concluding, let me say that we are now but on the threshold of the coming era of true cooperation. The time is fast going by for the great personal or individual

> achievement of any one man standing alone and without the help of those around him. And the time is coming when all great things will be done by the cooperation of many men in which each man performs that function for which he is best suited, each man preserves his own individuality and is supreme in his particular function, and each man at the same time loses none of his originality and proper personal initiative, and yet is controlled by and must work harmoniously with many other men."

He then went on to observe that one of the most important lessons taught by these experiments, particularly to the younger men, is, quoting Reference1-1:

> "That several men when heartily cooperating, even if of everyday caliber, can accomplish what would be next to impossible for any one man even of exceptional ability."

It is unfortunate that this part of Taylor's perceptive vision of the organization and management of manufacturing went unnoticed. If it had been otherwise, we might not have had to wait some 80 years for today's very positive multi-disciplinary team approach to manufacturing to be espoused by industry.

The Period of Secrecy Ends

Looking in retrospect at another aspect of Taylor's research work, a quite remarkable fact about the results of his 26-year program of machining research (and one which Taylor himself highlighted) is that during that entire period, to the best of his knowledge, not a single person involved in the program ever disclosed any of its findings to non-participating companies or other non-participating personnel in a position to benefit from them. Thus, the participating companies gained a tremendous productivity advantage (200-300 percent, as mentioned earlier) over their competitors relative to the output of their machine shops. The participating companies were, naturally, the sole funders of the program and had every right to keep its findings proprietary, which they did. However, that resulted in a 26-year lag in that knowledge becoming available to the bulk of the American manufacturing industry. As stated in Chapter 1, today the cost of metal removal operations amounts to some 15 percent of the value of all products produced by our manufacturing industry. As best we can determine, that figure was at least that high (and probably considerably higher) at the end of the 19th century, when Taylor began his program. Thus, the economic disadvantage to the nation's manufacturing industry — and to the economy of the country as a whole — of this 26-year lag was significant. Had a mechanism for public funding of research of such fundamental economic importance been available, the lag could well have been considerably reduced.

Fortunately, Frederick Taylor himself finally decided to break the wall of silence (presumably with the assent of his former sponsors). He did this in his mammoth ASME paper entitled "On the Art of Cutting Metals", which fills a 1½” thick printed bound volume. This he presented, in his role as president of that Society, as the President's Annual Address at the Society's 27th Annual Meeting in New York, on December, 1906. It was printed in full in the Transactions of the Society, Volume 28, 1906 (see reference 1-1). It comprises 248 printed pages, 24 huge foldouts containing tables and curves, and 64 pages of discussion ending with the author's closure. Some 1,300 persons attended that meeting, requiring the use of the New York Edison

Company's auditorium to accommodate the crowd of attendees.

Why did Taylor decide to make such a comprehensive disclosure of the results of his lengthy program of research and discovery, after it had been underway for 26 years? Taylor stated the answer to that question very simply; to quote, "It seems to us that the time has now come for the engineering fraternity to have the results of our work, in spite of the fact that this will cut off our former means of financing the experiments. However, we are in hopes that the money required to complete this work may be obtained from some other source." Although no significant source of such funding materialized to directly support research on this subject by Taylor and his team, per se, Taylor's hopes in a sense came true. His revelation of the findings of that program succeeded in opening the eyes of both academia and industry to a whole new world, both of engineering research to test, clarify, and extend the knowledge gained, and of profitable engineering activity to apply the results of the knowledge already gained to practice. A quiet revolution began, in both academic research and industrial R&D practice in this country, and one that spread around the world.

Some idea of the change that took place in the engineering climate relative to the engineering of the machining process, as a result of the publication of Taylor's paper, can be gathered from study of "A Bibliography on the Cutting of Metals," by O. W. Boston, published by the ASME in 1945. This publication (2-4) presented references to technical papers and books on metal cutting research, development and practice (with a brief abstract of each publication) drawn from a representative cross-section of engineering literature, worldwide, for the period of 1864-1943. For the years 1900-1904 (just prior to the publication of Taylor's paper in 1906), it cited 39 references. For the period 1905-1909, this increased to 48, followed by 73 for 1910-1914, 80 for 1915-1919, 180 for 1920-1924, 453 for 1925-1934, 1,102 for 1930-1934, and 1,086 for 1935-1939. Further, it is edifying to note that virtually all of these publications centered on contributing to the strengthening and development of the empirical basis for engineering of the metal cutting process, ushered in by Taylor. The age of empiricism in the engineering of machining was in full swing!

Empirical Research Proliferates

The effort to develop a strong empirical basis for the engineering of machining continued unabated through the 1940s. During all of this period, from 1906 on, a major part of the substantial progress made came from the efforts of American engineering researchers and manufacturing engineers. In contrast with Taylor's work, the effort was no longer confined almost wholly to industry, but quickly spread to universities as well. Further, and again in contrast to Taylor's work, the effort was marked by increasingly close cooperation between industry and academia. A substantial empirical understanding developed of how to engineer efficient and economic application of the metal cutting process in practice. A sizable contingent of proficient researchers in this field, in both academia and industry, evolved, with their "rallying point" being the Research Committee on the Cutting of Metals of ASME, organized in 1923. This contingent of researchers could be said to have been the "hard core" of the contributors to the development of this empirical understanding.

For example, one of the most prolific members of this contingent was an engineer from industry, namely Adolph L. DeLeeuw of the engineering staff of The Cincinnati Milling Machine Company (now Milacron, Inc.). Inspired by Taylor's work, he turned his attention to developing a sound empirical engineering understanding of the process of machining metals by milling. He carried out extensive tests at the company, aimed at developing information directed at making it possible for the engineering designer of milling machines to work in a more knowledgeable manner. In these, DeLeeuw determined the amount of metal removed per horsepower minute (which he termed "efficiency") for a very wide range of feed rates, depths of cut, cutting speeds, and cutter types. The findings from this research were published in Cincinnati Milling Machine Co.'s first edition, in 1922, of its "Treatise on Milling and Milling Machines." However, the findings also led DeLeeuw to his discovery, published in 1922 (2-5), that milling cutters having helical teeth, but with these teeth having much wider space between them than the conventional cutters of that day, were much more efficient than the conventional cutters. Milling cutter manufacturers then incorporated this discovery into their cutters, resulting in significant improvement in the efficiency of metal removal by milling machines. This pioneering research and experimentation by DeLeeuw, stretching from 1908 to 1939, established a tradition of research on the machining process at the Cincinnati Milling Machine Company, which continued for many years after his time. In fact, he himself was a keen observer of the changing scene in research in this field throughout industry and academia. He observed, somewhat prophetically in a paper in ASME’s journal in 1927 (2-6) that, in this field, "the day of theoretical men is at hand." DeLeeuw was indeed a substantial contributor among the ASME contingent to developing empirical understanding of how to engineer efficient and economic application of the metal cutting process.

A Major Academic Contributor Emerges

However, the member of that ASME contingent who was, without doubt, the most prolific and substantial contributor to that empirical understanding at that time was Professor Orlan W. Boston, former chairman of the Department of Metal Processing at the University of Michigan, and author of (among myriad other publications the comprehensive bibliography cited above and in reference 2-4.

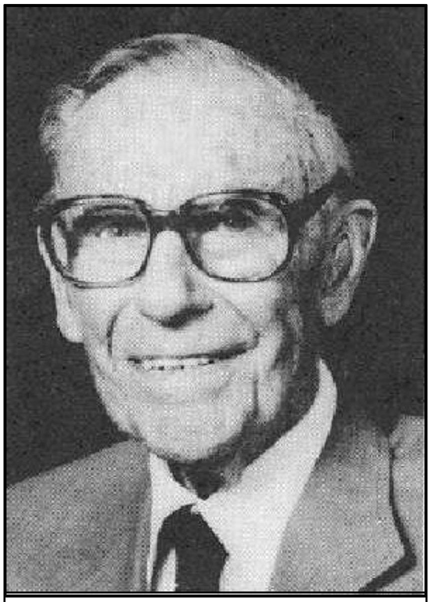

Fig. 2.3. O.W. Boston, 1891-1991

Orlan Boston was born on July 16, 1891 in Nashville, Michigan. He graduated from the University of Michigan in 1914, received a Masters degree there in 1917, and the degree of Mechanical Engineer there in 1926. He was an Instructor in Engineering Mechanics and Mechanical Engineering at the University from 1914-1917. As an Officer in the U. S. Naval Reserve Force, Boston worked in the Bureau of Ordnance from 1917-1919 on the design and manufacture of submarines used in the North Sea barrage. From 1919-1921, he was employed as an Industrial Engineer at the Cleveland Tractor Company, specializing in the economics of production. In 1921, he joined the University of Michigan again where he spent his illustrious career, until his retirement in 1956, on education, research, and training of outstanding engineers, and in leadership roles in various professional societies including the ASME, ASM, and SME.

When Orlan Boston rejoined the University of Michigan in 1921, he set about an enormous research task. That was, to determine and document as fully as possible whatever empirical, quantitative relationships could be established that would so accurately describe the performance of the machining process that they could be used as a basis for realistic engineering of that performance in practice. Of course, Taylor's research had begun that process, but he had confined his experimentation and development of empirical relationships almost entirely to machining by turning on a lathe, and to the taking of heavy cuts only. Boston's comprehensive research and experimentation, aimed at accomplishing the foregoing, continued steadfastly throughout the 25 years of his career at Michigan, until his retirement at the age of 65. He established a large and well-equipped laboratory at the University devoted to this effort, and engaged many undergraduate and graduate students over the years to work with him in that effort. Many of these students later went on to illustrious careers of their own in academia and industry. The roster of these included such renowned manufacturing engineers of that period as Dr. William W. Gilbert, Professor Lester V. Colwell, Dr. Alfred O. Schmidt, and Mr. Carl J. Oxford, Jr.

Professor Boston carried out that monumental research task to which he had dedicated himself with great success. It yielded effective empirical quantification of the technologies and economics required for realistic engineering of the performance of machine tools, cutting tools, the machining process and related entities, providing, in fact, a solid empirical approach to the engineering of the whole broad field of metalworking manufacturing, which has stood that field in good stead to this day. More specifically, it provided, for example, a wealth of empirical equations for such relationships as that between cutting parameters (cutting speed, feed, depth of cut, etc.) and tool life, cutting forces, power requirements, surface finish, and machining costs for various types of work materials and machining operations (turning, milling, drilling, etc.).

He made the results of that monumental research effort widely available to industry and academia, not only through consulting and teaching, but perhaps even more importantly, through his many publications. These included not just his over 130 technical papers (the great bulk of which were refereed papers published in the Transactions of the ASME) of particular interest to academia. He simultaneously provided documentation for the reduction of his research findings, reported in these papers, to engineering practice. This took various forms, including numerous articles in trade journals, sections of handbooks such as Marks' Mechanical Engineers' Handbook and the ASM Metals Handbook, his comprehensive Bibliography on Cutting of Metals, 1864-93, and his classic texts and reference books including Engineering Shop Practice in 1933-1935 and Metal Processing in 1941 and 1951.

A further undertaking by Orlan Boston, which provided a very strong medium for reducing some of his research findings to practice, was his prolific activity in developing American Standards. He chaired numerous ASME-sponsored standards committees in the field of cutting tools and the machining process. These produced a wealth of American Standards covering such subjects as cutting tool nomenclature, terminology and definitions, and tool life testing of cutting tools.

In addition to chairing ASME-sponsored standards committees over a long period of years, Professor Boston also chaired or was a member of a variety of ASME committees and subcommittees dealing with metalworking manufacturing, as well as similar committees in other professional societies. Further, he was instrumental in founding the Production Engineering Division of ASME (now the Manufacturing Engineering Division), in 1921, as an outgrowth of what had been called the ASME Subcommittee on Machine Shop Practice.

Boston was a man whose personal qualities were admired by all. His patient encouragement of young researchers and his constructive, perceptive but courteous comments on the work of his colleagues at various meetings and conferences won for him a host of friends and admirers. In retrospect, it might well be said that he (along with Taylor) was among the most influential persons in this country, as well as the world, in the advancement of manufacturing engineering. Further, his accomplishments in this realm clearly demonstrate the power of university research, and of university/industry cooperation, to support and enhance industrial manufacturing productivity and excellence, when accorded honest acceptance, fitting priority and adequate support by the university, as well as by industry.

Research on Tool Materials Proliferates

While Taylor, followed by Boston, had been concentrating on research aimed broadly at establishing a sound empirical basis for engineering the machining process, other experimentation and research had also been going on aimed at a more specific target, but one quite critical to increasing the rate of metal removal in machining. This was the development of cutting tool materials which would permit higher rates of metal removal for a given tool life.

Taylor himself, working with Maunsel White, his metallurgist colleague, actually made the first big step in this direction, although quite unexpectedly, in 1898, in the course of his experimentation. This was the discovery and development of the Taylor-White process of treating chromium-tungsten tool steel by heating it to the melting point, resulting in what came to be known as high-speed steel. (This is mentioned earlier in this chapter in the list of items that Taylor considered to be his more important accomplishments.) This discovery resulted from Taylor's running of a more or less routine series of tool life tests with high-tungsten-chromium air hardening tool steels of that day, heated to various temperatures (including their melting point) before quenching, to determine the optimum quenching temperature. Much to their surprise, the men found that when this tool steel was heated to just short of its melting point it underwent a sudden transformation that made it behave like an entirely different steel. That transformed steel permitted metal removal rates for a given tool life of more than double that obtainable at any lower quenching temperature, thus more than doubling machining productivity!

The next big advance in tool materials came in 1923 with the development of a new type of tool material, namely sintered cobalt-bonded tungsten carbide. Schroter carried out the empirical research resulting in the initial development of such tool materials in Germany in 1923. He made the discovery that, by coating tungsten carbide particles with cobalt by ball milling, cold pressing such into suitable shapes, and then sintering the compacts in accordance with powder-metallurgy methods, solid coherence was obtained, even at temperatures as much as 1000 degrees centigrade lower than customary. This process produced sound shapes suitable for use as cutting tools, thus making the properties of tungsten carbide initially usable for the machining of metals. However, these materials did not prove to be wholly practical. Then, in 1926, Hoyt (2-7) at the General Electric Company in the United States carried out research on utilization of hot pressing to form the compacts, resulting in significant improvement in the performance of sintered tungsten carbide tools for machining.

Such tools, however, still did not prove to be wholly practical for the machining of steel. This was because, when machining steel with this tool material, the chip flowing over the tool face rapidly wore a crater in it just adjacent to the cutting edge, causing rapid, early failure of that edge. Empirical research to find a means for overcoming this problem was carried out by Philip M. McKenna. Through this he discovered, in 1938, that compositions of tungsten carbide containing titanium carbide as well, prepared by a process that he patented (2-8), greatly reduced this cratering action of the chip. These compositions had immediate success in machining steel by virtue of their freedom from both cratering and breakage, permitting the machining of such at removal rates for a given tool life of more than double that obtainable with high-speed steel tools. Thus, once again, machining productivity was more than doubled by the results of United States research on tool materials.

These early years of metal cutting research in this country, featuring such star empiricists as Fred Taylor and Orlan Boston, supported and supplemented by a rapidly swelling coterie of others, had produced many striking advances in capability to engineer the machining process and in the capabilities and productivity of that process as applied in practice. However, the very fact that the research was so very empirical in nature began eventually to cause this age of empiricism to undergo a metamorphosis. The burgeoning wealth of empirical relationships produced by the ongoing research began to engender curiosity about the fundamental nature of this increasingly important process — about what actually happens in that process — about its relationship to science — a feeling seemingly reflected earlier by DeLeeuw. Out of this grew an effort to direct experimentation toward revealing theoretical, as well as empirical, understanding of the metal cutting process, in order to broaden and enrich our knowledge of the process and our capability to engineer it. As we shall see in the next chapter, a champion for accomplishing such appeared on the scene in this country.

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CHAPTER 3

UNDERSTANDING BROADENS –- EXPERIMENT-THEORY-SYNERGISM

The 1940s into the 1950s

A New Age Dawns

The age of empiricism -- which blossomed with Taylor's Herculean efforts and came into full bloom under Boston's comprehensive nurturing -- was too busy supplying industry's need for empirical knowledge about engineering the machining process to have much time for exploring what really went on in that process. Interestingly enough though, there had been exploration of the process in Europe toward the end of the nineteenth century. Experimental study of the chip formation process had been carried out, and analyses of the relation of chip formation to the forces and power involved in such had been performed. These experiments have are nicely described by Finnie (2-2) in his 1956 paper reviewing metal-cutting analyses of the past hundred years. However, because the conclusions of these early investigations concerning the mechanism of the cutting process were often very contradictory and even misleading, and because there was as yet no empirical basis for an engineering approach to machining in practice, these early studies were soon forgotten and remained almost wholly overlooked during the excitement of the age of empiricism.

But, as indicated in the previous chapter, toward the end of the age, unrest about the lack of understanding of the fundamentals of the metal cutting process began to grow, as reflected for example by DeLeeuw (2-6) of Cincinnati Milling Machine Company as early as 1927.

However, perhaps not wholly coincidentally, it was that same company which, in 1926, took a step that soon resulted in the emergence of a champion who developed an understanding of the fundamentals of the metal cutting process by uniting experiment with theory. This step was the establishment of a research department at the company and the hiring of Hans Ernst to head it as Director of Research, a position that he held for 32 years. It was he who became that champion. Figure 3.1 is a photo of him taken midway in that 32 years career.

Fig. 3.1. Hans Ernst, 1892-1978

Hans Ernst was born October 22, 1892 in Melbourne, Australia. He studied Mechanical and Electrical Engineering at Melbourne Technical College, graduating in 1911. Following that he was employed for two years in industry, first as an electrical engineer and then as a mechanical engineer, and then for two years as an instructor in mathematics and applied mechanics at a technical college. He then set out to make his way to America to obtain further experience in engineering, working his way there in the engine room of a ship. He worked in a variety of engineering jobs with a number of companies in California, then joined Western Cartridge Company in Alton, Illinois, where, after a year away to serve in the Royal Air Force of Canada during World War I, he was put in charge of their research and development on cartridge components and manufacturing equipment. He spent six years in that position and then left to assume the position of Director of Research at Cincinnati Milling Machine Company in 1926. He devoted his first years in that position to developing a new type of feed drive for machine tools, resulting in the first milling machine to be automatically controlled and operated by hydraulics. He proved to be a prolific inventor, earning over 100 machine tool patents during his career at Cincinnati Milling Machine.

As his creativity as a machine tool developer grew, so did a passion to really understand the metal cutting process that those machine tools performed. He soon decided to undertake research aimed at gaining this understanding. Here, the fact that he was not only a highly creative engineer, but also a consummate experimentalist, stood him in good stead. He devised experiments aimed at enabling him to understand the geometrical features of the chip formation and removal process carried out by a cutting tool. He studied this action through the microscope and took motion pictures of it, studying these in detail. He prepared photomicrographs of sections through chips still attached to workpieces, resulting from suddenly stopping the cut during the removal process, and studied these in detail. Using such techniques, he studied the effect of such variables as tool rake angle, tool sharpness, uncut chip thickness, application of a lubricant, cutting speed and type of material being cut on the geometry of the chip formation and removal process.

Qualitative Understanding of Basics Is Made Clear

In his 1938 landmark paper titled, "Physics of Metal Cutting," Ernst (3-1) presented a comprehensive report on his findings from these studies. In the early paragraphs of that paper, delivered as a lecture to the members of the American Society for Metals at their Twentieth National Metal Congress, he gave voice to the need to understand the basics of the metal cutting process. He felt a burning desire to satisfy this need, as demonstrated by these words:

> "Over the past few hundred years we have slowly learned to use metal cutting tools without really knowing how they work. We have learned a lot about speeds and feeds, but, in order that we may meet the increasing demands of modern production for greater output and higher quality of finish, it is necessary that we obtain a clear understanding of what is taking place at the cutting edge." (3-1)

He went on to point out that, although there had been a number of investigators who had tried to develop such understanding in the past, a state of confusion had been the main result, with many false conceptions of cutting tool action, both in the shop and in the literature, persisting. Then he stated:

> "Over the past twelve years there has gradually been built up the story of what is going on at the cutting edge. This story is not yet complete, but we are approaching the final chapters." (3-1)

He then proceeded to describe the careful, painstaking experimental studies that he had performed during that same period and his findings from them. What they revealed was a clear qualitative understanding of the basics of the nature and geometry of the process of chip formation in the cutting of metal. His work clearly demonstrated that the basic process by which a chip is removed from relatively ductile metal by a cutting tool is one of plastic flow of the metal, in shear. This shear takes place in two zones, a primary one and a secondary one. The primary shear takes place in a relatively narrow zone running from the cutting edge to the surface of the workpiece lying ahead of the tool. This is followed by secondary plastic flow of the metal, in shear, in a narrow zone lying below that face of the newly formed chip that slides over the face of the tool as the chip escapes.

In the case of relatively brittle metal, the primary shear taking place in the narrow zone running ahead of the tool can cause intermittent fracture to occur in that zone, producing a segmented instead of a continuous chip. In the case of ductile materials, if the face of the chip which slides over the tool face meets too much resistance there, the secondary shear occurring in that chip face due to that resistance may become so severe as to cause a portion of that face to shear away from the body of the chip and remain attached to the tool face, adjacent to the cutting edge. This more or less stationary blob of metal next to the cutting edge is called a "built-up edge." However, it is an unstable body, with the portion of it lying closest to the cutting edge growing in size in an outward direction from that edge as the cut progresses, then intermittently sloughing off and remaining attached to the machined surface of the workpiece. This causes that surface to be jagged, producing a rough surface finish on the part being machined.

Ernst’s work identified four basic processes, namely primary shear, secondary shear, fracture and built-up edge formation that occur in the cutting of metals. In addition, Ernst's painstaking microscopic and other observations under a wide variety of cutting conditions (speeds, chip thickness, workpiece materials, cutting fluids, etc.) revealed that these four basic processes normally occur in only a limited number of combinations in practice. While both primary shear and secondary shear always occur, he found that the occurrence of fracture in that zone of primary shear and the occurrence of a built-up edge on the tool nose adjacent to the zone of secondary shear (when either of these occur) were mutually exclusive. Thus it became evident to him that there were only three basic types of chip formation, which he called, simply Type 1, Type 2 and Type 3. Photomicrographs of sections through characteristic specimens of each of these three types of chips (still attached to the workpiece by very sudden arrest of the cut in each case) are shown in Figure 3.2. As can be seen, the Type 1 chip is a segmental chip produced by successive fractures in the zone of primary shear. Type 2, the simplest type, is a continuous chip produced in the absence of both fracture and a built-up edge. Type 3 is a continuous chip produced when a built-up edge is also present.

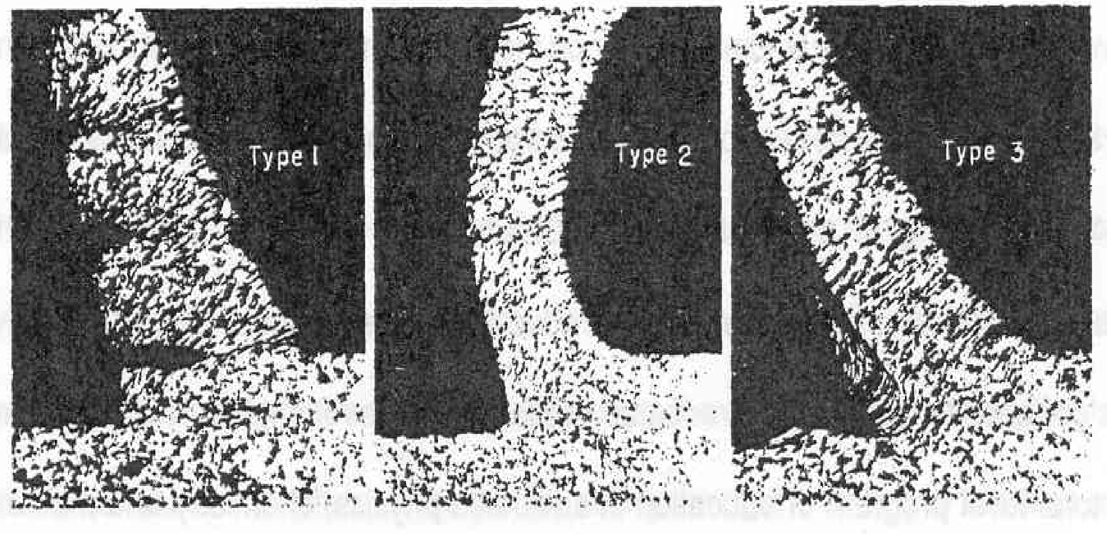

Fig. 3.2. The three basic types of chips found in the machining of metals (according to Ernst)

As simple as this understanding of the chip formation process, and its remarkably uncomplicated classes, were, it had not been comprehended before, leaving the perception of that process very muddled and confused until Ernst unraveled it. In concluding his historic paper, Ernst stated:

> "The story, 'what happens in metal cutting', is approaching completion, but it is still only a story. We can now form a better mental picture of chip formation under various conditions, and visualize the effect of certain metallurgical and machine operating factors, but our knowledge so far is qualitative rather than quantitative." (3-1)

However, Ernst's clear qualitative unraveling of "what happens in metal cutting" actually opened wide the doorway to the possibility of scientifically modeling and analyzing the process. As circumstances would have it, the person who undertook that challenge had already arrived on the scene.

Hans Ernst had published his landmark paper on the chip formation process in 1938. In 1936, Herman Schneider, father of the cooperative (co-op) system of education in this country and Dean of Engineering at the University of Cincinnati at that time, had established an experimental new fellowship program of co-op education at the graduate level at the university. This was designed to take newly-graduated baccalaureate-level engineers and expose them to a doctoral-level program of education in advanced physics, chemistry and mathematics. This was combined with a program of joint industry-university research to be carried out both at the university and at the research laboratories of the company sponsoring each student's fellowship, on a six-month cycle of alternating between the university and the company's labs. Hans Ernst, hungering to have some research directed at some of the basic questions that had arisen in his mind as a result of his metal cutting research, persuaded The Cincinnati Milling Machine Company to sponsor one of the co-op fellowships in the first class to enter this new program in 1936.

That was the year that M. Eugene (Gene) Merchant graduated from the University of Vermont, with a B. S. degree in Mechanical Engineering. During his senior year, he had told Tom Fulton, one of his professors of mechanical engineering who had taken a special interest in him, of his strong desire to do graduate study and to then pursue a career in industrial research in the field of mechanical engineering. One day Tom showed Merchant a news clipping from the New York Times announcing the new experimental graduate fellow co-op program at the University of Cincinnati. Both agreed that it sounded like an excellent opportunity. So, with Tom's help, Merchant applied for and won the fellowship sponsored by Cincinnati Mill.

Upon graduation, Merchant came to Cincinnati and entered the program. The first six-month period of his co-op program was spent in the Research Department of the "Mill" (as it was fondly called by its employees). Ernst explained to Merchant that a basic problem about the metal cutting process that deeply puzzled him was that of the nature of the friction acting during the sliding of the chip over the tool face. Since that frictional force was apparently sometimes so great as to cause a portion of the flowing chip to shear away near the cutting edge and form a built-up edge, it was evident that the coefficient of friction between chip and tool must be much higher than that normally experienced between sliding metal surfaces. Yet there was no theory of the mechanism of friction in existence, and so no way to explain this situation. Ernst asked Merchant to explore the nature of the friction between clean, dry metal surfaces and indicated that the university had agreed that this would be a suitable problem for joint industry - university research in this new program.

Merchant welcomed the challenge that this problem presented and willingly agreed. He immediately tackled the task of designing an apparatus that could measure the coefficient of friction between freshly machined metal surfaces in a high vacuum environment. Initial measurements of the coefficients of friction of these ultra-clean metal surfaces revealed friction coefficients of the order of unity, in contrast to values an order of magnitude less that supposedly clean unlubricated metal surfaces normally exhibit. This provided preliminary evidence that the friction coefficient between the freshly exposed inner surface of a chip sliding over its area of contact with the face of the cutting tool (and thus fully cleansing that area) might indeed have values of the order of unity as well.

Basic Theory Begins to Evolve

But what was the mechanism of that friction? At that time there was no theory of the mechanism of friction that could explain that, or even explain Amontons' historic empirical "law" that the force of friction between sliding bodies is proportional to the normal load on the sliding surfaces and independent of the (apparent) area of contact. The theory of elasticity would predict that the area of contact would be proportional to only the two-thirds power of the load (as pointed out by previous investigations). Efforts were therefore directed to providing experimental evidence on which a theory of the mechanism of any friction between solid bodies could be based and then developing such a theory. Extensive experiments were carried out in the high vacuum friction apparatus, referred to above, measuring friction coefficients between very clean surfaces of a wide variety of pure metals under a great variety of conditions.

Based on the early observations, Merchant postulated that the area of actual contact between opposing surfaces of crystalline solids is ordinarily only a very small fraction of their apparent area of contact. Thus opposing asperities of the two surfaces should deform plastically, rather than elastically under all but extremely light loads. If the asperities do deform plastically instead of elastically, the resulting area of actual contact, between opposing asperities will be proportional to load, as in hardness testing. Since the frictional resistance encountered when these surfaces are then slid relative to each other will be due to the average shear strength of these minute areas of contact, that resistance will thus be proportional to the load that produced these areas. The result is that the coefficient of friction will be equal to the ratio of the average shear strength, S, of the interfaces between the contacting asperities to the mean pressure hardness, H, of the softer of the two contacting surfaces. It was further postulated that in the case of very clean metal surfaces, the opposing asperities actually "cold weld" to each other at their points of contact, forming continuous metal "bridges" between the two "contacting" surfaces. Since the ratio of the shear strength, S, of these cold-welded metal junctions to the mean pressure hardness, H, of most common metals is of the order of unity, the coefficients of friction between them could be expected to be approximately unity, accounting for the observed values of that magnitude in the tests described above.

The extensive experiments referred to above, carried out in the high vacuum apparatus, fully confirmed this theory. That finding, and the results of those experiments obtained during the first two years of the co-op fellowship program were later published (3-2, 3-3, 3-4), immediately raised another question. How do the values of coefficient of friction occurring at the chip-tool interface in the metal cutting process compare with those predicted by the foregoing theory and experimentation? This could not be answered since, at that time, no theory of the mechanics of the metal cutting process existed. Thus, there was no clearly justifiable way to calculate values of chip-tool interface friction coefficients from measurements of forces in cutting. The knowledge here was in the same state of confusion as had been the state of understanding of the mechanism of chip formation prior to Ernst's studies. Merchant then set about remedying that situation during the second two years of the co-op graduate program.

He had by then fully familiarized himself with the findings of Ernst and had actually participated with Ernst in further advancing his findings. With the understanding clearly in mind of the mechanisms involved in chip formation in cutting, Merchant made observations of his own of the chip formation process through the microscope and studied Ernst's photomicrographs. It became evident to him that the process of shear occurring in the zone running from the cutting edge to the free surface of the workpiece (primary shear) was indeed the basic process in chip formation. Further, it became evident that the zone in which that process of shear occurred was so thin as to be well approximated by a plane. In fact, Ernst had already coined the term “shear plane” to describe that zone. Finally, it became clear that, of Ernst's three basic chip types, his simple Type 2 chip was the most representative of the basic

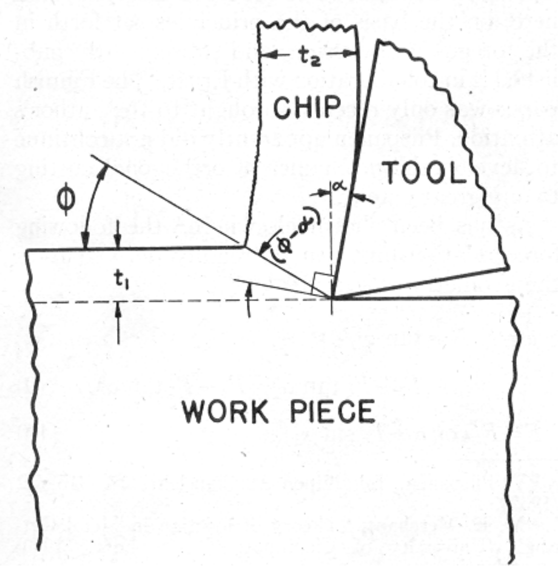

Fig. 3.3 Schematic representation of basic chip formation geometry

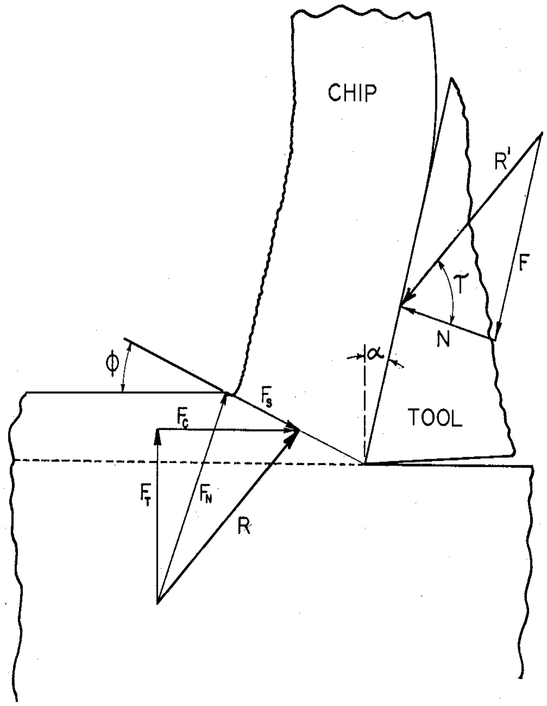

Fig. 3.4. Equilibrium force system acting on the chip

process of chip formation, as well as being the one most closely approximated in most machining operations in practice. Based on those conclusions, Merchant constructed an idealized line drawing sketch of the Type 2 chip in which the primary shear zone was represented by a geometrical plane running from the cutting edge of the tool to the free surface of the workpiece. This is shown in Figure 3.3, for the simple case where the cutting edge is perpendicular to the direction of tool motion, for which cutting condition he coined the term “orthogonal cutting”.

It became evident that in such a diagram, the chip could be considered to be a "free" body that, during cutting, is held in stable mechanical equilibrium between the force system acting on it at the tool face and that acting on it at the shear plane, as shown in Figure 3.4. Thus, the resultant of the force system acting on it at the tool face must be equal and opposite to, and collinear with, the resultant of the force system acting on it at the shear plane. This made it possible to construct the basic tool-chip-workpiece combined force system acting in the metal cutting process, as shown in Figure 3.5.

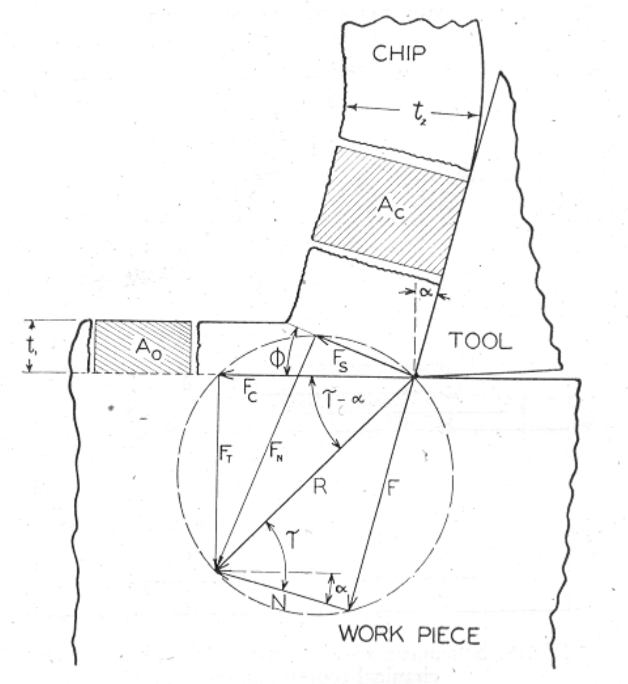

Fig. 3.5. Condensed force diagram illustrating relationships between component forces

This, in turn made it possible to derive a family of mathematical equations governing the basic mechanics of the metal cutting process. These were as follows:

$$\mu = F/ N = \tan t = (F_t + F_c \tan a) / (F_c - F_t \tan a) \tag{3.1}$$

$$F = F_t \cos a + F_c \sin a \tag{3.2}$$

$$F_s = F_c \cos F - F_t \sin F \tag{3.3}$$

$$S_s = F_s / A_s = (F_c \sin F \cos F - F_t \sin^2 F) / A_s \tag{3.4}$$

$$S_n = F_a / A_s = S_s \tan (F + t - a) \tag{3.5}$$

$$W_f = F/ A_s \tag{3.6}$$

$$W_s = S_s e \tag{3.7}$$

$$W_c = S_s e + F/ A_s = W_s + W_f \tag{3.8}$$

where μ = coefficient of friction between chip and tool

S_S = mean shear stress on the shear plane (= mean shear strength of material being cut)

S_n = mean compressive or normal stress on the shear plane

A_o = cross-sectional area of the "chip" before removal

A_c = cross-sectional area of the chip after removal

A_S = area of the shear plane

W_f = work expended in friction between chip and tool per unit volume of metal removed

W_S = work expended in shearing of the material being cut per unit volume of metal removed

W_c = total work expended in cutting

e = shear strain = cot F + tan F - a

t = friction angle

F = shear angle

a = rake angle of the tool

F_c = cutting force (as normally measured with a tool dynamometer)

F_t = thrust force (as normally measured with a tool dynamometer)

F = friction force on tool face

N = normal force on tool face

The results of Merchant's (3-4) research that first produced such equations was described in part in reference 3-5 in 1941, published in collaboration with Ernst. However, Merchant then extended that research and published the overall results in 1944 and 1945 (3-6, 3-7).

These equations of course, strictly speaking, apply only when machining is done under conditions of orthogonal cutting and Type 2 (and to a fair approximation) Type 1 chip formation. However, for machining under these conditions, they made it possible, for the first time, to calculate, from a few simple measurements and to a good approximation, such engineering quantities as the various forces, stresses, energy flows, etc., involved in the operation of the machining process in practice. Thus they broke ground for a wholly new direction to be taken in research on machining and grinding, namely that of research aimed at providing science-based analytical methodology, and science-based mathematical modeling of the machining process, for the engineering of such operations. Such research has continued to this day.

An Era of Science-Based Research Begins

Merchant immediately began to use the foregoing equations to explore what they could reveal about previously observed phenomena in the metal cutting process. The equations of course make it possible to calculate, among other things, the coefficient of friction, μ, between the chip and tool from measurements of force components and the known rake angle, a, of the cutting tool. Therefore, in light of his earlier research on friction between very clean metal surfaces in high vacuum, described earlier in this chapter, his first application of them was to calculate values of μ obtained from experimental measurement of force components with a tool dynamometer when machining various metals. He found these to be of the order of unity, correlating with the results obtained from the earlier research on the friction between very clean metal surfaces in high vacuum.

The existence of equations 3.1 - 3.8 also made it possible to seek an answer to a phenomenon which Hans Ernst had earlier observed, namely, that the value of the angle of the plane along which plastic flow in shear takes place ahead of the cutting tool (i.e. the shear angle) varies with variation of the cutting conditions, such as tool rake angle, type of cutting fluid applied, type of material being cut, etc. In other words, variation of these quantities changes the conditions for plastic flow in the work material (plasticity conditions).

Merchant had arrived at a preliminary explanation of this behavior during his initial research on the mechanics of cutting carried out during his co-op graduate study program. He had reasoned that shear must take place on a plane on which the shear stress in the body of metal lying ahead of the advancing cutting tool is a maximum (i.e. the plane on which the shear stress equals the shear strength of the metal). The condition for finding the value of shear angle, f, for which the shear stress is a maximum was found by differentiating the relation of shear stress, S_s to f and setting the result equal to zero. The resulting relationship that emerged was

$$2f + t - a = 90^{o} \qquad (3.9)$$

This result was published in reference 3-5 in 1941. However, as Merchant's research progressed following completion of his graduate study program, he found by experiment and analyses that the sum of the above three quantities is 90^0 only in the case of an ideal plastic material. Such a material would have a single-valued shear strength, independent of such quantities as temperature, rate of shear, shearing strain and the stress acting normal to the plane of shear. Of these, he found, by a combination of theory and experiment, that only the stress acting normal to the plane of shear seemed to have any significant effect on the plasticity conditions governing the plane of shear in metal cutting. Bridgman (3-8) had earlier established, by extensive experiment, that the shear strength of a polycrystalline metal increases virtually linearly with applied normal (compressive) stress on the plane of shear. Introducing this fact into the derivation of equation 3.9, it became

$$2 f + t - a = \text{arc cot } k \qquad (3.10)$$

where k = the slope of the shear strength versus compressive stress curve of the given metal. Data obtained from cutting tests on various steels were found to fit this relationship reasonably well. Merchant reported the results of this research in 1945 (3-9).

It should be noted here that, in Finland, Piispanen had independently (quite unknown to Merchant and researchers outside of Finland) developed a force diagram quite similar to that shown in Figure 3.4. He had published his findings in 1937 (3-10) in a paper written in the Finnish language (a so-called "rare" language). Although Merchant was able to secure a copy of the paper in 1944, it took almost a year to find someone who could produce a professional translation of it. (The first technical translator contacted stated "- - we would be unable to furnish you with a translation from Finnish. We do not know anyone we could recommend for this work" -- a rather sad commentary on this country's lack of interest in non-English-language technical literature in those days). When a professional translation was finally secured in mid-1945, it was found that Piispanen had not only developed a force diagram similar to that of Figure 3.4, but had also recognized the importance of the normal stress on the shear plane in influencing the angle of shear. He had worked out a graphical method, based essentially on the principal of minimum energy, for finding this angle of shear when the direction of the resultant force, R, is known. The treatment was entirely graphical and no mathematical results were developed.

It should also be noted that, very interestingly, Finnie (2-2) discovered from his 1956 review of the very early literature on metal cutting analyses that Zvorykin, in a free-standing Russian language paper published in Moscow in 1893, had developed an expression similar to equation 3.9. Assuming that the force in the direction of the cutting velocity would be a minimum in the stable state, he obtained the expression

$$F = 45 + a / 2 - t / 2 - t' / 2 \qquad (3.11)$$

where t' is a quantity which Zvorykin called the friction angle for the shear plane, and the other quantities are as defined earlier. It would appear from the nature of this definition of t' that Zvorykin believed that the chip was formed by fracture of the metal on the shear plane rather than by plastic deformation, a view prevalent throughout most of the research on chip formation which preceded Ernst's research.

Establishment of the plasticity condition given in equation 3.10 for the behavior of the geometry of chip formation in the machining of polycrystalline metals was of course revealing in itself. However, more importantly, this particular analysis was really only one example of the power of the previously non-existent family of mathematical relationships (equations 3.1 - 3.8) that govern the basic mechanics of the machining process. It is these equations that made possible such fundamental analysis of this process. This possibility immediately began to attract many other researchers to apply these relationships, and the theory behind them, to develop further basic engineering knowledge and understanding of the machining process.

A Highly Prolific Contributor Emerges

Fig. 3.6 Milton C. Shaw

One of the very earliest of these researchers was Milton C. Shaw (Fig. 3.6), a 1938 mechanical engineering graduate of Drexel University. Shaw had an advantage in this field, in that he had entered the new graduate co-op program at the University of Cincinnati at the end of its second year, as a fellow sponsored by Cincinnati Mill, replacing Merchant's previous alternate in that program. Thus he quickly was exposed to the results of Ernst's and Merchant's research.

Ernst had observed that a drop of carbon tetrachloride applied to the tool-chip interface when cutting steel at a low cutting speed immediately caused the shear angle to increase. Although carbon tetrachloride was not known to have ability as a lubricant, Ernst attributed its effect on chip formation to a reduction of friction at the chip-tool interface. Therefore, he recommended that Shaw's research in the graduate co-op program be directed at seeking understanding of the mechanism of friction reduction by cutting fluids in the metal cutting process. All parties concerned agreed to this.

Shaw (3-11) carried out extensive experiments with a great variety of pure liquid organic chemical compounds. He applied these drop-wise to the tool-chip interface when cutting a variety of different metals at low cutting speeds. In each case he assessed the resulting decrease in friction at the chip-tool interface, based on the understanding that Merchant's theory of the mechanics of cutting had provided. He found that, while virtually all the fluids tested produced some degree of reduction in the friction between chip and tool, they varied greatly in their ability to do such, both from one chemical compound to another, and from one workpiece metal to another. However, he also found that the fluids known to be most chemically active toward metals (such as the organic sulfides and chlorides) produced the largest reductions in friction in almost all cases. Combining such findings with the findings from Merchant's research on the mechanism of friction, he arrived at an understanding of the mechanism of friction reduction by cutting fluids in the metal cutting process. He found that, under the influence of the high chemical activity of the freshly exposed ("nascent metal") chip surface and the elevated temperature and high contact pressure at the contacting minute asperities of the chip-tool interface, the fluid reacts with the metal being cut to form a minute solid coating of the reaction products on these asperities. The products formed by such a reaction are invariably much weaker in shear than the metal being cut. Therefore, the resulting solid coating on the asperities will normally offer considerably less resistance to shear than do the usual metal-to-metal "bridges" which, in the absence of any contaminant, are formed at the contacting asperities. Thus, based on Merchant's theory of the nature of solid friction, the coefficient of friction should be reduced accordingly.

As initial direct evidence of the validity of such a mechanism, Shaw found that, in certain cases, a sufficient amount of the expected products of the reaction between the metal and the fluid were present on the removed chip for him to identify them by chemical analysis. He and Merchant then carried out a joint study to obtain further verification of this mechanism. They compiled values of the shear strength of solid films of the various chemical compounds that can be expected to be formed by reaction of various pure metals with various organic compounds (such as sulfides and chlorides). Ratios of these values of shear strength to the shear strengths of the pure metals themselves were then calculated, to determine the theoretically possible maximum percentage reduction in friction which might be obtained by applying these compounds as cutting fluids in the cutting of these metals. Next, these percentages were compared with the observed percentage reductions in chip-tool friction obtained when actual low speed cutting tests were run on these same pure metals, both dry and when using these same organic compounds as cutting fluids. (The values of the coefficients of friction used in calculating these percentage reductions were obtained by measuring the values of the force components acting during each cutting test and applying equation 3.1). Very good agreement was obtained between the observed values of reductions in friction obtained from the cutting tests and the theoretical values obtained from the calculated shear strength ratios.

Upon the completion of his graduate co-op program at Cincinnati Mill and the University of Cincinnati in 1942, Shaw joined the Materials Branch of the NASA Lewis Laboratory. Here he carried out original research on friction and boundary lubrication and became chief of the Branch. Then, in 1946, he became Professor of Mechanical Engineering at MIT. Here, over several years, he assembled a succession of very capable graduate students who not only made important contributions to advancement of engineering knowledge of the fundamentals of metal cutting and grinding under Shaw's guidance, but also went on, in many cases, to make continuing valuable contributions to the theory and practice of such during their own careers.

At MIT (and throughout all the rest of his career) Shaw performed and guided creative research on machining that made many major advances in the theory and understanding of the fundamentals of metal cutting and grinding processes. Perhaps the most important of all of these was his pioneering development of the theory and understanding of the mechanics and other fundamentals of the grinding process, starting in 1952. Until that time, while his and other research since the early 1940's had continued to advance understanding of the metal cutting process, no similar basic understanding of the fundamentals of the grinding process had been created.

In 1952, Shaw (together with his graduate student associates) published groundbreaking papers (3-12, 3-13, 3-14) resulting from his initial research on the fundamentals of grinding. These set forth the mechanics of the action of the individual abrasive grits in a grinding wheel as acting somewhat like individual cutting tools to remove individual chips, while collectively they remove the material being ground. However, he found that, in fine grinding, the action of these grits is not the same as that of conventional cutting tools. Instead, because of the high negative rake angle of abrasive grits, the chips are formed by a process of extrusion. Further, this action, combined with the tiny size of the chip, gives rise to a "size effect" arising from the minute size of the deformation zone, which inhibits deformation due to the lowered probability of encountering structural defects therein. As a result, the specific energy required for deformation of the metal was found to be almost an order of magnitude higher than that encountered in chip formation with conventional cutting tools. Shaw, with his associates, showed that, because of this size effect, chip size is a more important variable in grinding than wheel down feed. Drawing on these findings and applying moving heat source theory, he, with his associates, then developed methodology for calculation of mean surface temperature in grinding, thus providing an approach to predicting the likelihood of surface damage by overheating in grinding operations.

Shaw continued to make leading edge contributions to the theory and practice of grinding (as well as to metal cutting) during his tenure at MIT, where he was a world-class researcher and educator for 15 years. He then moved to Carnegie-Mellon University in 1961 where, as Mechanical Engineering Department Head, he continued his research until 1977. In that year, he moved on to Arizona State University where, as Professor of Engineering, he has continued, at a somewhat more leisurely pace, to make creative contributions not only to engineering knowledge and practice in manufacturing engineering, but also in such fields as mechanical design, materials behavior and tribology. The details of Shaw’s world class contributions to metal cutting and grinding technology have been well documented by Komanduri, his former colleague at Carnegie-Mellon University, in the comprehensive paper on "Machining and

Grinding: A Historical Review of the Classical Papers" (1-2).

Milton Shaw was the most prolific contributor of his day to the basic knowledge and understanding of machining through world class research into the fundamentals of the cutting and grinding of materials. Such research has been a major focus of his career, and he is still active in it, as of this writing, as reflected above. The contributions made by him, with his research associates, to the engineering knowledge and understanding of the machining and grinding processes have indeed been seminal to the continuing worldwide advancement of the capability and productivity of those processes!

Others Begin to Further the Basic Understanding

Stimulated by Shaw's groundbreaking activity in grinding research, other researchers began to devote effort to research on the fundamentals of the grinding process. For example, Backer and Merchant (3-15) carried out studies on the basic mechanics of the grinding process, establishing a basis for predicting forces on abrasive grits. However, of the many other researchers turning their attention to this field (and excepting Shaw), Robert Hahn of the Heald Machine Company made the most important contributions. Hahn, like Merchant and Shaw, did his graduate study at the University of Cincinnati, under the same unique co-op graduate study program established by Herman Schneider. It was, however, done under a fellowship provided by the Heald Machine Company. (Heald, a manufacturer of internal grinding and boring machines, had at that time, a loose cooperative arrangement with The Cincinnati Milling Machine Company, and in 1955 became a subsidiary of the Mill.) Upon attaining his doctorate from U.C. in 1944, Hahn was made Director of Research at Heald’s newly established research department, and before long he began active research on the grinding process.

Over the years, Hahn's research provided a wealth of new theory and understanding of the grinding process, as well as important applications of such in practice and on machine tools. His main research contributions ranged from the creation of new understanding of the fundamental mechanisms of material removal in grinding to the discovery of the fundamentals underlying the problems associated with precision grinding, such as chatter and vibration, and the creation of methodologies for their reduction or elimination. One of his most important contributions was the creation of the theory of regenerative chatter in precision grinding operations (3-16). The thinking underlying the development of that theory led to Hahn's conception of his most significant invention, namely controlled-force grinding in internal grinding (3-17). In this, the grinding force is continuously monitored during grinding and the signal is fed back to provide continuously varying feed rates. This is done in such a manner that the force acting between the grinding wheel and the workpiece, and thus the deflection of the spindle of an internal grinding machine, is held constant. This eliminates dimensional errors in the workpiece that otherwise result from variable elastic deflections due to workpiece stock size variations, workpiece hardness variations and wheel sharpness variations during grinding. This basic concept led to the development and introduction of controlled-force internal grinding machines -- a major technological advance. Today we find CFG machines as a standard machine tool on shop floors where internal grinding machines are used, such as in the finishing of bearings. Hahn's pioneering work on the theory of regenerative chatter in precision grinding, vibrations in flexible precision grinding spindles, and gyroscopically induced vibrations in grinding spindles has advanced not only the science but also the technology of precision grinding.

Hahn's other contributions to the theory and practice of grinding are many indeed. These are well described in a private communication from Professor Ranga Komanduri. In this he stated:

> "Hahn was among the first to recognize the relationship between the grinding conditions and the resulting thermal damage in the part ground. He applied the moving heat source theory of heat conduction to the grinding process and showed how high temperatures generated in grinding can cause thermal damage to the workpiece if grinding conditions are not properly chosen.
>
> "On the fundamental side, Hahn investigated the nature of the grinding process in detail and introduced the rubbing grain hypothesis, pointing out the major differences between grinding and metal cutting due to differences in the tool geometry. He showed three distinct processes to occur in grinding, namely, rubbing, plowing, and cutting, depending on the grinding conditions used. He also introduced the metal removal parameter and the wheel removal parameter and how normal force influences them.
>
> "Together with Richard Lindsay, Hahn prepared a five-part article on the

> Principles of Grinding published by the Machinery Magazine in 1971. This work deals with the basic relationships in precision grinding; the dependence of the metal removal and wheel removal parameters on the normal force; surface finish, part geometry and surface integrity; and finally chatter and how it can be controlled in grinding. Just as Shaw contributed immensely in educating students in the university in the field of machining and grinding, Hahn played a similar role in industry. He presented numerous seminars, sponsored by such professional societies as SME, to industry practitioners on the basic principles of grinding, with emphasis on internal grinding and controlled force internal grinding in particular.
>
> “Perhaps there are very few, if any, other than Hahn, who understand the intricacies of the grinding process and how numerous input parameters are complexly related to the output parameters in a highly complicated grinding system comprising the machine tool, the grinding wheel, and the workpiece.”

As research on the fundamentals of grinding blossomed, leading to better understanding of the nature of those fundamentals, research on the fundamentals of the metal cutting process continued to advance fundamental understanding of that process, through application of the theory of the basic mechanics of metal cutting. Of the various advances being made, perhaps the most important at this time was in the matter of heat and temperatures generated in metal cutting. When machining a given work material with a given cutting tool, the rate at which the cutting tool wears and becomes dull is, under normal circumstances, far more sensitive to the temperature to which the cutting process subjects the tool than to virtually any other variable. That rate of wear is, of course, the determinant of the tool life obtained from the given machining process. As will be explained later in this chapter, tool life is the prime factor controlling the cost of machining. Thus, understanding of the generation of heat and temperatures in metal cutting is of prime economic importance.

Concerning heat generation in machining, it is fascinating to note that in 1798, even before the physical nature of heat itself was known, Thomas Benjamin, Count of Rumford, in England, used a calorimetric method to study the heat generated in boring a cannon barrel, in the hope that this would shed some light on the nature of heat. Further, concerning temperatures in metal cutting, direct measurement of these had been carried on for some time using a method conceived by Gottwein in Germany during the 1920's, which employed the cutting tool and the workpiece as the two elements of a thermocouple (3-19).

Nevertheless, no theory permitting direct calculation of the temperatures generated in cutting -- the archenemy of cutting tools -- had been developed until Trigger and Chao tackled that problem in the early 1950's. In their elegant and now classic paper in 1951 (3-20), they set forth the first analytical treatment of chip-tool interface temperatures in metal cutting. Utilizing the theory of the mechanics of cutting developed by Merchant in 1945 (3-7), and considering the heat generated in the shearing of the metal on the shear plane to be a stationary heat source, and that generated by friction of the chip on the tool face to be a moving heat source, they developed an analytical expression for calculating the average chip-tool interface temperature and verified it experimentally. They, and many other researchers attracted by this important breakthrough, then went on to expand and refine the analytical basics of the thermal aspects of both metal cutting and grinding over the next ten or more years. In particular, Outwater and Shaw applied a similar analytical approach to analysis of temperatures in grinding and developed an analytical expression for the mean surface temperature reached at the tip of the grinding grit (3-21).

Analytical Relationships for Machining Economics Emerge

As the practical dividends attainable from the development of fundamental analytical relationships for the metal cutting process began to become increasingly clear as a result of the research findings described in the foregoing part of this chapter, interest in developing such for another aspect of machining began to grow. That was the area of the economics of machining. Here again, Hans Ernst, with his research associate Michael Field, played an initiating role.

Michael Field began his association with Ernst when he joined the Research Department of The Cincinnati Milling Machine Company in 1938 as a research engineer, having obtained a B.S. degree in Mechanical Engineering from the City College of New York in 1937 and an M.S. degree in Mechanical Engineering from Columbia University in 1938. Here, under Ernst's guidance, he began to carry out comprehensive empirical research on the relation of the performance of the milling process to the characteristics of various workpiece materials, milling cutters, etc. In 1944 the Mill sponsored a fellowship for him at the University of Cincinnati for graduate study, from which he obtained a Ph.D. in Physics. Part of his research done during that fellowship was devoted to a study of the economics of the machining of metals by milling.

Field's research on the economics of the milling process resulted in his development of an analytical expression for the total cost of the machining of parts by milling. He showed that the two significant components of the cost are the cost of setting up and performing the actual machining of the parts (the metal cutting cost) and the cost of resharpening and reconditioning the cutters used for the machining of the parts (the cutter preparation cost). These two costs are made up almost solely of the times required for carrying out the metal cutting and cutter preparation operations, multiplied in each case by the labor and overhead costs involved in each of these operations. What Field found from this analysis, using data from his extensive tool life tests in milling, was that the metal cutting cost per piece in general decreases with increasing cutting speed, while the cutter preparation cost per piece in general increases with increasing cutting speed. This results in the sum of these two -- the total cost per piece -- exhibiting a minimum at some particular cutting speed. That speed is therefore the optimum cutting speed at which to operate the machining operation, from the point of view of cost. Until Field's research resulted in this analytical quantification of the total cost of the machining of parts, the fact of the existence of an optimum cutting speed for machining had not been known. The results of this research were published in papers authored by Field and Bullock (3-22) and Ernst and Field (3-23) in 1945 and 1946.

Meanwhile, William Gilbert, who was at that time Associate Professor in the Metal Processing Department at the University of Michigan, Ann Arbor, had been participating since 1934 with Orlan Boston, Department Head, in Boston’s comprehensive research, described in Chapter 2, to establish empirical quantitative relationships which would accurately describe the performance of the machining process. Gilbert, like Field, had become interested in understanding the economics of machining and had developed an analytical expression for machining cost. This was similar in principal to Field's, being based on calculation of the sum of the metal cutting cost and the tool preparation cost, but was directed at turning operations rather than at milling operations. Nevertheless, using his analytical expression and data from turning tool life tests, he too found that the curves for total cost per piece versus cutting speed exhibited a minimum. He then developed an analytical expression for calculation of that minimum from cost and tool life data by differentiating the expression for the cost per piece with respect to cutting speed and setting it equal to zero. The resulting relationship was

$$V = C\,(n / 1-n)^{n}\,[K_1 / (K_1TCT + K_2)]^{n} \qquad (3.12)$$

where V = cutting speed for minimum cost/piece, ft/min

K_1 = direct labor + overhead rate for machining, \$/min

K_2 = direct labor and overhead rate for tool grinding, \$/min/tool

n = exponent in Taylor's equation $VT^n = C$ (see chapter 2, equation 2.1)

C = cutting conditions constant in Taylor's equation

T = tool life, min

This relationship has proven to be a very useful one for the engineering of machining operations and, in an assortment of variations for different applications, continues to be used as such today. The results of Gilbert's research on this subject were published in a paper authored by him in 1950 (3-24). In 1954, Gilbert joined the General Electric Company, where he quickly became manager of the Machining Development Operation in their Corporate

Manufacturing Engineering department. There he incorporated the results of his continuing research on the economics of machining into an analog type machinability computer as well as into a slide rule. These tools became quite widely used in industry.

Hans Ernst - In Retrospect

Chapter 2 sets forth the fact that Fred Taylor and Orlan Boston played the major roles in advancing empirical engineering knowledge and understanding of machining, laying the groundwork for subsequent continuing research. Looking back over the present chapter, it is no doubt evident to the reader that Hans Ernst played the major role in initiating and supporting research to create understanding of the engineering fundamentals of the metal cutting process, including the breeding, or the direct influencing of such key researchers in that field as Merchant, Shaw, Hahn, Trigger, Chao, Field and many others who followed. Ernst's devotion to the cause of creating understanding of those fundamentals was contagious and clear, as demonstrated by the quote from his paper (3.1) on "Physics of Metal Cutting" which we presented early in this chapter. His conviction stemmed from a deep and abiding philosophy concerning the role of basic and applied research in general, which he coined very early in his career as the first Director of Research at what is now Milacron, Inc. He gave voice to that in 1932, in the opening paragraphs of a paper which he wrote setting forth his thoughts concerning appropriate characteristics for industrial research. (3-25). To quote:

> "Industrial (or applied) research is simply the application, to industrial problems, of the three elements of research - Experiment; Observation; Analysis. By careful experiment and accurate observation the facts of the

> case are made known. By critical analysis of these facts, and a skillful blending with the facts derived from basic research, the way is pointed toward further experimentation, and thus the cycle may be repeated. Each successive cycle leads nearer and nearer to the desired goal. But at each stage of analysis we must add the facts derived from basic research, hence basic (or pure) research is truly the life blood of applied research, and unless the former is fostered and developed the latter must inevitably starve."

Ernst continued to communicate that philosophy, and his precept of "Experiment; Observation; Analysis," to his research staff throughout his career, creating salutary effects evident from this chapter. In fact, his precept of Experiment; Observation; Analysis seems to ring out as epitomizing the experiment - theory synergism, dealt with in this chapter, which characterized the era of 1940 - 1960 -- an era which Komanduri (1-2) has characterized as "the Golden Age of metal cutting and grinding research."

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Chapter 3

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CHAPTER 4

DEVELOPMENT AND APPLICATION BEGIN TO FLOURISH — PROCESSES AND MACHINES

– The 1950s into the 1960s

Addressing a Serious Hiatus

As we have seen, machining research carried out during the early part of the 1900's had, under the aegis of such star empiricists as Fred Taylor and Orlan Boston, produced a wealth of empirical knowledge that served as the basis for initial development of realistic capability to engineer the utilization of the machining process in practice. However, as such research continued, it gradually highlighted the existence of an unfilled gap in the knowledge needed for true engineering of the machining process, namely knowledge providing theoretical understanding of that important process. However, as we have seen, that gap began to be filled, during the 1940's under the inspiration of such observant and perceptive researchers as Hans Ernst. However, even as such understanding then began to emerge, it served to create awareness of a situation that had arisen and was beginning to become acute, particularly in this country. That was the fact that, even as the pace of the emergence of the knowledge needed to support the engineering of the machining process had been quickening, the application of such knowledge in American industry had begun to lag farther and farther behind such. The gap between the level of the engineering knowledge of machining and the average level of the practice of machining in U.S. industry was becoming woefully large.

In fact, by the close of the 1950s, the outlook for improving that situation actually became even bleaker. This is because, at that time, American universities came to the conclusion that manufacturing engineering, even when taken as a whole, lacked a sufficient science base to make it worthy of inclusion in the new science-based engineering curricula which were then beginning to be adopted by U.S. academia. Thus, research and education in manufacturing engineering, including that directed toward engineering of manufacturing's most widely-used and basic process, that of machining, virtually came to a halt in American universities! That situation unfortunately persisted to various degrees for over twenty years. As one result, by the close of the 1950's, what Komanduri (1-2), speaking as an academic, characterized as "the Golden Age of metal cutting research" had, in his opinion, come to an end.

A Rescuer Begins to Emerge

However, in the 1940's awareness of the growing gap between engineering knowledge of machining and its application in practice referred to above, began to emerge in some sectors of the research community and in certain individuals therein. Among these, the person who was probably most acutely concerned about it was Dr. Michael Field. He, as we saw earlier, was making important contributions to the knowledge and understanding of the machining process through the research that he was carrying out at the Cincinnati Milling Machine Company in association with Hans Ernst. He, with Hans Ernst, had performed the pioneering research on the economics of machining described in the previous chapter. In addition, Field (4-1) had begun a program of trail-breaking research (which he continued to successfully pursue well in the 1950's) establishing the relationship of the microstructure of cast iron and other ferrous work materials to the machinability of such materials.

In his pursuit of that research, Field had occasion to have continuing contact with a variety of manufacturing companies in connection with machining problems that they were experiencing. Their shocking lack of understanding and application of the current engineering knowledge of the machining process made a deep impression on him. This was also shared by his close associate in the ongoing research and associated industrial contacts at the Mill, Norman Zlatin. As a result, the two of them decided to undertake a major effort to help American industry overcome this situation. They left the Mill in September of 1948 and set out to establish a company devoted to doing research and development aimed not only at helping American manufacturing companies solve their immediate machining problems but also at helping to deploy existing and new machining technology into American industry. Their success in this undertaking has turned out to be one of most salient factors in the reduction that has since occurred in the previously existing large gap between the state of the research-generated engineering knowledge base in machining and the state of its reduction to practice in American industry.

Agents of Change Are Created

Dr. John Kahles, who was at that time Professor of Metallurgy at the University of Cincinnati, and who had become equally concerned about the industrial gap between knowledge and practice in machining, joined Field and Zlatin in this undertaking. The trio had to struggle very hard at first, since the initial response of industry was highly muted. However, their firm belief in the need, and in their approach to meeting it, kept the partnership alive. Then the ice began to be broken by enlightened believers in a few larger companies, including Philip McKenna, the founder of the Kennametal Company, himself a brilliant tool material researcher, and Roy Hurley, Manager of Manufacturing at the Ford Motor Company (and later president of Curtiss-Wright Corp). They funded some machining research and testing projects at the tiny enterprise and it began to grow.

It soon assumed the name Metcut Research Associates, Inc. But, its struggles were far from over. Then, at the end of the 1940's a new source of funding of its R & D and deployment of machining technology entered the picture and began providing financial backing that undoubtedly was a critical factor in its early and abundant fulfillment of the national mission for which it had been founded. This new player was an entity that had been established in 1947 by the U.S. Air Force in response, in part, to the broad need, touched on above, to deploy existing and new machining technology into American industry. That entity was the Manufacturing Technology (ManTech) Division of the Air Force Materials Laboratory located at Wright-Patterson Air Force Base, Dayton, Ohio. The stated function of this Division was (and is) to upgrade and demonstrate new and improved practical techniques that would meet manufacturing needs of both government and industry. It therefore constituted a major source of funding of both small and large programs of manufacturing R & D, targeted at meeting those manufacturing needs that were of such a nature and/or magnitude as to be “beyond the risk of industry” to undertake. Furthermore, and of particular significance to Metcut, was the fact that its initial overall program was strongly focused on enhancement of materials processing capabilities in industry.

Late in 1949, the ManTech Division contracted with the Curtiss-Wright Corporation for execution of a large program to investigate the machining characteristics of alloys used in aircraft structure and aircraft engine components. This was to be carried out under the direction of Roy Hurley, who by that time had become president of Curtiss-Wright. Hurley then subcontracted with Metcut to carry out the laboratory research and testing on the machinability of the alloys to be investigated under that contract. The results of this first contract were found to be so valuable that it was followed by a succession of three more ManTech contracts with Curtiss-Wright on the same subject, with the machinability research and testing work again subcontracted to Metcut in each case. The four contracts together covered the period 1949 through 1960. Then, in 1963, the Air Force ManTech Division contracted directly with Metcut to carry out machinability research and testing on additional alloys used in aircraft structures and engine components. This resulted in a total of seven such contracts with Metcut, all performed under the direction of Norman Zlatin during the period of 1963 through 1975.

The machining research conducted under these entire series of contracts, spanning the period from 1949 through 1975, covered 115 alloys used in aircraft structures and engine components. Alloys investigated included nickel and cobalt based high temperature alloys, stainless steels, maraging steels, refractory alloys, high strength steels, titanium alloys, and aluminum alloys. Machinability data was produced for turning, milling, drilling, tapping, routing, sawing, and surface grinding. These data have proven to be instrumental in the successful manufacture and well-founded development of jet engines and aircraft from the 1950's through the present era.

The findings from the research performed in the initial subcontract had also demonstrated the need for a much broader and more fundamental program of R & D on the machinability of commonly used structural alloys in general. In particular, as had begun to become evident from Field's earlier research on the effect of microstructure on the machinability of cast iron (4-1), what was lacking and greatly needed was an engineering understanding of the role which microstructure plays in governing the machinability of such alloys. Thus, the series of following contracts from the Air Force included specific support for research on such. The results of that research have made clear the role of microstructure in governing the machinability of most materials. It demonstrated that the properties of each of the individual constituents of the microstructure of a material, together with their relative predominance in that microstructure, play the major role in determining its machinability. Field presented and published a paper in 1963 (4-2) that clearly illustrates this fact. It concisely summarizes the results of a tremendous number of tool life versus cutting speed tests that Metcut ran on a wide range of cast irons and wrought steels that together possessed a great variety of very different microstructures. The tests were run with both high speed steel and sintered carbide tools. Comparison of the photomicrographs of the microstructure with the those values of cutting speed that resulted in a thirty minute tool life, made the close correlation between microstructure and permissible cutting speed abundantly evident.

The rapidly growing wealth of new and excellent machinability data and information coming from Metcut's research and testing during the 1950's and early 1960's and the growing recognition of the value of such to industry, led to a further notable event in the evolution of Metcut's manufacturing research activities. Here again the Air Force Mantech program played a major role. This was their granting of an Air Force contract to Metcut in 1964, to establish and operate, within Metcut, an activity named the Air Force Machinability Data Center. The prime function of that Center was to collect, evaluate, store and disseminate machining data and information. The Center continued under that name until 1972, when the U.S. Army's Materials and Mechanics Research Center assumed its sponsorship, under a Department of Defense contract from the Defense Logistics Agency, and the Center became the Metcut Machinability Data Center.

By that time, the Center had become the core of Metcut’s program of deployment of data, knowledge and understanding of metal cutting and grinding technology throughout American industry. That technology information covered, of course, not only existing technology, but also that being constantly generated by Metcut’s ongoing research and that of other research organizations throughout the world. The Center carried out its deployment to industry of existing machining technology, and of the results of machining research, through a variety of media. It developed a world-class library on machining technology, supplying literature searches to industry and to researchers throughout the world. (That library was invaluable to the authors in the writing of this historical review.) It developed and offered a continuing program of seminars on state-of-the-art machining technology, and, most ambitiously, it undertook development of a handbook of data on “starting recommendations” for speeds and feeds for machining practice.

A Unified Machining Data Base is Born

It was John Kahles, working closely with Mike Field, who masterminded this curtain-raiser research program. This was devoted to producing, for the first time, a compendium of best-practice machining data, recommending machining parameters (such as cutting speed, feed and depth of cut) for first-time machining operations (such as turning, milling, drilling, etc., as well as for grinding and non-conventional material-removal processes) on all commonly-used work materials with all commonly used tool materials and types of cutting tools. As can be judged, this was a mammoth research undertaking, well beyond the risk of any private research organization. However, most fittingly, Metcut was awarded a contract in 1959, in support of this pioneering venture, by the U.S. Army's Material Command, through its Rock Island Arsenal in Illinois.

This prodigious research endeavor involved first of all, the collection of both published and unpublished machining data that had previously been created by machining research and testing, plus actual production operations, in universities, research laboratories and manufacturing companies. This data had to be combined with the wealth of machining data that Metcut had already generated (and continued to generate) from its own machining research and testing. The data had then to be analyzed, interpolated, evaluated for consistency, weeded and spot-checked for accuracy by additional in-house machining tests. This immense research effort, impossible though it may have seemed to be at its inception, resulted, in 1966, in Metcut’s publication of the first edition of the Machining Data Handbook. That unique publication quickly became industry’s machining “bible” and has remained so. The research effort that produced it became an ongoing one for Metcut. The Handbook, which is currently in its third edition, now comprises two volumes and lists data for sixty-one classes of work materials and fifty-eight types of conventional operations. It is now one of TechSolve’s publications.

Engineering of Surface Integrity Is Enabled

Meanwhile, while the Handbook project was still in a relatively early stage, Mike Field, working together with John Kahles and William Koster, launched research into another virtually unexplored area. This was an investigation of how to control and mitigate the detrimental surface alterations resulting from the disturbed layer that is usually created on the surface of components produced by metal cutting and grinding operations. They coined the term “surface integrity” to characterize the state of such an altered, disturbed surface relative to that of a pristine one (4-3). Although Tarasov (4.4), followed by others, had carried out research in this country on the subject as early as 1946, the true nature of the characteristics of metal surfaces whose integrity had been deteriorated by cutting or grinding operations was still not clearly understood in the early 1960's. Therefore, Field and Kahles initially carried out a comprehensive study of the condition and characteristics of a variety of metal surfaces that had been produced by cutting or grinding operations performed under a wide variety of machining conditions. From this they pinpointed the various sources from which the disturbances and alterations found in the surfaces so produced arise. These include, for example, such factors as the severe plastic deformation and large temperature gradients to which the metal cutting and grinding operations can subject workpiece surfaces. These can, in turn, produce such effects as rehardening, over-tempering, high residual stresses and cracking of the disturbed surfaces. Those effects can result in such detrimental consequences as distortion, increased susceptibility to stress corrosion and increased vulnerability to fatigue failure of the components being produced. Components that are used in critical applications and subjected to such conditions as high stresses and severe environments are thus placed at considerable risk if the machining conditions employed in their production result in such deterioration of their surface integrity. However, the study gave clear indication that the degree to which such deterioration was produced was very dependent on the machining parameters employed in the production of the surfaces.

On the basis of this understanding, Field and Kahles carried out extensive research to arrive at a sound engineering basis for selection of machining parameters that would provide maximum surface integrity of parts produced by metal cutting and grinding operations. This was concentrated first on the grinding operation, since their investigation had made clear that grinding was more prone to aggravate deterioration of surface integrity than was metal cutting. They ran extensive machining tests on a variety of critical, susceptible work materials, over wide ranges of machining parameters; identified the metallurgical and other changes that had occurred in the machined surfaces; and evaluated the surface residual stresses, fatigue life, etc. of the resulting machined specimens. By the end of the 1960's, they had arrived at firm understanding of the nature of the relationship between machining conditions and surface integrity. Based on this, they prepared extensive guidelines (4-5) for maintaining surface integrity in performing metal removal operations on critical materials. These covered operations performed by both grinding and metal cutting (as well as by electrical, chemical and thermal material removal processes). They also covered inspection practices and related post-processing activities. The landmark accomplishments of this research undertaking have drastically changed practices employed in the machining of critical parts throughout the world, contributing very significantly to improved safety and reliability of mechanical products through surface integrity.

Dr. Michael Field, through his pioneering founding and continuing leadership of Metcut Research Associates (as well as through his own research) accomplished major narrowing of the very threatening, wide and growing gap, present in the 1940's between the state of the research-generated engineering knowledge base in machining and the state of its reduction to practice in American industry. The deployment by Metcut of such research-generated knowledge into practice proved to be a leading-edge factor in the steady and significant rise since then of productivity and quality in American industry’s performance of the machining process—manufacturing's most widely-used and basic process! Others began to follow in Mike Field’s footsteps, undertaking R & D and deployment of machining technology. Machining research slowly began to blossom again in some universities, laying groundwork for the eventual wide-spread return of manufacturing-oriented engineering research and education to American universities, which came into full bloom by the end of the 1980's.

Although Metcut's accomplishments in successfully removing significant roadblocks to productivity in machining practice, through its research and the application of such, were the paragon of that field in the 1950's and 1960's, other research organizations also made significant contributions during that period. Many of these have been detailed by Komanduri (1-2) in this excellent historical review and so are not dealt with further here. However, it does appear appropriate to briefly treat one set of these because it relates rather closely to Field's research on the role played by microstructure in the machinability of materials. This is the research done at Battelle Memorial Institute in Columbus, Ohio, to develop so-called free-machining steels. That research resulted in the enablement of significant increases in metal removal rates in the machining of appropriate types of steel. A key player in this research, as it progressed, was Francis W. Boulger (who provided the principal author with the information that follows).

Free-Machining Steels Are Demystified

Fran Boulger joined the Battelle Columbus Laboratories in 1937 as a metallurgist. At that time, Dr. Clarence Sims, a prize-winning metallurgist at the Battelle labs, was carrying out a research program to develop an open-hearth steel with machining properties at least comparable to those of high-sulfur Bessemer steels, widely used because of their good machining characteristics. Fran became interested in this project and followed it closely. In those days, the widely held opinion as to the reason that resulfurization improved machinability of steel was that the sulfur acted as an embrittling agent. That view was supported by the fact that steels made in air-blown Bessemer converters had higher nitrogen contents than open-hearth steels. It had just been proven, very convincingly, that nitrogen was the principal cause of strain-age embrittlement in low-carbon steels. Sims therefore ran some simple sawing tests on a series of experimental steels, prepared by a previous investigator, to which various embrittling agents had been added.

The cuttings tests were run by measuring the rate at which each steel was sawed by a gravity-fed hacksaw. Sims found that three of these steels, namely those to which tin, antimony or arsenic had been added, cut much faster than did either the base steel or any of the others. However, these three additives each had been introduced into their lot of steel either by wrapping them with lead foil or by alloying them with lead. Sims then made some batches of steel to which lead only was added, or lead plus each of the three embrittling agents in turn, or each of the three embrittling agents only. Only those that contained lead, with or without the presence of the embrittling agents, sawed very easily! Large batches of steel containing various amounts of lead were then made in a steel plant and evaluated by screw-machine tests in commercial shops. Those containing 0.15 to 0.35 percent lead were found to have machinability ratings some 40 percent higher than standard resulfurized Bessemer-grade free-machining steels. In tensile tests at room temperature the lead-containing steels exhibited strength, reduction in area and elongation values comparable to those of lead-free steels with similar base compositions. Thus, leaded free-machining steels were born (4-6).

Studying the results of this research, Boulger came to the conclusion that the reason such inclusions as lead and iron-manganese sulfide improved the machinability of steel was, very likely, that they reduced the friction between the cutting tool and the chip by interposing a miniscule layer of these low shear strength materials between the tool face and the chip that is sliding over it. This reduces the amount of heat generated (and thereby the temperature level) at the tool-chip interface. [This reduction in friction by such inclusions was later confirmed and quantified by Merchant and Zlatin (4-7) in 1948.] This surmise, together with the demonstrated effectiveness of the simple gravity-fed hacksaw test in discerning the improved machinability of leaded steels, as demonstrated in practice, led Boulger to develop what has proven to be a well-engineered, reliable, yet simple and quick method to test the machinability of free-machining steels (4-8).

The test method that Boulger developed employed a special test lathe that his team developed. The method consisted of feeding a cutting tool into the rotating workpiece with a constant force and measuring the rate of infeed of the tool. Such a test method is almost ideally suited to evaluating the machinability of free-machining steels, since the infeed force being applied is roughly equal and opposite of the friction force exerted by the tool on the sliding chip. Thus, the infeed rate must increase when friction is reduced, to keep the two forces in balance. The fact that reliable ratings can be obtained quickly on small samples of a metal by this method is a major advantage in laboratory studies. Additionally, the method facilitates the use of replicate tests and statistical methods of interpreting data.

Using this test method, Boulger then undertook a very significant research program that resulted in the development of an improved class of free-machining steels. This was initiated in about 1946 to explore the reason for the high degree of variability in machinability being experienced universally between various batches of resulfurized free-machining steels, even though they met chemical specifications. Tests were first run with his new method to see whether the resulting measured values of feed rate correlated well with the machinability of the given free-machining steels in practice. Agreement was excellent. Tests were then run on samples of steel bars from over 200 heats of Bessemer free-machining steels. Even though the chemical composition of all these samples from regular production met the standard specifications, namely those for carbon, manganese, phosphorous and sulfur, their machinability ratings, as measured by the constant-force test, varied considerably. Cross-correlation analysis showed minimum correlation of unintentional variation of the levels of these four standard elements with the machinability data. However, when the level of silicon content (which was not normally specified or determined) was measured, good correlation was obtained. Increase in the silicon content by as little as 0.005 percent increased the machinability rating by 8 units.

The next step was to determine the reason for this correlation between silicon content and machinability. Examination of the microstructure of the steels provided the answer. It was found that steels with poor machinability usually contained thin, elongated sulfide inclusions and these steels were ordinarily characterized by higher-than-average silicon content. On the other hand, the steels having unusually good machinability contained sulfide inclusions of a semi-globular shape and ordinarily contained very little silicon. This research program resulted in a patent on superior resulfurized free-machining steel having low silicon content. (4-9) Its application in practice resulted in capability to use higher cutting speeds, obtain longer tool life and minimize tool changes. As a result, production costs for the machining of steel were lowered some 25-30 percent in many factories.

Machining Chatter is Tamed

As we have seen, beginning in the 1950's research and development of machining process technology began to team up to successfully remove such major roadblocks to machining excellence as inferior surface integrity, adverse metallurgical factors and unavailability of machining process data and information. However, they had also begun to team up to shatter some equally restrictive obstacles to high quality machining that were plaguing the machines that carry out the machining process, namely, metal cutting and grinding machine tools. One of the most serious and restrictive of these obstacles was the chatter and vibration of machine tools that occurred during their performance of metal cutting and grinding operations. Such chatter and vibration had, through the years, placed serious restrictions on the rate at which metal could be removed by a given machine tool. In addition, it had very detrimental effects on surface finish, dimensional accuracy, tool life and machine life.

Hans Ernst had recognized the seriousness of such vibration and had carried out research, together with Dan Grieb and Mike Field, to try to suppress its occurrence during machining. This resulted in this team's successful invention in 1946 of a tunable vibration damper incorporated in the overarm of a milling machine (4-10). However, Ernst recognized that this was at best a palliative, and one primarily limited to a specific type of machine. He therefore never ceased to encourage his staff to seek a fundamental and generic approach to understanding and control of chatter and vibration in machine tools. However, that did not occur prior to his retirement from the Mill. Further understanding of the nature of machine tool chatter first had to develop.

By the 1950's this began to come about, in light of the following facts: In almost all types of machinery, one common source of vibration is forced vibration, caused by such things as imbalance of rotating members, or in machine tools, by the impacts of the successive entry of the teeth of a multi-tooth cutter into a workpiece. However, because of its generality to virtually all types of machinery, the theory of forced vibrations had become rather well developed by the 1950's, and was readily applicable to machine tools as well. However, in machine tools, a much more serious type of vibration predominates, namely self-excited vibrations. This can cause violent, destructive chatter to occur. Such chatter arises from fluctuations in the force exerted on the cutting tool during the machining process. These fluctuations can, of course, arise from other sources. However, by far the most common cause occurs when the path of the cutting edge of the tool continuously overlaps its previous path, as in normal turning or milling operations. In this case the force fluctuations arise from the (out-of-phase) undulations in the surface of the metal being cut, left there by the passage of the vibrating tool during the previous revolution of the workpiece (in turning) or the passage of the preceding tooth of the cutter (in milling). Depending on the cutting conditions and the dynamic compliance of the machine structure, these force fluctuations can so excite the structure as to cause violent regenerative self-excited chatter to build up rapidly.

The first significantly successful efforts to establish a sound engineering basis for mitigating and controlling such self-excited chatter were made in Europe by Tobias (4-11) and his associates in England and Tlusty (4-12) and his associates in Czechoslovakia. Applying conventional vibration-theory methodology, they developed theories that could be used to estimate, for a given machining operation, the limiting conditions under which instability would begin to occur, causing regenerative self-excited chatter to build up. Also, as mentioned in Chapter 3, by 1954, Hahn (3-17) had developed an initial theory of regenerative chatter in precision grinding operations. All of these theories were, indeed, pioneering and trail-blazing accomplishments. However, none of these were sufficiently generic to cover all the effects observed in machine tool chatter. Also, because of the approach taken, these failed to significantly link machining process considerations to machine structural considerations. Further, they were computationally difficult to apply in engineering practice.

Here again the U.S. Air Force's ManTech program, the mission of which was to address the national need to fill major gaps in manufacturing technology and in its implementation in U.S. government and industry facilities, came to the rescue. Recognizing the fact that no generic and adequate theory of chatter and vibration in machine tools yet existed, it issued, in 1962, a request for proposal for research on that serious problem. Merchant, at the Cincinnati Milling Machine Company was among those receiving that request. Being acutely aware of the serious need for a major program of research on such, especially in light of Hans Ernst's early continued emphasis of that need, he investigated whether the research staff could respond. In response, Herbert Merritt, a Section Head in that staff, conceived a way to blaze a trail in a new direction to attack the problem of machine tool chatter (4-13). He proposed that, instead of applying conventional vibration-theory methodology to that problem, he apply control theory methodology. That proposal resulted in a ManTech contract to so do and he proceeded to pursue that direction. The approach he took was to represent self-excited machine tool chatter by a closed-loop feedback system. In this (drawing as well on Merchant's analysis of the mechanics of cutting) the cutting process dynamics were directly coupled to the dynamics of the machine structure in the system's main path, with two feedback loops encompassing them, namely, a negative feedback of position (primary path) and a positive feedback of delayed position (regenerative path). The regenerative feedback path is most serious and is only present when overlap of successive tool paths, described above, is occurring. The approach thus embraces the dynamics of both the cutting process and the machine structure, as well as their behavior and interaction under both regenerative and non-regenerative self-excited chatter conditions, in a single system. Based on this approach, Merritt succeeded in developing clearly stated equations (transfer functions) governing both the machining process and the machine structure. Further, to simplify utilization of these in practice, he developed a special, uncomplicated chart (which later came to be called a Merritt chart) to find harmonic solutions of the characteristic equation that defines the borderline of stability for a machine tool having a structure with n degrees of freedom. The resulting theory not only encompassed all the published theories of chatter existing at that time but also went beyond them, being quite generic. It has thus become the primary basis for engineering practice in the mitigation and control of chatter in the machining process.

Merritt's trail-blazing approach to tackling the need for sound, simple, generic engineering understanding and analysis of the crippling problem of machine tool chatter, suitable for ready application in practice, was in tune with the ethos of the times. That ethos was, as described earlier, that of dedication to reduction of the large gap that, by the 1940's, had come to exist between engineering knowledge of machining and its application in practice—an ethos pioneered in large measure by Mike Field. Merritt came to the Cincinnati Milling Machine Company, in 1961 from the Gas Turbine Division of the General Electric Company where he specialized in the simulation and stability evaluation of jet engine controls. He brought that background to bear on the problem of chatter in machining, in the machining and machine tool research environment provided by the Mill. The result was a solution to the problem that was not only generic in nature but also was, at the same time, one readily utilizable in engineering practice, thus bridging the knowledge/practice gap. That salutary accomplishment opened a new era in the engineering design of machine tools, providing a basis for such subsequent developments as:

a. Computer analysis of machine tool structures to predict chatter performance in advance of their being built

b. Development and use of more advanced instrumentation, such as Transfer Function Analyzers, to measure the dynamic characteristics of structures

c. A better understanding of the dynamic characteristics of the cutting process

All of these have combined to yield significant advance in the capability of machine tools to perform the machining process.

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CHAPTER 5

MEANWHILE - A QUIET REVOLUTION

– The 1960s into the 1990s

Watershed Events Had Occurred

As reflected in the two preceding chapters, the decades of the 1940's and 1950's were an exciting and productive time for those engaged in research in machining and for those engaged in the implementation of research results in industry. For most of those two decades, researchers engaged in these activities encountered little in the way of technological changes in the field of manufacturing that offered sufficient challenge to distract them from the pursuit of their research aimed at providing increased capability to understand and engineer the machining process. However, during the latter part of the second decade an event took place that was destined not only to offer powerful challenge for change to those doing such research, but also to begin to transform the very character of that research during the coming decades. This "watershed" event (though not recognized as such at the time) was the invention and development of the numerical control (NC) of machine tools. That event had its roots, in turn, in another watershed event, namely the invention of the digital computer and its associated technology in the 1940's. In essence, numerical control of machine tools is a process that employs digital output of the type provided by a digital computer to program and control the motions that a machine tool must make in moving a cutting tool relative to a workpiece along such tool paths as are required to carry out desired machining operations on that workpiece.

An Inventor Who Changed History

The inventor of the numerical control of machine tools was John T. Parsons, of the Parsons Corporation in Traverse City, Michigan. He filed his initial patent on such in 1952 (5-1). It was an invention that eventually brought Parsons national and international recognition and acclaim for his history-changing concept. Among these was the award by the Society of Manufacturing Engineers of its SME Engineering Citation in 1975, which read:

> "John T. Parsons, industrialist and inventor, whose brilliant conceptualization of numerical control marked the beginning of the second industrial revolution and the advent of an age in which the control of machines and industrial processes would pass from imprecise craft to exact science".

He also was a recipient of the National Medal of Technology in 1985 and was elected to the National Inventors Hall of Fame in 1993. The research that led up to that invention began in the latter part of the 1940's. At that time, Parsons was running the Parsons Corporation, founded by his father, and it had become the country's major producer of helicopter blades. These were produced by innovative techniques that Parsons had developed, working closely with the Air Material Command at Wright-Patterson Air Force Base, Ohio. In the course of this they exposed him to drawings of new supersonic planes that the Air Force was planning to build. There he recognized airfoil shapes that were essentially impossible to produce by conventional machining methods.

Parsons then began research to devise methodology to solve that problem, based on extension of an innovative technique that he had developed in 1947 to produce airfoil templates for the helicopter blades on a precision jig mill. In this, an operator used only numerical data produced with IBM punched card machines to manually position the milling machine's lead screws in two axes. That data consisted of 200 points on the airfoil curve, calculated by the punched card machines using a method developed by Parsons and Frank Stullen, an aeronautical engineer who headed the company's engineering department. That technique was found to be capable of producing, in Parson's own words, "air foil templates to a tolerance of 0.0015" plus the height of the cusps."

Based on the success of this course of research, Parsons conceived the then seemingly far-out idea of automating this quite tedious process by using a drive mechanism actuated by digital information (in the form of punched cards or tape, in his case) to directly operate the lead screws of the milling machine. He reasoned that this technique could make possible the machining of such otherwise essentially impossible shapes as he had seen in the drawings of the planned supersonic planes. This was the heart of his invention. In a private communication to us, Parsons succinctly describes that conceptualization, and the milestones along the beginning of the long research trail that resulted, as follows:

> May 1948: Conceptual expansion of the (foregoing) principle to 3-D to permit machining integrally stiffened wing sections for jet airplanes.
>
> December 1948: Demonstration of the validity of the concept to an Air Force

team. A scale model wing section tapering in planform and section was machined on a Swiss boring mill with a universal table.

June 1949: Signing contract #AF 33(038) 6878 with the US Air Force paraphrased as follows: "to design and construct a milling machine using servo-mechanisms actuated by punch cards or tape to produce wing sections."

Air Force ManTech and a University Become Enabling Partners

So here, once again, the Air Force ManTech program stepped in at the critical moment to begin the process of enabling realization of R&D of fundamental importance to major advancement of the capabilities and productivity of the machining process -- R&D that otherwise lay far beyond the feasible risk of the originating company alone!

John Parsons was, of course, already well aware of the inability of his company to carry out such an undertaking alone. Encouraged by the very favorable response of the Air Force team resulting from the 1948 demonstration, and the strong likelihood that they would award a contract, he had already contacted several potential subcontractors having capabilities suited to carrying out parts of the required R&D. Among these was the (then so named) Servomechanisms Laboratory at MIT headed by Professor Gordon Brown. As referred to by Professor Francis Reintjes (5-2), Parsons' representatives met with Brown and his associates at MIT in June of 1949 and described his project to them. They explained that, because their small company did not have the technological resources in the field of digital electronics and control systems to design and build the required lead screw drive mechanism capable of being actuated by digital output from punched cards or tape, they would be interested in having the Laboratory carry out that part of the project. The Lab responded with much interest to the challenge offered by this project, and in July of 1949 a Memorandum of Agreement was signed for the Lab to study Parsons' system, to enable it to design the necessary unique servomechanism system.

So now the resources of another type of partner—a university—had been brought to bear on this momentous project in its early and very critical stage, further enabling the performance of R&D appropriate to the fundamental importance of such to major advancement of the capabilities and productivity of the machining process. The Lab took the project in a somewhat different direction than Parsons had envisioned. Its research engineers first did a much needed incisive systems study. They then designed and built a digitally-controlled, three-dimensional servo system and applied it to a conventional milling machine. By March of 1952, a working laboratory prototype numerically controlled machine tool resulted, validating the essence of Parsons invention. As Reintjes observed in a private communication to us, "The MIT machine bore no resemblance to the machine for which Parsons was awarded his patent. The MIT prototype machine did validate Parsons idea that a computer could be used to control a machine tool." MIT filed a patent on the prototype numerically-controlled servo system, which was assigned to Parsons when it eventually issued (5-5).

It should be observed here that, as this joint industry-university- government cooperative activity evolved, it by no means had gone smoothly, as descriptions of what took place by Reintjes (5-2), by Ashburn (5-3) and by Noble (5-4) have made clear. As Reintjes observed in a private communication to us, "in the beginning of (such) a research effort, there is likely to be false starts, thrashing around, and professional differences of opinion (not personal animosities) on how to proceed—all in the spirit of trying to really understand the problem and `the best' way to solve it". Perhaps that was particularly to be expected here in view of the great import of this undertaking, its unique character, the differing objectives of the three partners and their differing views of the world of industry. In any case, however, the descriptions of what took place by Reintjes, by Noble and by Ashburn, though conflicting, offer much food for thought relative to how to make momentous industry-university-government cooperative undertakings still more workable and efficient.

On September 15, 16 and 17, 1952, the prototype was successfully demonstrated to a total of 242 representatives from industrial organizations and government agencies. Unfortunately however, as a laboratory prototype, the NC machine failed to convey a sense of practicability to the machine tool industry and to the manufacturing industry in general. In fact, as Professor Milton Shaw of Arizona State University, who attended the MIT Servo Lab's three day demonstration of that prototype NC machine, stated in a private communication to us, after having read our above statement in the preliminary edition of this monograph:

> "Your statement…is a gross understatement. The participants from the larger companies were downright hostile and tried to shut the project down, declaring it was inappropriate to use defense funds on a project that had no chance of success."

Thus, the results of this major R&D program, holding potential for major advancement of the capabilities and productivity of the machining process, failed initially to motivate the American machine tool industry, to any significant degree, to begin the process of reducing it to a commercially available product.

The Air Force Acts to Catalyze Reduction to Practice

On the other hand, there was an influential constituency that was strongly motivated to having that reduction to practice take place as quickly as possible. That was the Air Force Air Material Command’s Manufacturing Technology Division. They, of course, already had made an appreciable investment in the R&D aimed at bringing NC into being, having funded the contracts which resulted in the prototype NC machine. They also, and even more importantly, recognized and understood its tremendous potential to greatly increase the capability of the machining process and, particularly, to do so for their prime beneficiary, the U.S. aircraft industry. That recognition and understanding resided particularly in two of the ManTech Division’s engineers, namely William M. Webster and Max A. Guenther. They had carefully shepherded the contract R&D carried out by Parsons and MIT, and now yearned to find ways to motivate commercialization of the results of that work.

Fortunately, just at that time, the early 1950's, the services (Air Force, Army and Navy) were initiating a program to purchase machine tools to be put in a reserve against future mobilization requirements. Final decisions on the kind of machines to be purchased and how the orders for these would be allocated were the responsibility of the Air Force. Webster was a member of the working group that handled the details of that planning. Here then was an opportunity to create a market incentive strong enough to cause the machine tool industry to develop and produce commercially available models of NC machine tools. Webster and Guenther brought their recognition and understanding of the potential of NC to bear on the working group. This was instrumental in helping the group come to the decision not only to include NC machines in this “bulk buy” of machine tools, but also to put those NC machines into immediate use in the production of military aircraft rather than putting them into storage until needed for a mobilization. Of the 500 machine tools finally authorized for purchase at the end of 1955, 105 were numerically controlled skin mills and NC profile millers, plus their machine control units. The Air Force had thus come full circle, from first playing a major role in enabling the technological realization of NC machine tools to having finally created the initial market that resulted in motivating the commercialization of such technology. These were both events that, without that government seed money, would have taken very much longer to occur. [As Merchant (5-6) observed in 1979: “There seems to be quite general consensus in the US manufacturing industry that, as a result of this (NC) Federally supported program, this country gained five to ten years’ lead time, initially, in the innovation of numerical control technology in industry.] American industry was much benefited by that overall cycle. But it was a unique cycle and one that has never since been repeated in full to accelerate innovation of other major revolutionary technologies.

Looking at the still broader picture, it was the collective exceptional vision, creativeness, commitment and persistence of the key individual actors in this phenomenal industry-university-government machining R&D program -- Parsons, the MIT Servomechanisms

Laboratory staff and the Air Force Manufacturing Technology division staff -- that brought the undertaking of this revolutionary venture to success. Both this country and the world have been truly enriched thereby!

The University Moves to Demolish a Technological Roadblock

As industry began to put NC to work, following the "bulk buy," one significant technological impediment to practicable economic utilization of it on a broad scale by the manufacturing industry remained. That was the very long time required to prepare each program to be input to the machine controller on punched cards or tape, i.e., the program of minute incremental motions which the machine tool must make, in sequence, to move the cutting tool along the (often intricate) paths which it must follow to carry out the machining of a workpiece. The time required to manually prepare such a program for the automatic machining of a part could (including card or tape preparation) be more than 50 times that required to machine that part in some cases (depending on the complexity of the part).

The Servo Lab staff very early recognized this impediment and, even before the prototype NC system had been put into operation, they began taking some first steps to find a means to automate the programming process. It was evident to them that the only technology that had real potential to do this effectively was that of the then evolving digital computer. By that time MIT had developed and was operating its embodiment of that technology, in the form of the Whirlwind computer. The Lab therefore began small-scale research on this. That event marked the beginning of a wholly new type of machining research, namely research on machining process software.

A Gifted Researcher Creates the Solution

The research was begun in a small way, first by a graduate student, followed by a staff member of Jay Forrester's newly established Digital Computer Laboratory, a spin-off of the Servomechanisms Laboratory. The results obtained by both showed much promise and established some initial concepts, but both their approaches had severe limitations. However, in view of the promise shown by these initial efforts, in 1956 a young software researcher in the Servo Lab, Douglas Ross, was commissioned by the Lab to undertake a program of research to find and pursue a wholly workable approach to automatic programming of NC machining. Doug had been a mathematics major at MIT and had then come to the Servo Lab to work in the realm of human-computer systems for high-speed data processing. He was an ingenious, creative, but take-charge type of software person and also a systems thinker. He brought those talents to bear very effectively in the planning and execution of the much-needed research. His stellar performance of that, during the years 1956-59, resulted in his creation of the ultimate solution to automatic programming of NC, namely the Automatically Programmed Tool (APT) system—Doug's brainchild!

The approach that Doug took to accomplish this breakthrough was as follows. He started with the premise that persons doing the part programming should be able to express their machining instructions in a simple, English-like language. This was a premise that had shown promise in the earlier work but which had encountered limitations in the rather narrow approach used there. Doug realized that what was needed was that the language, though simple, should constitute a rational system and, most importantly, one which was open ended. It would therefore be readily expandable and capable of growing with use-based experience. Further, he viewed the required language as a system enabling interaction between a human and a computer in such a way that the human could work back and forth with the computer in a conversation-like mode, interchanging ideas with it, to arrive at an overall program. To quote Ross, “The language must bridge the gap between the fundamentally incompatible characteristics of the two parties. The human is quick-witted but slow, while the computer is slow-witted but extremely fast (5-7).”

The language system which resulted from this approach thus turned out to be one that permitted, to quote Reintjes, “a person with no programming skill to give instructions for machine-tool motions in easy-to-learn English-like terms and to relegate to a general purpose digital computer the jobs of translating these instructions into a language that would be understood by the computer; making the mathematical and geometric calculations required to implement the instructions; and post-processing the numerical calculations and instructions in a way that would be understood by any one of several different digital directors (5-2).” (The reference to the different digital directors relates to the fact that several companies had already begun to develop NC controllers at the time that the APT program got underway.)

Thus, Doug Ross had indeed succeeded in removing the last significant technological impediment to practicable utilization of NC on a broad scale by the manufacturing industry. To again quote Reintjes, “The development of APT was a major turning point in the evolution of

NC, for it settled once and for all the issue of whether or not NC could be made economically viable in the light of programming costs." Justifiably then, the APT language became the American standard for programming of numerically-controlled metal-cutting machine tools in 1974, and the international standard in 1978.

The Manufacturing Industry Nurtures the Reduction to Practice

Another significant aspect of the R&D that produced the APT system was that of the modes of its funding. In contrast to the almost sole funding by the Air Force of the R&D resulting in the prototype NC machine, the support of the R&D of APT was provided, primarily, by the Air Force together with the aircraft industry, with the vehicle for the latter support being the industry's Aircraft Industry Association (AIA). The AIA's role grew rapidly as the APT project continued, due in large part to the confidence in the anticipated benefits from that project that Doug Ross's technological competence, leadership and systems thinking inspired. The form of the industry support was primarily in-kind, and this in due time began to include such support from the controls manufacturers as well. Finally, in 1961, AIA assumed full responsibility for the project, and the Servo Lab was able to gradually withdraw from it. The AIA, in turn, soon contracted with the Illinois Institute of Technology Research Institute (IITRI) to take responsibility for a long-range APT development and maintenance project supported by annual subscriptions from user companies. That successful industry-university partnership lasted for quite a number of years, until such time as the need for it finally disappeared, in 1970.

The New Technology Spawns New Research Directions

The results of the watershed event of the innovation of the harnessing of digital computer technology to automatically perform the machining process began slowly to appear in industry during the latter part of the 1950's, in the form of commercially available numerically controlled machine tools. This demonstration of the potential and power of such technology to radically change the way in which this well-established manufacturing process could be carried out began, during that period, to have a salutary effect on machining research. What it did was to stimulate the thinking of some machining researchers about the long-term implications, for the machining process, of the advent of such a unique and powerful tool as the digital computer. It became almost immediately evident to them that the computer, as a programmable tool, had significant inherent capability to flexibly automate virtually all aspects of the machining process. However, it also brought Merchant, during the 1950's, to the realization that the computer was a systems tool as well and, as such, possessed major potential not only to automate, but also to integrate the various technological elements of any manufacturing enterprise to form a system, and to then operate each as a part of that system. Thus the potential to integrate the machining process with the other technological elements of the product realization process, to form a "computer integrated machining system" then became evident. That integrated system would stretch from the initial concept and design of a product, through the planning and control of its production to the production equipment itself, and to the final fabrication thereon of the product. His initial illustration of that concept of the computer integrated machining system, as it appeared in reference 5-8, is shown in Figure 5.1.

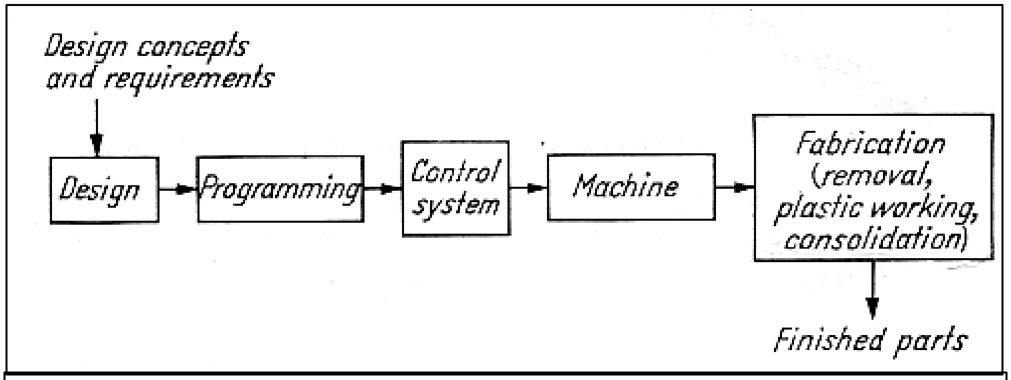

Fig. 5.1. Initial concept of the computer integrated manufacturing system

Thus, the concepts of the system approach to manufacturing and the computer integrated machining system were born. In such a system (then hypothetical), the performance of the machining processes could be carried out online and in conformance with the performance and results of all of the other technological elements of the conceived system of manufacturing, including all of the other production processes. Furthermore, research on machining (as well as on all of the other technological elements of the system) could then be carried out within the context of the fact that that process, during its performance, would be able to interact, online, with all of the other activities going on in the system. This obviously would considerably broaden the scope and change the character of such research. Merchant published the initial results of such thinking and research in his paper titled “The Manufacturing-System Concept In Production Engineering Research”, presented at the General Assembly of the International Institution for Production Engineering Research (CIRP) in 1961 (5-8). He concluded that paper with the words:

> "It appears likely that the new concept of the manufacturing system, developed as a unified, coordinated and automated whole, will produce a revolution in the

> field of manufacturing as we know it today. As such, this concept and its development provide all of us who are working in the field of production engineering research with a tremendous challenge, an increased impetus, and a changed approach to our research. The era ahead should be a most exciting one for all of us, as well as one of greatly accelerated progress. We can all look forward with great enthusiasm to it."

In retrospect, as that concept evolved into reality, the approach to machining research did indeed change. More about some of the aspects of that change are covered later in this chapter.

As the foregoing thinking had been going on, somewhat similar thinking had been taking place at MIT by Reintjes and Ross, along with others there (5-2). They began to realize that creative design of the product was indeed a part of an overall system of manufacturing and if it was to be integrated with the numerically-controlled machining process in a computer integrated system, it too needed to be computer automated. Therefore, as the expiration date of their Air Force contract that had supported the APT R&D was drawing to a close, they began to lay groundwork to obtain Air Force support for research on what in due time came to be known as computer aided design (CAD). Once again, they approached Bill Webster, who had been their project engineer and prime mentor in the Air Force ManTech office throughout the conduct of the NC and APT R&D programs. Here again they found him understanding and supportive of the need and importance of computer automation of the product design process. In December of 1959, they were granted the first of the series of contracts that would result in fulfillment of that need, supporting a program that stretched through the decade of the 1960's. Once again, Air Force R&D funding had come to the rescue, just as it had so many times in the past in supporting generic advancement of the frontiers of machining and manufacturing capability and productivity.

The major technological innovation needed to enable realization of capability for computer automation of the product design process, compatible with the technology already created for computer automated programming of the machining process, was the conception and creation of an automated engineering design programming system. Under the aegis of the Air Force funding, Ross tackled that need and began research on such in 1960. Earlier exploratory research by others at MIT had established that the realistic goal of such research should be to enable the computer to serve as a design tool, and not as a replacement for the human designer, in the process of creative design. Ross's research slowly led him to a realistic concept for a generalized programming language system for automated product design.

That concept envisioned a general problem-solving system composed of a number of systems programs organized in an internally coherent hierarchical structure. The input end of the system would be able to communicate with the designer in terms familiar to designers and the output end would be able to communicate directly with machine tools in the terms that they required for execution of their varied and complex operations. To accomplish this, the internal hierarchical structure of the system would contain applications programs that were easily modifiable to handle the wide variety of situations encountered in practice. Further, the system would need to be both problem-independent and machine-independent. The element essential to realization of such a system was creation of a wholly new and very comprehensive computer language, a mammoth task, comparable to that of creating any one of the major existing spoken languages. Ross and his associates, together with a consortium of aircraft companies, proceeded to do just that, resulting in the creation of the AED languages and their system of programming. This brought the CAD project to a close in January 1970, a time roughly coincident with the retirement of Bill Webster and Max Guenther from the Air Force's Manufacturing Technology Division.

Thus, in a sense, an almost two-decade era of revolutionary change in machining technology, engendering major new directions in research on metal cutting and grinding, had come to a close. The era had been ushered in by John Parsons' invention of numerical control of machine tools in 1952. That watershed event (virtually unrecognized as such at that time) had triggered at least two developments that opened up virgin fields for machining-related research. The first of these was the development of the long term "partnership" between MIT and the U.S. Air Force's Manufacturing Technology Division in research on the application of digital computer technology to the general field of the production of parts by machining. The second development, triggered indirectly by Parsons' watershed invention, was that of the twin concepts of the systems approach to manufacturing and the computer integrated manufacturing system, described earlier in this chapter.

The virtually unique long-term partnership between MIT and the ManTech Division during that era spawned at least three new directions in the field of machining research. These were research on the application of computer-related technology to (1) the control of machine tools and their machining processes, (2) the computer programming of the numerical control of the machining process and (3) the computer aided design of parts to be produced by NC machining. The development of the twin concepts of the systems approach to manufacturing and the computer integrated manufacturing system generated major research activity in the wholly new field of harnessing the systems capability of the computer to optimize, flexibly automate and integrate the machining process, on-line, as a key element within the system of manufacturing as a whole.

A New Era of Machining Research Blossoms

As this era of major change in machining-related research drew to a close at the end of the 1960's, the NC-related and integrated systems-related research that it had spawned had begun to coalesce, ushering in a new era of machining research. The most visible physical representation of this coalescence, as the era began, was the so-called “flexible machining system” (FMS), which had just begun to emerge in prototype form at the beginning of the 1970's. It combined the new numerical control technologies with the emerging computer integrated manufacturing (CIM) technologies to integrate a number of different types of NC machine tools and computer-controlled workpiece transfer devices into an optimizable, programmable system for automatically machining a variety of different workpieces from start to finish. In the U.S., research aimed at realizing such a fully integrated system was pioneered by Perry in the 1960's at the Cincinnati Milling Machine Company (5-9). This research resulted in 1970 in an operating prototype that is still considered to be the first FMS prototype in the world that embodied integrated computer control of both the NC machine tools and the automated work transfer in the system. However, very active research in this field was already underway in many places throughout both the United States and the world, resulting in a variety of flexible machining systems (albeit with relatively low levels of integration and flexible automation) beginning to appear in manufacturing companies by the early 1970's.

Thus the successes achieved by the research efforts of the era of the 1950's and 1960's in bringing the capabilities of the newly developing digital computer technology to bear on manufacturing had resulted in significant change in the nature of metal cutting and grinding research. It had appreciably changed the emphasis of such research and even more importantly, had greatly broadened its perspective. This change has had two main effects on such research in the years since then, one of which may be considered to be positive and the other detrimental. These effects both derive from the major new capabilities which digital computer technology has brought to machine tools and manufacturing.

The positive effect has been to engender a broader perception of the machining process; namely, that it is the process most basic to the successful operation of the computer-controlled machine tools and computer controlled systems of manufacturing that would be found more and more in evolving factories. This perception in turn engendered a more control-oriented and systems-oriented perspective of the machining process, broadening the thinking involved in the research on that process to include factors related to the impact of the process on the reliability, quality, capability, productivity and economy of the performance of not only machine tools but also of manufacturing systems as a whole. The increasing prevalence of such thinking can be detected more and more in the character of the metal cutting research conducted progressively throughout the decades of the 1970's, 1980's and 1990’s.

However, a second effect of the development of computer control of machines and systems on machining research was somewhat detrimental. This aspect of that development relates to the fact that it represented an exciting new technology demonstrating tremendous potential to increase the efficiency of utilization of the machining process, rather than the efficiency of the process itself. This potential to increase dramatically the heretofore very low percentage of time during which an operating machine tool could actually engage in removing metal (caused by the very long times required for set up, tool-change, waiting, etc.) was exciting indeed. As a result, research emphasis shifted significantly away from machining technology and toward technology supporting what has since come to be called “lean manufacturing”. This effect can be noted in the decreased number of classical research papers on machining and grinding per se during the decades of the 1960's and 1970's, compared to the 1940's and 1950's.

However, as the 20tsh century drew to a close, that situation started to reverse and emphasis on machining process research is once again growing, ushering in a new era of such. One reason for this is the fact that the results of the research aimed at improving the efficiency of utilization of the machining process have now produced such large increases in that utilization that the payoffs potentially derivable from improving the efficiency of the machining process itself have once again become quite significant. However, there are at least two other factors that are probably even more influential in this change than that above.

The first of these is the considerably increased emphasis on quality in manufacturing. This has brought home the fact that the quality of parts produced by machining, in terms of such things as accuracy, uniformity, surface finish, surface integrity, etc., depends very heavily on the limits of capability of the machining processes utilized to produce those parts -- that is, on process capability. Thus, there is now growing emphasis on research to increase the limits of the quality-determining capabilities of the various machining processes.

The second strongly influential factor in the current shift in emphasis back toward research on machining processes is one related, once again, to the growing pervasive role of computer technology in manufacturing. That has now progressed to the point where machine tools are being required to run more and more autonomously under intelligent computer control, even to the extent of autonomously avoiding or correcting, in process, processing errors or failures. The key to advancing such technology beyond its present, somewhat rudimentary state is the accuracy and realism of the process models available to the controlling computer. Thus, emphasis is now steadily increasing on research on, not only mathematical modeling, but also computer-based process modeling of machining and grinding processes -- research to create more and more accurate and realistic computer-based models of such processes.

Given the continually growing pressures for increased quality and increased autonomous operation of manufacturing, emphasis on machining and grinding research directed at the two foregoing areas is destined to become more and more intense. As this happens, the fundamental knowledge created by past machining and grinding research, which has to some extent been lost sight of in recent years, will become increasingly important.

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APPENDIX 1

INFORMATION GATHERING APPROACH

As explained in Chapter 1, the procedure used in gathering the information for this review of research was somewhat unusual in that, in addition to the usual searching of the literature, it employed a large component of information gathering from first-hand sources; i.e., those living persons who actually performed or had first-hand knowledge of the most significant portions of that research

The first step in this process was a questionnaire that was sent to thirty-eight known living persons in that category. The list of those to whom this was sent (including their **then** most recent affiliations) is provided as Appendix 2. The recipients of this questionnaire were asked to respond to the three following questions:

1. What do you consider to be your own most important contributions to the research on machining and grinding?
2. What do you consider to be the seminal and "milestone" events in the history of research on machining and grinding from Taylor to 1980?
3. What is your perception of the impact of these events, including your own contributions, to the theory and practice of machining and grinding?

Twenty-five replies were received. These replies were analyzed and became an initial reference source for the further steps in the production of this historical review. In addition, special attention was paid to the replies to Question 2 above, giving the respondents' opinion as to what they considered to be seminal and milestone events in the history of U.S. research on machining and grinding. It was found that six events, attributable to specific researchers, were so nominated by five or more of the respondents. These six events, together with the names of those whom the respondents perceived to be the U.S. originators of the events, are listed in Table A 1-1.

Table A 1-1

"Milestone" Events in History of U.S. Research on Machining and Grinding, from Taylor to 1980

YEAR OF PUBLICATION	EVENT
1906	Deduction of empirical cutting speed/tool life relationship by F.W. Taylor.
1906	Invention of high speed steel (18-4-1) tool material by F.W. Taylor
1925	Development of cobalt-bonded sintered tungsten carbide tools by S.L. Hoyt.
1945	Development of basic theory of the mechanics of the cutting process by M.E. Merchant
1951	Development of theory of temperatures in metal cutting by K.J. Trigger and B.T. Chao
1952	Invention of numerical control of machine tools by J.T. Parsons.

Replies to this first questionnaire were then summarized in a second questionnaire that was sent to 21 of the respondents to the first questionnaire—that being the number who had provided specific information—plus a few selected additional researchers. This second questionnaire summarized and tabulated most of the thoughts concerning "milestone" events (Question 2 above) contained in the twenty-five responses to that first questionnaire. That summary and tabulation is reproduced herewith as Appendix 2. The recipients were asked to supply, via markup of the tabulation, the following kinds of information:

1. Names of event originators where they were missing or incorrect.
2. Approximate year in which the event originated, if unpublished, or in which it was first published (and where, if known).
3. In the case of events recognized as not occurring first in the United States, please so indicate, including country of origin if known to you.
4. Additional events that should be considered for inclusion in the historical review. In particular, the number of events proposed in the field of grinding research seems rather sparse. Is this the actual situation?
5. The research events considered to have had the maximum effect on advancement of the capabilities of the machining and grinding processes in practice.
6. General reaction to this Summary of Events in terms of its content, significance, etc.
7. Any general comments offered as guidance in the conduct of this historical review.

Eighteen detailed replies were received. These were analyzed and became a prime reference source for the further steps in the production of this historical review. In addition, special attention was directed to the replies to the request, made in Item 5 above, for the respondents' opinion as to what U.S. research events have had maximum effect on advancement of the capabilities of the machining and grinding processes in practice. It was found that eight events attributable to specific researchers were so nominated by five or more of the respondents. These events, together with the names of these whom the respondents perceived to be the U.S. originators of the events, are listed in Table A 1-2. (Dates have been added to provide the general chronology.) It is interesting to note the types of research results that the respondents considered to have had maximum impact on practice. As can be seen, these range all the way from basic theory and empirical findings to application to practice. Nevertheless, such opinions were helpful in guiding the handling of the overall subject of this monograph.

Table A 1-2

U.S. Research Results Having Highest Impact on Machining and Grinding Practice

Year of Announcement	Research Result	Perceived Originators
1906	Cutting speed/tool life relationship	F.W. Taylor
1906	High speed steel (18-4-1) tool	F.W. Taylor
1938	Understanding of chip formation	H. Ernst
1945	Theory of basic mechanics of the cutting process	M.E. Merchant
1946	Control of surface damage in grinding	L.R. Tarasov; M. Field
1951	Theory of temperature in metal cutting	K.J. Trigger, B.T. Chao
1952	Invention of numerical control of machine tools	J.T. Parsons
1966	Machining Data Handbook	J.F. Kahles, M. Field

The next step taken was to conduct telephone interviews with some twenty of those living researchers who had been key players in significant portions of past research on machining and grinding. Approximately half of this number was drawn from those who had responded to both of the two questionnaires described above. Of the remainder, a few had responded to the first questionnaire only, while the remainder had responded to neither. (All of the interviews were conducted by the authors.) In the case of those who had responded to one or both of the questionnaires, any issues raised by their answers were discussed. In addition, all of those interviewed were asked for any issues that they would especially like to see considered in the writing of this historical review. The responses to that question were then analyzed for common themes, and it was found that nearly all of the participants proposed, in one variation or another, three principal issues for consideration in the historical review. These were as follows:

1. Manufacturing engineering education and research in U.S. universities

- A long period of neglect of such by universities had begun in the 1960's, resulting in a missed generation of researchers
- A resulting lack of qualified mentors in the field of machining and grinding research
- A resulting lack of focus on industrial practice of university research in machining and grinding
- A loss of experimentation on actual processes and machinery in favor of information-oriented modeling and simulation in university research
- A loss of research focus on obtaining basic understanding—qualitative as well as quantitative—of what actually takes place in the machining

and grinding processes

2. Loss of coherency in machining and grinding research

- A steady buildup of a coherent body of engineering knowledge of machining and grinding was accomplished by the research done during the period from 1940 to 1960
- Then a “watershed” was encountered and the coherent approach to such research was lost
- Most researchers of this subject were not aware of the existence of the coherent body of knowledge developed earlier and therefore floundered

3. Manufacturing systems aspects of machining and grinding

- Recognition of manufacturing as a “system” came into being in the late 1960's, but recognition of the implications of this for machining and grinding research grew very slowly
- Too much of such research was still done in isolation from researchers working on other facets of manufacturing technology that have implications for it, and even in isolation from other researchers working on other aspects of machining and grinding
- Cooperative research on broad systems-oriented programs of research in machining and grinding, carried out by multi-disciplinary teams, can produce far more meaningful advancements in manufacturing technology knowledge and capabilities than can the isolated activities of an equivalent number of isolated researchers

- Such cooperative research effort need not be limited to the confines of a

> single institution. Examples of such effort have demonstrated significant benefits from globalization of such activity, through joint international programs and projects — cooperative effort in which researchers draw on each other's work.

The final step in this study was to convene a series of "roundtable" meetings of some of the still living U.S. early major contributors to metal cutting and grinding research. The purpose of these roundtables was to capture, first hand, the key researchers' relevant knowledge, understanding and perception of their earlier research and, in particular, any important information pertinent to such which had never been published. It was also believed that the group dynamics of such a session would further the collective recall of significant facts.

Three such roundtables were held following the telephone interviews. However, what might be considered a pilot roundtable meeting was held very early on, even prior to the mailing of the first of the two questionnaires. This took advantage of the occasion of the 1990 North American Manufacturing Research Conference, held at Pennsylvania State University to bring together two of the oldest living eminent machining and grinding researchers, namely, Dr. Alfred O. Schmidt, retired, formerly of the Kearny and Trecker Corporation, and Dr. William W. Gilbert, retired, formerly of the General Electric Company and the University of Michigan, for a discussion of their early research. That meeting was also attended by Dr. Marvin F. DeVries, initial NSF Program Director for the project, and Dr. Branimir F. von Turkovich, Director of the NSF Division of Design and Manufacturing Systems at that time. As at all of the subsequent roundtable meetings, both of the authors were present. Also, as at all subsequent roundtable meetings, the discussions were audio-taped.

The initial roundtable meeting provided substantiation of the value of holding further such meetings, in that it captured first hand the key researchers' knowledge, understanding and perception of their and others' earlier research. It also provided very helpful experience and guidance pertinent both to the conduct of the future roundtable meetings and to all of the other information gathering activities of the project already described.

The three remaining roundtable meetings were held after the conclusion of the telephone interviews. Each of these was held at a geographical location that was not more than a few hours travel by automobile from the current residence of each of the invited living participants. Figures A 1.1, A 1.2 and A 1.3 provide photos of the participants, taken at the time of each of these three roundtables. The dates, locations and participants in each of the roundtables are given in Table A 1-3.

Figure A 1.1. Photo of Participants at the Cincinnati Roundtable Meeting:
Left to right - Seated - Dr. John F. Kahles, Dr. M. Eugene Merchant, Dr. Michael Field.
Standing - Dr. Marvin F. DeVries, Herbert E. Merritt, Kenneth J. Trigger

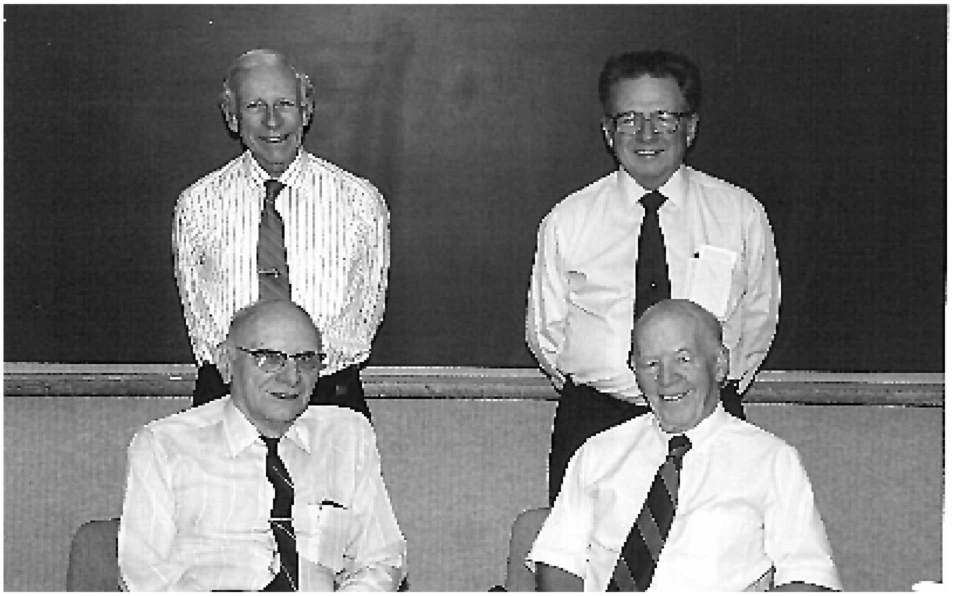

Figure A 1.2. Photo of participants at the MIT roundtable meeting:
Left to right: Seated - Dr. J. Francis Reintjes, Dr. Robert S. Hahn
Standing - Dr. M. Eugene Merchant, Anderson Ashburn

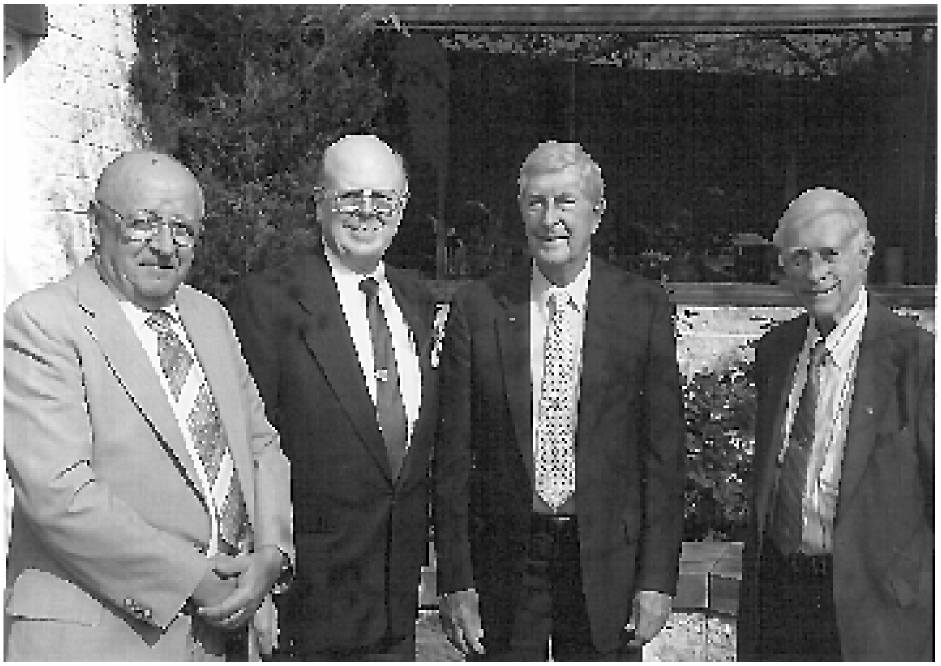

Figure A 1.3. Photo of participants at the Perrysburg roundtable meeting:
Left to right: Elbert J. Weller, John T. Parsons, Clyde A. Sluhan,
Dr. M. Eugene Merchant

Table A 1-3

Roundtable Meetings of Early Contributors to U.S. Research in Machining and Grinding

DATE	LOCATION	PARTICIPANTS
September 30, 1993	Institute of Advanced Manufacturing Sciences (now TechSolve}, Cincinnati, OH	Dr. Marvin F. DeVries University of Wisconsin-Madison Initial NSF Program Director for the project
		Dr. Michael Field, retired, Metcut Research Associates
		Dr. John F. Kahles, retired, Metcut Research Associates
		Herbert E. Merritt, retired, Cincinnati Milacron, Inc.
		Prof. Kenneth J. Trigger, retired, University of Illinois at Urbana-Champaign
October 17, 1991	Massachusetts Institute of Technology, Cambridge, MA	Anderson Ashburn McGraw-Hill Publications Co.
		Dr. Robert S. Hahn, retired, Cincinnati Milacron, Inc. Heald Division
		Dr. J. Francis Reintjes, Professor Emeritus Massachusetts Institute of Technology
October 23, 1991	Master Chemical Corporation Perrysburg, OH	C.J. Oxford, Jr., retired, National Twist Drill & Tool
		John T. Parsons, President, John T. Parsons Co.
		C.A. Sluhan, Chairman, Master Chemical Corp.
		Elbert J. Weller, retired, General Electric Co.
Invited But Unable To Attend		Dr. Nathan H. Cook, Professor Emeritus Massachusetts Institute of Technology
		Dr. Douglas T. Ross, Chairman, SofTech, Inc.

Participants at these three roundtable meetings were provided in advance with the type of information given in Tables A 1-1 and A 1-2 concerning the consensus of the two questionnaires relative to high profile historical events. They were also provided with information on the issues proposed by the telephone interviewees for consideration.

The agenda for each meeting covered three subjects, namely,

1. Observations by each participant on the high profile events and his own contributions, and discussion of these by all.
2. Observations and discussions by all concerning what they considered to be important information pertinent to earlier research, but which had never been published.
3. Observation and discussions by all of critical issues which should be considered in the preparation of the historical review.

Although each meeting ran from 10:00 a.m. to 4:00 p.m., it turned out in each case that the largest part of the time was spent on the first item, with almost all of the remainder spent on the second, and only a very brief discussion, if any, of the third. It had been anticipated in constructing the agenda that this might happen if the participants were willing and able to contribute extensive knowledge, understanding and perception of earlier research. The fact that it did happen validated the value of making such roundtable meetings an important part of the information gathering process.

APPENDIX 2
List of Recipients of First Questionnaire
(including their affiliations at that time)

Dr. Dell K. Allen Professor Brigham Young University	Anderson Ashburn Editor Emeritus American Machinist McGraw-Hill Publication Co
Orlan W. Boston (Professor Emeritus University of Michigan-Ann Arbor)	Francis W. Bougler (Battelle Columbus Laboratories-Retired)
James B. Bryan (Lawrence Livermore Laboratory-Retired)	Professor B.T. Chao Department of Mechanical and Industrial Engineering University of Illinois at Urbana-
Professor George Chryssolouris Department of Mechanical Engineering University of Patras, Greece	Dr. Nathan H. Cook (Professor Emeritus - MIT)
Dr. Richard E. DeVor Professor Department of Mechanical and Industrial Engineering University of Illinois at Urbana-Champaign	Professor Marvin DeVries Department of Mechanical Engineering University of Wisconsin-Madison
Dr. David A. Dornfeld Associate Professor Department of Mechanical Engineering University of California-Berkeley	Dr. Michael Field (Metcut Research Associates, Inc. - Retired)
Dr. Iain Finnie Professor Department of Mechanical Engineering University of California- Berkeley	Dr. W.W. Gilbert (General Electric Company - Retired)
W. Andrew Haggerty (Cincinnati Milacron, Inc. - Retired)	Dr. Robert S. Hahn (Cincinnati Milacron, Inc., Heald Division - Retired) President Hahn Engineering, Inc.

APPENDIX 2

List of Recipients of First Questionnaire (continued)
(including their affiliations at that time)

Dr. Inyong Ham Professor Department of Industrial Engineering Pennsylvania State University	Dr. John F. Kahles (Metcut Research Associates, Inc. - Retired)
Dr. Shiro Kobayashi Professor Mechanical Engineering University of California-Berkeley	Professor Ranga Komanduri MOST Chair in Intelligent Manufacturing College of Engineering, Architecture and Technology Oklahoma State University
Dr. Richard P. Lindsay Norton Co	Dr. Frederick F. Ling Institute for Productivity Research Columbia University
Dr. Erwin G. Loewen University of Rochester	Dr. Keith E. McKee Director The Manufacturing Productivity Center Illinois Institute of Technology
Herbert E. Merritt (Cincinnati Milacron, Inc. - Retired)	Wayne Moore President and CEO Moore Special Tool Company, Inc.
C.J. Oxford, Jr. (National Twist Drill & Tool Co. - Retired)	John T. Parsons (The Parsons Company - Retired) President John T. Parsons Company
Dr. J. Francis Reintjes Professor of Electrical Engineering, Emeritus Department of Electrical Engineering and Computer Science Massachusetts Institute of Technology	Dr. Douglas T. Ross Chairman SofTech, Inc.
Dr. Alfred O. Schmidt (Kearny and Trecker Corp. - Retired)	Professor Milton C. Shaw Aerospace & Mechanical Engineering Department Arizona State University

APPENDIX 2
List of Recipients of First Questionnaire (concluded)
(including their affiliations at that time)

C. A. Sluhan Chairman & CEO Master Chemical Corp.	Dr. Erich G. Thomsen Professor of Mechanical Engineering, Emeritus University of California
Prof. Kenneth J. Trigger (University of Illinois at Urbana-Champaign- Retired)	Robert. L. Vaughn (Lockheed Missiles & Space Co. - Retired)
Dr. Branimir F. von Turkovich Professor of Mechanical Engineering & Material Science Department of Mechanical Engineering University of Vermont	Elbert J. Weller (General Electric Co. - Retired)

APPENDIX 3

Summary and Tabulation of "Milestone Events" Proposed by Recipients of Initial Questionnaire Survey of Distinguished Early US Performers of Machining and Grinding Research

Category 1: Development of Empirical Machinability Knowledge Base

EVENT ORIGINATORS	EVENT TOPIC	PROPOSERS
Taylor	Quantification of tool life as a function of cutting speed as a functionof cutting speed	Black, Gilbert, Thomsen, Weller
Schmidt, Gilbert, Boston	Characterize heat in metal cutting, 1945-1949	Black, Boulger, Schmidt
Boston	Tool life testing methodology, machinability rating	Black, DeVries
Clarebrough & Ogilvie {UK)	(Single crystal machining)	Black
Tarasov & Boyer	Surface damage in grinding, 1940's	Boulger
Armitage & Schmidt	Effects of tool angles	Boulger
Boston	Force and power relationships	DeVries
Ernst	Chip formation mechanisms	DeVries, Merritt, Sluhan
Ham	Machinability of cast iron, 1952	Schmidt

Category 2: Development of Basic Mechanics, Physics and Chemistry of Machining and Grinding

EVENT ORIGINATORS	EVENT TOPIC	PROPOSERS
Merchant	Basic mechanics of metal cutting	Black, Boulger, Chao, Kobayashi, Merritt, Thomsen, Trigger
Trigger & Chao. von Turkovlch	Thermodynamics of machining	Black, Boulger, Trigger
von Turkovich & Black	Dislocation mechanics of machining	Black
Usui (Japan)	(Use of FEM to predict orthogonal machining performance)	Black
Kendall & Sheikh, Ramalingam.	Probabalistic tool life	Black
Trigger & Chao	Cutting temperature/tool wear relationships	DeVries, Sluhan
Trigger & Chao	Restricted tool-chip contact as a research tool	Trigger

Category 3, Advancement of Capability to Engineer Machining and Grinding Processing

EVENT ORIGINATORS	EVENT TOPIC	PROPOSERS
Gilbert & Atalay, Boston & Colwell, Ernst & Field	Economics of machining, 1946-49	Black, Boulger, Gilbert
USAF, Curtiss-Wright, Met-cut	Machinability handbook. and database	Boulger
Field, Kahles, Koster...	Control of surface damage in grinding, 1968-74	Boulger
Schlesinger (Germany)	(Accuracy test for machine tools, 1927)	Bryan
Abbott	Development of Profilometer, 1938	Bryan
Reason (UK)	(Talysurf, 1940, and Talyrond, 1953)	Bryan
Gilbert, General Electric, Carboloy	Machinability database and tool management systems on analog computer, 1950's	Gilbert

Category 4: Improvement of Cutting Tool, Grinding Wheel and Work Material Characteristics

EVENT ORIGINATORS	EVENT TOPIC	PROPOSERS
Schroeter (Germany)	(Cobalt-bonded tungsten carbide tools, 1923)	Boulger
Hoyt	Hot-pressed tungsten carbides, 1925	Boulger
Battelle	Lead-bearing free machining steels, 1934-37	Boulger
McKenna	Reduced crater wear with carbides containing Ta, Ti, Cb, 1938 patent	Boulger, Weller
Ford Scientific Lab	Ni-Mo binder for titanium carbides	Boulger, Weller
Taylor	High speed steel	Chao, Cook, DeVries, Thomsen, Vaughn, Weller
----------	Ceramic tools, 1950's	Chao, DeVries, Haggerty, Hahn, Persons, Shaw, Thomsen, Vaughn
----------	Free-machining steel	Chao
----------	Sintered carbide tool material, 1940	Cook, DeVries, Haggerty, Hahn, Parsons, Shaw, Thomsen, Vaughn, Weller
----------	Coated tools, 1969	Cook, DeVries, Haggerty, Shaw, Trigger, Weller
----------	CBN tools, 1969	Cook, DeVries, Haggerty, Parsons, Shaw, Trigger, Vaughn, Weller
----------	Polycrystalline diamond tools	DeVries, Haggerty, Shaw, Trigger, Weller
----------	Carbide inserts with chip-breaker grooves	Gilbert
General Electric	Orientation of synthetic diamond in diamond tools	Gilbert
----------	CBN abrasives, grinding wheels and truing means truing means	Hahn
DeLeeuw	Wide spacing of milling cutter teeth, 1910	Merritt
Kennametal	Mechanically-held inserted-tooth tools	Parsons, Trigger
----------	Sintered high speed steel tools	Trigger

Category 4: Improvement of Cutting Tool, Grinding Wheel and Work Material

EVENT ORIGINATORS	EVENT TOPIC	PROPOSERS
------------	Diamond grinding wheels for carbide tools	Weller
------------	Silicon carbide grinding wheels for carbide tools	Weller
------------	Disposable carbide inserts	Weller

Category 5: Advancement of Machine Tool's Machining and Grinding Capabilities

EVENT ORIGINATOR	EVENT TOPIC	PROPOSERS
Norton Co.?	Crush dressing of grinding wheels.	Boulger
Bryan	Techniques for ultra-fine grinding and machining	Boulger, DeVries
Renishaw (UK)	(Touch probe)	Bryan
----------	Laser interferometer	Bryan
Hashimoto {Japan)	(Ductile grinding of glass, 1974)	Bryan
---------	Robots	Cook
Merritt (Tlusty, Tobias)	Understanding of machine tool dynamics -- chatter, stability	DeVries.
---------	Hydrostatic (and aerostatic) wheelheads and workheads	Hahn
---------	Slide-positioning servo-systems with sub-micron resolution	Haggerty, Hahn
---------	Centerless. grinding, 1922	Merritt
Ernst	Hydraulic servo control of feed, 1927	Merritt
--------	Electro-hydraulic servo controls, 1952	Merritt
--------	Computer analysis of machine tool structures	Merritt
--------	Pulse-type servomechanisms, 1946-50	Reintjes
Kearney & Trecker	Milwaukee-Matic (first machining center), 1960's.	Schmidt, Shaw
Schmidt, Kearney & Trecker	Machine tool requirements for higher speed milling machines, 1943 -	Schmidt
--------	Creep feed grinding, 1960's.	Shaw
Fersing & Herbert, Jones & Lamson	High speed machining	Sluhan
-------	High speed spindles and machines, 1960's and 1970's.	Vaughn, DeVries

Category 6, Development of Computer-Aided Machining and Grinding Capabilities

EVENT ORIGINATOR	EVENT TOPIC	PROPOSERS
Parsons. USAF, MIT	Demonstration of feasibility of digital control of machine tools, 1949-52	Boulger, Bryan, Cook, DeVries, Merritt, Parsons, Shaw, Reintjes, Thomsen, Trigger, Vaughn, Weller
Ferranti (Italy)	(Computer-controlled coordinate measuring machines)	Boulger, Bryan
--------	Flexible manufacturing cells	Boulger, Reintjes
Perry?	FMS	Boulger, DeVries, Reintjes
--------	Computer Numerical Control, (CNC), 1960's.	Devries
Merchant	CIM system, 1980's.	DeVries, Thomsen, Vaughn
GE?	Interface of machinability databases with NC tape generation, 1970-71	Gilbert
----------	Microcomputer controls for machine tools	Hahn
Leone, CMU	Mechanical feeler NC tape precursor to 1960's NC machines, 1945	Schmidt
Ross, MIT	APT language, 1960's.	Shaw
MIT	CAD/CAM, late 1960's.	Shaw, Thomsen, Weller

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