High Speed Machining

Edited by
RANGA KOMANDURI
K. SUBRAMANIAN
B. F. VON TURKOVICH

PED-Vol. 12

High Speed Machining

presented at

THE WINTER ANNUAL MEETING OF THE
AMERICAN SOCIETY OF MECHANICAL ENGINEERS
NEW ORLEANS, LOUISIANA
DECEMBER 9-14, 1984

sponsored by

THE PRODUCTION ENGINEERING DIVISION, ASME

edited by

RANGA KOMANDURI
GENERAL ELECTRIC COMPANY

K. SUBRAMANIAN
NORTON COMPANY

B. F. VON TURKOVICH
UNIVERSITY OF VERMONT

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
United Engineering Center 345 East 47th Street New York, N.Y. 10017

Library of Congress Catalog Card Number 84-72447

Printed in U.S.A.

PREFACE

The need to increase manufacturing productivity has been a global concern since the mid seventies due to rapidly escalating costs. Efforts to improve productivity of machining operations have resulted in the development of flexible manufacturing systems, computer integrated manufacturing, adaptive control of machining processes etc. While these methods have attempted to increase machine utilization, the machining time for a given part has essentially remained unchanged. This has lead to the development of High-Speed Machining (HSM) – an approach to significantly reduce the actual machining time. HSM is an attractive economic and technological proposition, especially in cases where the machining time is a significant fraction of the total cycle time. It should, however, be emphasized at the outset that currently not all materials can be machined at very high speeds due to limited tool life with some materials. But there are some materials such as aluminum alloys and composites which can be machined at cutting speeds significantly higher than are commonly used in industry today.

An objective of this symposium is to rapidly transition this technology to the manufacturing shop floor. Many practical demonstrations of high-speed machining of aluminum alloys are reported here with a significant reduction in machining time, as well as a significant reduction in cost, especially of aerospace components. For those searching for a drop in cutting temperatures at higher cutting speeds, it may be pointed out that there is no established data to substantiate such a claim, especially for machining of hardened ferrous alloys, titanium alloys and nickel base superalloys. However, this search has led to a substantial increase in cutting speed for machining these materials. Papers related to this subject are also included in these proceedings. The second objective of this symposium is to stimulate researchers and to encourage them to continue this search for developing new tool materials and tool geometries to further increase productivity in machining these difficult-to-machine materials. The third objective of this symposium is to clarify some of the earlier claims and put the HSM process on a sound technical basis.

The origin of much of the earlier interest in high-speed machining was the controversial and *yet to be proven* work of Salomon in 1931. He claimed that tool temperatures increased with cutting speeds, reached a peak close to the melting temperature of the work material under consideration and then decreased rapidly at very high cutting speeds, thus promising better machining features at higher cutting speeds. In the USA, R.L. Vaughn conducted pioneering studies in the 60's on HSM and formulated a new model of HSM which invoked for the first time very high shear angles ($\simeq$70 deg.), equivalent to considering chip to be thinner than the uncut material or the chip velocity to be higher than the cutting velocity. This was followed by similar work by Arndt in Australia. Their studies tended to lend some support to Salomon's claims. Prof. A. O. Schmidt also in the 60's, based on his own work in high-speed milling and that of others, argued that there is no such thing as the promised land beyong the 'Valley of Death'. He criticized Salomon's work and pointed out that Salomon's graph has been discussed in many languages and was the basis of more speculation than any other claim in the metal cutting literature. Recently, the U.S. Department of Defense funded projects on HSM. An objective of these projects was to evaluate some of the optimistic claims made by earlier researchers. That work lent support to Schmidt's findings. For example, the work of F. J. McGee and R. F. Recht has indicated that only the first part of Salomon's claim, namely, that tool temperatures increase with cutting speed, reaching asymptotically the melting temperature of the work material, is valid. Thus for the realization of HSM, cutting tools should be capable of withstanding these temperatures. Or, to paraphrase Vaugn: What is required is a tool material that can withstand the melting temperature of the material it is cutting. While this is feasible with some materials such as aluminum alloys and composites, it is a challenging task for other difficult-to-machine, high melting temperature materials. The search will continue and we are optimistic that even higher cutting speeds will be realized in the future.

R. I. King and F. J. McGee took a different approach to HSM. Since toolswear is not a limitation in the machining of aluminum alloys at higher speeds (eg. 6000 sfpm), yet these speeds are significantly higher than the speeds used in industry, they concentrated their effort on the production implementation of machining at higher cutting speeds. Some of the papers presented at this symposium are a continuation of this work by other researchers.

The goal of the High-Speed Machining symposium conducted at the 1984 ASME Winter Annual Meeting is to bring together researchers of several disciplines, with a common goal of understanding the theory and principles, demonstrated applications, machine tool and cutting tool developments and the application methodology related to HSM. We are fortunate that many experts and pioneers in this field have graciously accepted our invitation to participate in this symposium. The papers contained in these proceedings were presented at the HSM symposium. From these papers, it will be observed that the goal and the objectives of this symposium have been accomplished. The authors represent various segments of the research community: industry, academic and research institutions in the U.S. and abroad. Throughout the organizing of this symposium, emphasis has been on the demonstrated applications of HSM. This has resulted in several papers focusing on actual end results, application methodology and specific needs of future machine tool system developments.

These proceedings are a direct result of the original contributions of the authors and it is with great pleasure that we acknowledge their valuable contributions. We also thank the reviewers of the papers for their unselfish contribution. In conclusion, we sincerely hope that industry and university in general and members of the Production Engineering Division of ASME in particular can benefit from this work and the stimulating discussions at the symposium.

R. Komanduri,
General Electric Company

K. Subramanian
Norton Company

B. F. von Turkovich
University of Vermont

CONTENTS

HIGH-SPEED MACHINING-OVERVIEWS

HIGH-SPEED MACHINING-FUNDAMENTALS

HIGH-SPEED MACHINING APPLICATIONS

HIGH-SPEED MACHINING-MACHINE TOOLS

SENSORS AND IN-PROCESS INSPECTION

GRINDING

HIGH-SPEED MACHINING – WHITE PAPERS

A SYNOPTIC REVIEW OF HIGH-SPEED MACHINING FROM SALOMON TO THE PRESENT

R. I. King, Consulting Scientist and R. L. Vaughn, Director of Productivity
Lockheed Missiles and Space Company, Inc.
Sunnyvale, California

ABSTRACT

The results, theories and test methods relating to high-speed machining research and development will be discussed, compared, and critiqued covering the period between 1924 and 1983. Contributions will be grouped into four periods starting with the original work of Professor Salomon and ending with the most recent research program sponsored by the United States Air Force and managed by the General Electric Research Center in Schenectady, New York.

The discussions will be developed from an industrial user's point of view rather than one from the academy. Suggestions for further research and development will be offered relative to production processes and supporting machinery rather than basic causation such as metal chip morphology and other theoretical metallurgical considerations. Industrial process limitations and unused machining technology will be included as a guide to more effective use of currently available data.

Aspects of the term Ultra-high-speed machining will be addressed so as to include the many benefits which would be derived from this area of application when new metal removal equipments and tooling can be made available.

INTRODUCTION

The United States now spends approximately $115 billion annually to perform its metal removal tasks using conventional machining technology. Of this total amount, approximately $14 billion is invested in the aerospace and associated industries. It becomes clear that metal removal technology is a very important candidate for rigorous investigation looking toward improvement of productivity within the manufacturing system. To aid in this endeavor, work has begun to establish a new scientific and technical base that will provide principles upon which manufacturing decisions may be based.

One of the metal removal areas which has the potential for great economic advantages is high-speed machining and related technology. The injection of new high-rate removal techniques into conventional production procedures, which have remained basically unchanged for a century, presents a formidable systems problem, both technically and mangerially (1). The proper solution requires a sophisticated, difficult process whereby management/worker relationships are reassessed, age-old machine designs are reevaluated, and a new vista of product/process planning and design is admitted. The key to maximum productivity is a "systems approach." The "bottom line" is to increase the overall effectiveness of the factory from whatever source, i.e., the greatest return on investment.

Consider the technical problem of increasing the speed of the cutter through the base material by one magnitude. To realize the benefits of this increase, the table feed must be increased to a compatible rate. This in turn requires lighter inertia tables, more powerful drive motors, and more responsive control systems. As the speed increases, new dynamic ranges are encountered which induce undesirable resonances in the machine and parts being fabricated, thus requiring additional dampening consideration. From the point of view of the cutter/material interface, the basic chip morphology changes as new cutting regimes are experienced; hence, Taylor's age-old empirical equations no longer hold since they are not velocity dependent. Even the cutter configuration must now be considered a function of the cutting speed regime as well as the normal process parameters. The proper incorporation of high-speed machining into factory processes requires the integration of all of the above technical considerations plus many others — a difficult systems problem requiring professional attention.

High-speed machining should be selectively applied, and only when it is economically justified. This manufacturing procedure is not a panacea for underproductive, high cost operations. If used properly, when economics dictate, in a well loaded and balanced factory, the results can be extremely gratifying.

Dr. Carl J. Salomon's Research — the genesis

The concept of high-speed machining was conceived by Dr. Carl J. Salomon during a series of experiments from 1924 to 1931. This is documented in German patent number 523594 dated April 27, 1931. The patent was based on a series of curves of cutting speeds plotted against generated cutting temperatures. These experiments were performed on non-ferrous metals such as aluminum, copper and bronze. Salomon obtained speeds up to 54,200 surface feet per minute (sfm) using helical milling cutters on aluminum. His contention was that the cutting temperature reached a peak at a given cutting speed; however, as the cutting speed was further increased, the temperature decreased. Figure 1 is a simplistic presentation of this concept.

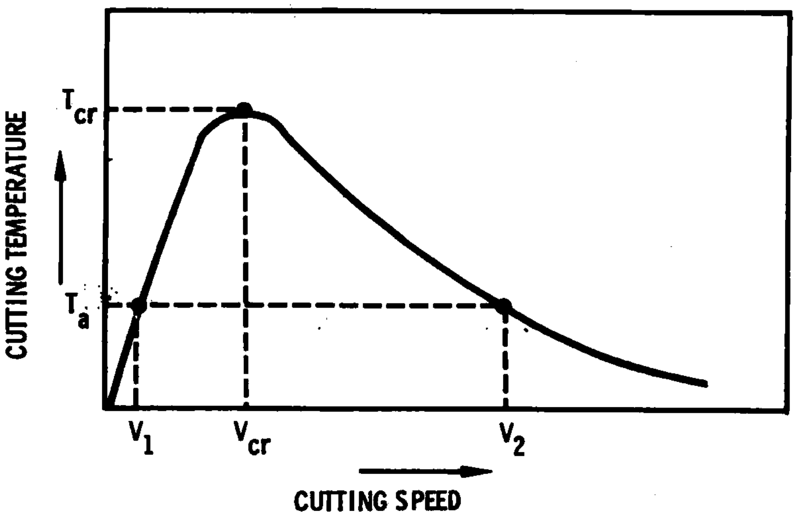

Fig. 1 Idealized cutting speed — cutting temperature plot

As the cutting speed is increased from 0 in the normal mode, V_1, the temperature will increase in a direct relationship until a peak value, T_{cr}, is achieved. The cutting speed at T_{cr} is commonly called the critical cutting speed, V_{cr}. If the cutting speed is further increased, it was predicted that the cutting temperature would decline. On either side of V_{cr}, Salomon suggested that there was an unworkable regime in which cutters were not able to stand the severe process temperatures and forces. The shape of the curve was thought to be dependent on the exact nature of the base material being cut. When the cutting speed was sufficiently increased, the resulting temperatures, at V_2, were reduced to those of the normal cutting temperatures, at V_1, and the materials and cutters would once again permit practical cutting procedures. The same cutting temperature, T_a, found in the normal speed range, V_1, could possibly be reproduced in the high-speed range, V_2.

There have been many versions of Salomon's curves used as reference by current researchers. Since much of the supporting data was lost during World War II and none of the participants in the research are alive to comment, the exact shape of the curves is left for speculation. However, the most commonly used version cited in most of the recent technical papers is shown in Figure 2. The solid lines represent data that Salomon was supposed to have been developing from experimental results. The broken lines indicate estimated results that were extrapolated by Salomon but not actually verified in the laboratory.

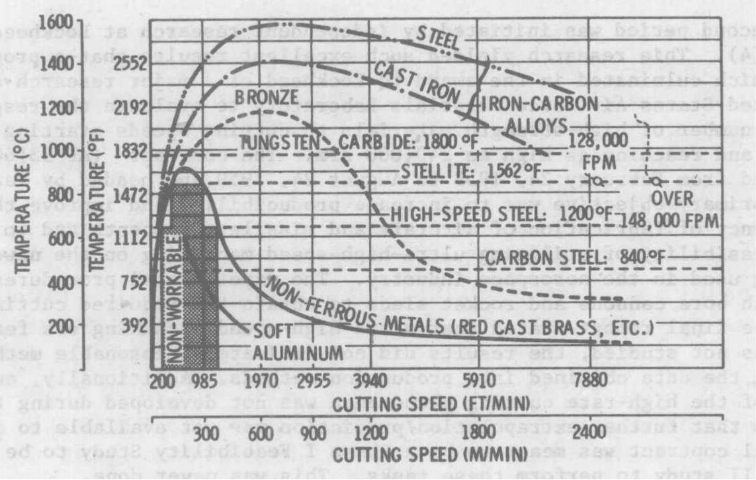

Fig. 2 Illustration of Dr. Salomon's theory for the effect of cutting speed on cutting temperature

Possibly the most significant contribution of this work is the concept of the bounded non-workable regime. Cast red brass, for example, is unmachinable with high-speed steel cutters at surface speeds between 200 and 1,100 sfm, and with Stellite cutters at speeds from 300 to 985 sfm, according to Salomon's results. A theoretical rationale was not offered and the assumptions and design of the experiments are not known. However, Dr. Salomon is generally given credit as the father of "high-speed" machining, i.e., machining at speeds higher than those considered in Taylor's early work. His results are now mainly of historical interest since current research is developing more definitive data using more sophisticated test techniques.

FOUR PERIODS OF DEVELOPMENT

The evolution of high-speed machining can be conveniently divided into four periods of time, starting with the original work of Salomon. Each subsequent period having a higher level of research activity than the previous period, and a significant event separating each. The first period includes the 1930's, 1940's and 1950's. It started with Salomon's research and ended with the first major research project in high-speed machining, sponsored by the United States Air Force, 1958-1960. These three decades produced neither significant data nor interest. However, an article noting a curious phenomenon was published in December 1949, in the American Machinist. William Coomly, General Superintendent of the Rice Barton Corporation, reported that at 180 feet per minute, his planer was drawing 92 horsepower at 310 sfm, but at 310 sfm, it drew only 55 horsepower in planing semi-steel castings. This would tend to indicate that the conventional assumption that "cutting force is independent of cutting speed" is incorrect. Occasionally, this period produced similar statements that a slight reduction in cutting force is obtained when cutting speeds are relatively very high.

During the first period of time, R. L. Vaughn of Lockheed Aircraft Corporation, California Company, became aware of Dr. Salomon's patent and acquired limited information through the United States Consul in Berlin, Germany. Salomon's test data were then translated from German to English by Max Kronenberg. The Vaughn group was familiar with the many references on oil well tube perforation at high speeds. It is well known to the art of oil well drilling that explosive perforation cutters were used to perforate oil well casings. These concepts stimulated thinking about very-high-speed cuttings of metals and set the stage for the second period.

The second period was initiated by independent research at Lockheed by Vaughn (3)(4). This research yielded such excellent results that a program was proposed which culminated in the award to Lockheed of a major research contract by the United States Air Force Materials Laboratory to evaluate the response of a selected number of high-strength materials to cutting speeds starting at 20,000 sfm and reaching as high as 240,000 sfm. The contract (AF 33[600]36232) was executed from February 24, 1958 to August 24, 1959 and headed by Vaughn (2) (7). The primary objective was to increase producibility and improve the quality and efficiency of fabrication of aircraft and missile components and to investigate the feasibility of utilizing ultra-high-speed machining on the newer materials being used in the aerospace industry. The experimental procedures used 20 mm smooth bore cannons and rocket sleds to obtain the required cutting speeds. The final report stated that ultra-high-speed machining was feasible. Since it was not studied, the results did not indicate a reasonable method of translating the data obtained into production methods. Additionally, an analytical model of the high-rate cutting phenomenon was not developed during this contract so that further extrapolation/prediction was not available to industry. The original contract was meant to be a Phase I Feasibility Study to be followed by a Phase II study to perform these tasks. This was never done.

The 1960's returned to relative quiescence in high-speed machining research. Notable exceptions included Arndt in Australia, Vaughn (8)(9), Colwell, Quackenbush (12), and Recht (21) in the United States, Fenton in England, and Okushima (17) and Tanaka (28) in Japan. The second period saw a considerable increase in activity over the first period, although industry and academia still considered the subject an intellectual puzzle without practical application.

The third period was initiated by a series of studies contracted by the United States Navy in the early 1970's with Lockheed Missiles & Space Company, Inc. The objective of these studies was to determine the feasibility of using high-speed machining in a production mode, initially with aluminum alloys and later with nickel-aluminum-bronze. A team under the direction of R. I. King demonstrated that it was economically feasible to introduce high-speed machining procedures into the production environment to realize major improvements in productivity. This resulted in a significant increase in overall interest, and a very active period of both experimental and applied research resulted as can be noted in a review of the literature. It soon became clear that some centralized direction was required to resolve several of the conflicts arising out of the results of a myriad of small research studies.

In 1979, the United States Air Force awarded a contract to the General Electric Company (F 33615-79-C-5119) to provide a science base for faster metal removal through high-speed machining and laser-assisted machining. Approximately one year later the Air Force awarded a second contract to General Electric (F 33615-80-C-5057) to evaluate the production implications of the first contract. Both contracts have been supported by a consortium of industrial firms and universities within the United States, integrated by a General Electric team headed by D. G. Flom (18). These contracts initiated the fourth period, which continues to the present.

INDUSTRIAL STUDIES

In 1958, Vaughn (2)(3)(4) studied a series of variables involved in traditional machining that become very important in high-speed machining. According to Vaughn:

> The rate at which metal can be machined is affected by: (1) size and type of machine, (2) power available, (3) cutting tool used, (4) material to be cut and (5) speed, feed, and depth of cut. These five general variables can be broken down further into: (a) rigidity of machine, cutter, and work piece, (b) variations in speed from the slowest to the fastest, depending on machine used, (c) variations in feed and depth of cut from light to heavy and whether cut dry or with the aid of lubricant and/or coolant, (d) type and material of cutting tool, (e) variations in cutter shape and geometry, (f) type and physical characteristics of work material and (g) specific requirements of desired cutting speed, tool life, surface finish, horsepower required, residual stress, and heat effects.

Recent advances in the development of computer control systems have provided the capability of accurately manipulating high-performance, automatic production machines. Progress in the field of bearing design, alternative spindle power sources, automatic tool changing, tool retention devices, and cutter materials have also made contributions toward proving Vaughn's experiments. The results of his research (5)(6)(7) indicate a theoretical limit to improving productivity with several commonly used industrial materials, although no practical limit was shown; improvements range from 50 to 1000 times conventional machine performance. "Today, practical limits vary with each material, but it is highly unlikely that a productivity improvement of greater than ten is possible with today's technology." Comments at the end of this paper will discuss this point. Extensions of this research aimed at practical understanding of the data attained are noted in references (8) and (9).

King and McDonald (10) set out to confirm and advance Vaughn's research. In doing so, these researchers worked with Bryant Grinder Corporation and others to equip an existing Sundstrand, five-axis, Model OM-3, Omnimil with a 20,000 revolutions per minute (rpm), 20-horsepower spindle. Based on results obtained with that modified machine, a good potential for the high-speed machining of aluminum was reported. They state that, without speculating on the reasons why Vaughn's conclusions were not pursued, other than machine tool technology limitations, it would appear that machine tool technology had progressed to the point that it was now possible to capitalize on the results of his research.

Certainly one of the more profitable types of parts for high-speed milling would be those requiring large quantities of material removal (hog-out parts). It is obvious that if the process were capable of high rates of metal removal, then the more there is to remove, the greater the advantage the process has over conventional techniques. Implicit in this capability for high rates of metal removal is the need to develop tradeoff studies for parts normally requiring castings or forgings for economical production. Since the time required for metal removal can be dramatically reduced, it is quite likely that the cost of developing castings/forgings and the associated elaborate holding fixtures will no longer economically offset the machining time of the higher rate cutting methods. King and McDonald state that, "In parts that usually require castings and forgings an additional advantage can be derived from high-speed milling. Often it requires several months (or even years) to develop castings and forgings and to produce sufficient quantities to support production requirements. It is not without precedent that castings and forgings become the pacing milestones in producing a new product. High-speed milling, when economically justified, can significantly reduce the time span between engineering design and production by eliminating castings and forgings."

Thin-walled parts qualify as additional candidates for high-speed milling. Conventional milling techniques with excessive cutter loads cause heat buildup that permanently distorts thin-walled parts. The maintenance of close tolerances under these circumstances may prove to be impossible. This can force the design engineer to develop a less than optimum part configuration to stay within the limitations of the production process or to find an alternative that is more expensive. High-speed milling of thin-walled parts is possible because the cutter loads are greatly reduced or eliminated. Internal stresses are caused chiefly by heat buildup and are dissipated, which allow thin-walled parts of 0.013-inch to be obtained.

A Vought (LTV Company) study, under the direction of F. J. McGee (11), provided data concerning the effect of cutting speed and cutter geometry on cutting temperature when turning 2014-T652 aluminum. These data indicate that the alloys tested showed that cutting temperature curves tend to peak near the melting point of the aluminum alloys. "It is expected that the cutting temperature curve would plateau at the melting point of the alloy. It would not be expected that the cutting temperature of the material would exceed its melting temperature." When the curves are examined, it would appear "that most of the cutting edge temperature rise occurs at low rather than high cutting speeds and that this is one feature or characteristic which does much toward opening the door to high-speed machining."

An extrapolated, theoretical cutting speed indicates that, where the cutting edge reaches a temperature of 1200°F (the melting point of the aluminum alloy), and when the cutting speed is 19,600 sfm, it may be postulated that there is a unique cutting speed at which cutting edge temperature ceases to rise. If this is the case, several interesting possibilities arise. For one, it would be theoretically possible in this example to continue turning at infinitely higher speeds than 19,600 sfm, because there should be no further rise in cutting edge temperature and, therefore, no further reduction in cutter-life wear rate. The Vought study, within the cutting speeds tested, did not show a reversing trend as presented on the Salomon curve, but the plateauing effect indicates that infinitely high cutting speeds may be feasible for the machining of aluminum alloys.

Vaughn, Colwell and Quackenbush (8)(9)(12), in extensive studies of high-speed milling of titanium, including heat and vibrations, indicated that a cutting chip can be too thin. In these studies, the chips seemed to be hotter when the theoretical chip thickness was relatively thin and that notch sensitivity of metals was an important machining property.

In the Vought (LTV Company) study, the test cutting feeds or chip thicknesses converge near the melting point of aluminum. "Near a cutting temperature of 1200°F and a cutting speed of 19,000 ft/min, the theoretical point in this instance at which cutting temperatures cease to rise....it would be theoretically possible at cutting speeds beyond 19,000 ft/min to continue turning aluminum at infinitely higher feed rates than 0.0075 inch revolution." It is possible that if such metal removal rates as these are achieved with no further rise in cutter temperature, there would be no further reduction in cutter life at these speeds and feeds. If these theoretical parameters can be achieved, productivity could progress a quantum jump.

Williamson (13) describes a system of manufacture for small machined components in a paper dated September 1967, "System 24 — A New Concept of Manufacture." This system offers advantages far beyond anything presently available. The high-speed machining system, made by Molins Limited, enables the cost of components machined on it to be reduced by a factor between five and ten in comparison with conventional production methods. It also brings large reductions in space, personnel, and surprisingly, capital investment for a given level of manufacture. The most fundamental limitation to increasing the speed of component manufacture is the metal-removal rate. In order to take advantage of high-speed machining rates, the Molins machine uses a turbine-driven cutter spindle that provides high stiffness and long life at speeds up to 30,000 rpm. Mounted on the rear end of the spindle is a 20-bucket Pelton wheel driven by a tangential jet of oil.

King (14) writes that Lockheed Missiles & Space Company, Inc. contracted with the Naval Regional Procurement Office at Philadelphia to provide certain technical services for purposes of evaluating the application of ultra-high-speed machining techniques to the milling of large nickel-aluminum-bronze (Ni-Al-Brz) cast propellers. Significant improvements in metal removal rates were realized and verified repeatedly even though the tooling used had not been optimized. Cutting rates of four to five times those of the control test rates established during first tests were obtained. Optimization of cutter designs and process parameters should further improve the performance. King (15) stated that Ni-Al-Brz propeller production can be improved by 100 percent through use of high-speed milling techniques. "Use of solid carbide end mills was extended to include inserted cutters of the type and style used in the actual production processes. The data base has now been increased to include cutter insert performance and additional process efficiency information."

The metal removal rate in the test operations indicated a significant increase over those rates presently being experienced at shipyards during propeller machining operations. If the controlled cutting of the test series is used as a basis for comparison, the average metal removal rates during the second test series were three to four times higher, and the maximum rate was over four times higher (i.e., 31.5 in.^{3}/min versus 6.30 in.^{3}/min). It is recognized that maximum rates are indicative only of limiting conditions, however, an average rate improvement from 2.76 in.^{3}/min to 9.0 in.^{3}/min has significant production implications. It should be noted that the cutters used for the first (control) tests were designed for the cutting speeds used, whereas the cutters used in the second tests were not designed for higher cutting rates.

It can be expected that when the cutter designs are finalized for the higher cutting speeds, the possible metal removal rates should be much greater. It is reasonable to expect eventual test rates of five to ten times the current production metal removal rates, although other considerations such as cutter wear, spindle horsepower, and cutter force will undoubtedly have a modifying effect on final production process recommendations.

A metal removal study summarized by Fenn (16) states that,

> The successful commercial implementation of high-speed machining promises dramatic increases in productivity and significant concomitant reductions in manufacturing costs. One of the more profitable types of operation is where the parts being machined require the removal of large quantities of material. The results demonstrate that cutting speed increases of 500 percent yield a reproducible 300 percent increase in metal removal efficiency regardless of the depth of cut. Machines performing a complex contouring sequence may not reflect all of these savings; however, as cutting speeds increase production, costs decrease.

Okushima (17) adds the following:

> The most important advantages of super-high-speed machining are to improve the productivity of the machine operation and to produce an excellent surface finish and dimensional accuracy. In addition, it is expected by this machining operation to machine those alloys which in missiles and high-performance aircraft are required to withstand high temperatures. On the other hand, super-high-speed machining has disadvantages: rapid wear of cutting tools and vibration of machine tools.

DEVELOPMENT ON METAL SEPARATION THEORY

Researchers in the intervening years have found that machining temperature phenomena may be asymptotic as cutting speeds increase, but the cutting forces tend to reduce at the accelerated speeds. To study these phenomena, a host of researchers have been working on investigations centered in the theories of chip formation, metal fracture, catastrophic slip, and adiabatic shear, as well as chip formation in various materials. To gain some understanding of the fundamentals of the cutting mechanism of chip formation, R. Komanduri and B. F. von Turkovich (18) provide some illumination through their discussion of "New Observations on the Mechanism of Chip Formation When Machining Titanium Alloys." In this presentation, they refer to Professor Shaw's (19) suggestion that "Chip segmentation was due to the onset of instability in the cutting process, resulting from competing thermal softening and strain hardening mechanisms in the primary shear zone." Shaw (20) also stated that "The formation of concentrated shear (also called adiabatic shear) bands was due to the poor thermal properties (low thermal conductivity and low specific heat) of these alloys and consequent concentration of thermal energy in those bands."

This instability concept is given further explanation by Recht (21), who states,

> ....that ductile metals strain harden as they slowly deform plastically. When deformation rate is low, the process is essentially isothermal. Initially, plastic shear strain is restricted to a few weak shear zones within the material. Strain hardening strengthens the weak material in these zones and the burden of strain is distributed through the material. However, if strain hardening did not occur, deformation would remain localized. During rapid plastic deformation, the heat generated locally establishes temperature gradients; maximum temperatures exist at points of maximum heat generation. If the rate of decrease in strength, resulting from the local increase in temperature, equals or exceeds the rate of increase in strength due to the effects of strain hardening, the material will continue to deform locally. This unstable process leads to the catastrophic condition known as "adiabatic" slip.

Recht states further that,

> ....apparently catastrophic shear develops in mild steel at machining velocities near 1300 sfm where apparent shear strength begins to drop. Near the critical velocity, slip planes are close together, spreading farther apart as velocity increases. Fully developed catastrophic slip occurs in the machining geometry when the distance between zones reaches a geometrical maximum. ....Catastrophic slip reduces the strength in the manner indicated. When the zones are close together the average apparent stress approaches the uniform deformation value. Reduction in strength progresses further when the zones are more widely spaced and thus the average apparent stress is lower.

Recht expresses the following concern:

> Of extreme interest is the fact that a second shear-strength plateau is reached at ultra-high machining speeds. After the average shear stress appears to be independent of strain rate....strain rates within the catastrophic shear zone are as high as 10^8 in./in./s. The implication is that, when catastrophic shear is well established, dynamic shear strength tends to be insensitive to strain rate.

Recht concludes that,

> ....heat generated during the dynamic deformation of materials creates temperatures and temperature gradients which can exercise significant influences upon observed dynamic behavior. Certain materials possess thermophysical properties which render them particularly susceptible to catastrophic shear. Catastrophic shear occurs when local temperature gradients offset the strengthening effects of strain hardening; the burden of plastic strain must be supported by a very small portion of the material. ....The thinness of adiabatic slip zones is helpful for heat-transfer considerations.

Vaughn (5)(7), when writing about adiabatic shear, states

> As the velocity of machining increases, an adiabatic condition is approached in which thermal energy is restricted to the preferred slip zone (shear plane -compromises of many atomic planes). Because of weakening in the preferred slip zone, additional slip occurs, terminating in complete shear.

Professor von Turkovich (22) states that, according to Arndt,

> The shear zone has a volume consisting originally of solid material. When the speed increases, minute molten regions are generated in the shear zone resulting in a reduction of solid material volume. The shear zone is resolved into planes of infinitesimal thickness which are parallel to the shear plane.

In his conclusions, von Turkovich states, "The solution of the energy balance equation in the shear layer indicates that an adiabatic process may take place leading to a rather sharp (thin) transistion layer."

Rogers (23) writes that,

> All of the adiabatic shearing phenomena are based on two facts: Approximately 90 percent of the work of plastic deformation is converted to heat, and, the flow stress of most metal is quite sensitive to temperature, decreasing as the temperature increases. That localized temperature increases and strain concentration plays a major part in high-speed deformation of metals was recognized by Zener and Hollomon in 1944. The phenomenon is most clearly identified in most steels, in which heating above the transformation temperature causes the transformation of ferrite to austenite. On rapid cooling the austenite retransforms to a product that etches with difficulty and appears as a white band against the dark background of the remainder of the etched steel. These materials thus retain evidence of adiabaticity of the deformation, while in most metals the evidence is significantly less definite.

Rogers cautions,

> ....the use of the term "adiabatic deformation" is obviously an oversimplification in the sense that some heat always transfers out of any deforming region. Moreover, to categorize one situation as "adiabatic" and another not, is in many instances equivalent to labeling shades of gray as black or white. It will nevertheless be used herein for convenience, recognizing these limitations.

Rogers continues:

> ....all the characteristics described above for highly localized deformation through adiabatic shearing instabilities are also found in high-speed machining operations. In fact, because of the tool-workpiece geometry in orthogonal cutting, there are two zones of intense shear. The primary shear zone results from the initial deformation of the layer to be removed. The geometry of the metal chip flow is such that, after shearing, the metal in the forming chip is forced to flow normally to the surface of the solid being machined. This flow is also parallel to the rake face of the tool against which the chip is forced with considerable pressure. Frictional heating causes the chip to seize on the rake face. The differential flow between the dead metal at the rake face and the rapidly moving chip takes place over the narrow zone of secondary shear.

Wright (24) showed that even in lowcarbon iron, temperatures as high as 1000°C could be generated in this zone.

More significant from the adiabatic shearing standpoint are the studies by Lenaire and Backofen (25) of discontinuous chip formation, and the study by Recht (26) of catastrophic shear zone formation in chips during machining. In the former study, the separation of discontinuous chips was shown to take place through one of three possible mechanisms. The light etching bands can be seen in the type 2 and 3 schemes for chip formation observed in this 18 percent nickel steel as the cutting speed increases. From the horizontal cutting force time curves, Lenaire and Backofen were able to correlate discontinuous drop in force with the formation of the bands. Furthermore, Recht's analysis shows that the only way to obtain the temperature sufficient to produce these bands is to release the elastic energy stored in the machine into the locally adiabatically deforming zone.

According to Arndt (27), in a model of the cutting process at very high speed "....the shear zone has a volume consisting originally of solid material. When the speed increases, minute molten regions are generated in the shear zone. ....The shear zone is resolved into planes of infinitesimal thickness which are parallel to the shear plane."

A few years ago, Tanaka, et al. (28) stated in "Cutting Mechanism in Ultra-high-Speed Machining".— (1) The cutting mechanism is affected mainly by temperature and its distribution in shear and tool-chip contact zones. (2) With increase in cutting speeds, shear angles increase, for the decreasing of tool face friction force is achieved by temperature rise on tool-chip interface up to the softening or melting point of the tool or work materials. (3) With cutting speed, the metal strength of shear plane does not drop, but rather increases in appearance. "The cause may be in the following: In shear zone, temperature gradient in direction normal to the shear plane becomes steeper with increasing cutting speed; it is then expected at higher speeds that the strength of the next coming shear plane may not be affected by heat effects, a positive tendency in V_c relationship exists. (4) Except for the size effect, specific cutting force and shear energy remain constant irrespective of cutting speed. Those are proper to each of the work materials.