161

Modeling of Machining Operations

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Foreword

This working paper intends to be a contribution to the discussions to be undertaken at the meeting of the Working Group on Modeling of Machining Operations of STC C at the January 1996 meeting of CIRP in Paris. The paper should be read as a companion paper to the first working paper [Lutt '95] submitted by Luttervelt at the CIRP General Assembly held at Enschede in August 1995.

1. Why this Working Group?

Several decades ago, a research thesis concerned with chip formation in cutting was submitted for certification to the Supreme Certficate Committee for Scintific Degrees of the former U.S.S.R. One of the members of the Committee was a well known metallurgist. He noted that chips actually are scrap and, hence, opined that public funds should not be wasted on researching scrap. Being an influential man he suceeded in barring theses on chip formation from being submitted to the Committee for years to come!

Machining is a complex process involving a large number of inter-related variables. The human mind can't (possibly ever) *fully* comprehend it. From an engineering viewpoint, neither is there a need to comprehend it all at once. Specific aspects of machining are of engineering interest at a particular time. Since the aspects of interest are varied and varying with time (under external influences), cutting process modeling is not a linear activity. It will, by its very nature, take a tortuous path with its own twists and turns. The study of these twists and turns is itself a fascinating task. Thus, **tracing the historical locus of machining operations modeling is one of the possible tasks for the working group.** Appendix 1 gives one view of the locus of cutting process modeling.

On the other hand, as engineers, we need to periodically assess the status of machining operations modeling and decide whether we need to give a nudge or push in a specific direction to suit our engineering purposes as we perceive them in the short as well as the long term. **The working group may we wish to identify the nature of the nudge, if any, we need to give in 1997.** In particular, we need to direct our attention towards modeling work which helps us achieve higher productivity, lower cost and higher quality in machining. At the ame time, we need to discourage wastage of resources through aimless modeling, duplication of effort, and unhealthy competition. We should remember that the end users of our modeling results are practically minded professionals from the industry.

In this context, Luttervelt says the following: "Worldwide there is a need to increase the level of performance of metal cutting operations in terms of lower throughput time, higher precision, less waste and higher reliability. This causes a need for new means to predict and to maintain the state variables and the output variables of metal cutting operations within tight limits. [1] Modern modeling techniques have the potential to provide such means. The field of application of modern modeling techniques is too wide to be covered by several rather unorganized discussions during the meetings of STC "Cutting". It is much better to organize some form of concentrated action during a limited period of time with a clear purpose." [Lutt '95].

2. The nature of modeling

According to the dictionary, a 'model' is an *image* or *representation* of some object. Thus, a model is like a painting or a sketch which captures how the object looks from a particular viewpoint. It carries, in a stylized fashion, the essence or some interesting set of features of the object as perceived by the artist.

However, an image or representation is always less than the object itself. It is man made for the aesthetic or practical purposes of man.

Why do we paint? We indulge in it for one or more of the following reasons:

- save for posterity (desire for immortality)

[1]What exactly are *modern* modeling techniques? In particular, are we referring to computer based numerical (such as FEM, etc.) and simulation techniques? Are we precluding classical analytical techniques?

- personal aesthetic gratification
- commercial interest
- show off (ego)
- practical necessity (to keep up with institutional pressure to publish).

The aesthetic driving the scientific pursuits of man is logical elegance. Hence, a scientific model must be logically consistent with the current human knowledge and scientific understanding of nature. At the same time the model should be elegant; it should be beautiful in itself. Modeling is a creative activity.

From the point of view of engineering, the model should serve some material purpose(s). It should provide some understanding which has the potential of leading to some engineering action (or, inaction).

Clearly, the motivation of our Working Group should be engineering utility.

Models, like paintings, can be categorized into two fuzzy classes: *broad brush*, and *fine brush*..

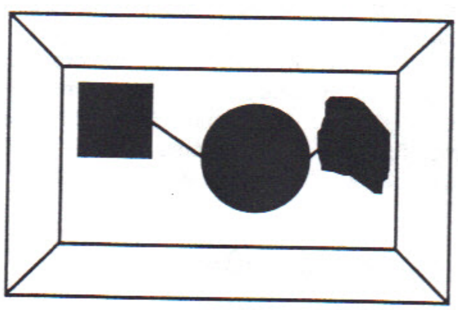

Fig. 1 Broad-Brush Modeling

A broad brush model (painting) is
- usually simple (involves a relatively small number of model parameters) at the cost of fine detail (and, possibly, accuracy)
- (but) manages to capture the essence of the process (object) from some point of view
- involves big leaps of imagination (simplifications) — their conception requires much creativity and inspiration.

Merchant's model of cutting forces is a classic example of a broad-brush model. In fact, the majority of the models developed during what Merchant calls the "golden age" of Metal Cutting (see Appendix 1) were of the broad-brush nature. These models have provided us with much understanding of the cutting process in general by adopting simple and easily understandable schema.

In contrast, a fine-brush model usually
- contains much fine detail
- contains a large number of model parameters
- is capable of more accurate quantitative prediction
- requires the use of powerful computers.

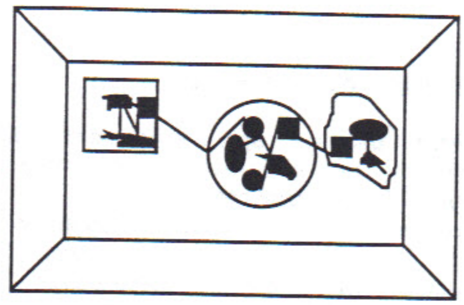

Fig. 2 Fine-Brush Modeling

The Finite Element Models (FEM) of Shirakashi are examples of fine-brush models.

3. Machining Operations

A large variety of machining operations are employed today in manufacturing. However, we are interested here only in "chip removal operations with metals and other materials by tools with *defined* cutting edges ..." [Lutt '95].

Appendix 2 summarizes some methods of classifying machining operations. It is observed that there are well over (17x2x2x3= 204) types of cutting operations in the realm of rough/finishing cutting alone. Each of these operations is a worthy subject for modeling in view of its unique nature (in some respects) and practical importance. A review of machining literature reveals that very few of these operations have been modeled to any reasonable degree. Some of the operations have in fact never been modeled.

Clearly, it is useful for the Working Group to undertake the tasks of
- **fully listing and classifying machining operations,**
- **evaluating the current status of modeling these operations from the point of view of industrial requirements, and**
- **short-listing the operations which require significant modeling efforts in the immediate future.**

4. Model Outputs: Machining Performance Information

Armarego [Arma '95] has recently argued that the there is a pressing need for models which are capable of quantitatively predicting the machining performance information (see Appendix 3 for details). A similar opinion was expressed in a CIRP report presented in 1987 [Kahl '87].

We suggest that the Working Group focus on the models needed for being able to quantitatively predict machining performance information.

What constitutes Machining Performance Information?

The ultimate answer to the above question of course is that Machining Performance Information refers to all the information that is needed for assessing the Cost, Quality and lead time or productivity associated with the operation. However, the study of these high-level output measures is usually labeled as Economics of Machining.. Luttervelt has already suggested that 'the scope of this working group should be limited to the technical nature of machining operations and not include economic aspects like cost calculations" [Lutt '95]. We are in agreement with this view.

What then are the technical outputs from a machining operation which are of importance from the point of view of machining performance?

Appendix 4 summarizes the performance measures identified recently by Armarego [Arma '95].

The outputs from a machining model should be the machining performance information expressed in a quantitative fashion with some degree of accuracy. The following is a partial list of such output parameters:

⇒ Chip Formation Geometry
  - Chip Thickness, Length and Width
  - Chip/Tool Contact Length
  - ?
  - ?

⇒ Cutting Forces
  - 3 forces, torque and thrust, etc.
  - Cutting Power
  - ?
  - ?

⇒ Cutting Temperatures
  - Mean Rake, Mean Flank, etc.
  - Temperature Field(s)
  - ?
  - ?

⇒ Tool Wear and Life
  - Flank Wear Parameters
  - Crater Wear Parameters
  - Groove Wear Parameters
  - Tool Fracture
  - Tool Life (Taylor Constant, Index, etc.)
  - Failure Modes (Entry and Exit Failures, etc.)
  - ?
  - ?

⇒ Surface Finish and Integrity
  - Surface Roughness and Topology
  - Residual Stresses
  - Surface Hardening
  - Surface Damage (?)
  - ?
  - ?

⇒ Component Dimensional Accuracy/Error

⇒ Cutting Vibrations and Chatter (?)
  - ?
  - ?

⇒ Chip Form for chip control
  - Classification according to Spaans, ISO 3685-1977, INFOS (Germany), JSPE, etc.
  - ?
  - ?

⇒ Burr Features
  - Entry Burr
  - Exit Burr
  - ?
  - ?

⇒ ?

⇒ ?

5. Inputs to machining operations: Model inputs

In order to obtain the desired output from a machining operation it is necessary to choose and, if possible, control the inputs. the many 'factors' (inputs) which affect the cutting process and performance measures (outputs) of any machining operation are well known from years of research and practical experience. These generic 'factors' can be summarized as in Appendix 4.

It is also evident that some factors can be represented by several clearly defined and readily controllable variables, which often depend on the particular machining operation considered, while other factors can only be described and quantified in terms of vaguely interrelated sets of 'properties'. Examples of the former factors are the cutting conditions, tool geometry and workpiece geometry, e.g. feed depth of cut, number of teeth, geometrical features of the cutting part of the tool. By contrast the tool and workpiece material can only be represented by sets of chemical and physical 'properties' or parameters, e.g. chemical composition, microstructure, mechanical and thermal properties. For the purpose of the working paper the former 'factors' will be represented by the operation input variables while the latter will be represented by the material properties.

The following is a partial list of the operation input variables and the associated (input) material 'properties'.

(i) Operation input variables

⇒ Tool Geometry (see ISO 3002/1)
- Single point tools (e.g. major and minor cutting edge angles, normal rake and clearance angles, cutting edge inclination angle, nose radius)
- Twist Drills (e.g. diameter, web thickness, helix angle, point angle, chisel edge angle, etc.)
- Peripheral Milling Cutters (e.g. diameter, number of teeth, cutter width, helix angle, etc.)
- Face Milling Cutters (e.g. diameter, number of teeth, major and minor cutting edge angles, etc.)

⇒ Cutting Conditions
- Cutting Speed, feed speed, resultant speed
- Feed/rev., feed/tooth
- Depth of cut, radial and axial depths of cut
- Cutting fluid flow rate
- ?
- ?

(ii) Material Properties

⇒ Work Material
- Type or code (mild steel, cast iron)
- Chemical composition
- Microstructure
- Mechanical (stress-strain relationship, hardness, ultimate strength)
- Thermal 'properties' (thermal conductivity, etc.)
- Electric 'properties (resistivity)
- ?

⇒ Tool Material and Coating
- Type or code (H.S.S., Carbide)
- Chemical composition
- Microstructure
- Mechanical, thermal and electrical properties
- ?

⇒ Tool-Work Material Combinations
- Frictional 'properties'
- Thermo-electric properties
- Wear, diffusion, etc.
- ?

⇒ Cutting Fluids
- Chemical properties
- Physical properties
- Application method
- ?

⇒ ?

6. Machining Operations as Transformations

All conventional material removal (machining) operations using tools with defined cutting edges [Lutt '95] can be represented as systems and models which transform the operation input variables and material properties into the intended outputs, e.g. performance measures.

As noted in section 3 above, a wide variety of geometrically and kinematically complex practical machining operations have been developed to increase the flexibility of this important manufacturing process in industry. However in order to gain a fundamental understanding of the material removal or 'cutting' process, simplified or idealized machining operations referred to as 'classical' orthogonal and oblique cutting operations (see Appendix 5) have been devised and modeled.

In these 'classical' operations the input variables, {I}, directly represent the fundamental tool-workpiece interference geometry (e.g. cut thickness and width of cut) and the resultant cutting velocity, $\{I_p\}$, essential for material removal and cutting process modeling. The cutting process has been shown to be subject to plastic flow, friction and ploughing mechanisms which can be mathematically modeled by a set of 'process parameters' and material parameters, [P], which transform the inputs to the outputs, $\{O_p\}$.

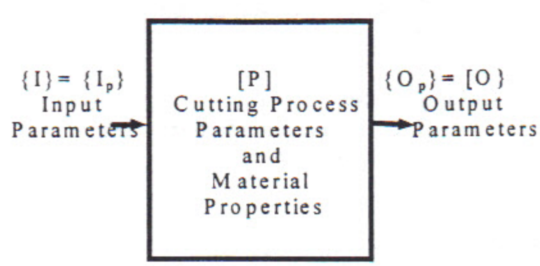

Figure 3

$$\{I_p\}[P\} = \{O_p\} \qquad (1)$$

where

$\{I_p\}$ = a vector of a subset of input parameters and material properties,

$[P]$ = a model/transformation which utilizes a set of process parameters and material properties, and

$\{O_p\}$ = a vector consisting of the (intended) subsets of output parameters.

For the purpose of the above model and transformation for the 'classical' orthogonal and oblique cutting operations the operation input variables, {I}, such as the cut thickness, width of cut, normal rake angle, inclination and resultant cutting velocity are identical to the corresponding input parameter, $\{I_p\}$, in Fig. 3. The process parameters of the chip formation process during material removal depend on the model representation and include the shear angle, the chip flow angle, the shear stress and the friction angle at the tool-chip interface of the particular thin shear zone (plane) models for continuous chip formation. The output parameters, $\{O_p\}$, such as the force components can thus be established in terms of the input parameters and the transformation involving the 'process parameters'.

It should be noted that in the more complex machining operations, such as turning, the operation input variables, {I} (e.g. the feed, depth, rotational speed and lathe tool geometrical specification), have to be transformed by $[P_i]$ into the appropriate input parameters, $\{I_p\}$ (such as the cut thickness, width of cut, normal rake angle and inclination angle), before the cutting process model and transformation, [P}, can be used to establish the output parameters, $\{O_p\}$, in Fig. 3 and eq. (1). Similarly the output parameters, $\{O_p\}$ (such as the force components from the process model) may not be in the preferred or required directions so that a further transformation, $[P_o]$, may be necessary to obtain the required practical operation outputs, {O}, i.e. $\{I\}[P_i]=\{I_p\}$, $\{O_p\}[P_o]=\{O\}$, so that from eq. (1)

$$\{I\}[P_i]\ [P]\ [P_o]=\{O\} \qquad (2)$$

Two important aspects may be raised from the above discussion. Firstly, unless an adequate understanding of the physical phenomena and engineering science principles involved in the chip formation process can be understood achieved it would be impossible to develop reliable models for performance prediction purposes and the cutting process would remain a 'black box'. Secondly, the transformation $[P_i]$ between the operation specific input variables and input parameters to the cutting process models and transformations are far from trivial. These rely heavily o a precise knowledge and specification of the practical tool geometry followed by geometrical transformations between the various practical tool angles given in standard specifications and those of fundamental importance to the cutting process model [p]. This task can be rendered particularly difficult by the unnecessary ambiguities in the standard tool specifications or the lack of information offered in practical source material. Such geometrical ambiguities can threaten the development of quantitatively reliable predictive models for the various machining performance measures sought by CIRP [Kahl '87]. Similarly the process transformation $[P_o]$ can be mathematically complex requiring computer assistance.

The Working Group may wish to consider how ISO 3002/1 can in fact be adequately implemented in practice in the various standards of practical tools and by tool manufacturers.

Following from the above discussion, it can be argued that a machining operation model <u>must</u> involve one or more cutting process parameters to justify its recognition as a machining operation *model*.. If the model representation involves only the technological input and output variables, it is not a process model. **This litmus test enables us to decide what should be *in* and what should be *out* of the deliberations of our Working Group**.

Following the above logic, it should be apparent that Merchant's cutting model is indeed a process model since it includes a number of process variables such as the shear angle, mean friction coefficient at the rake and mean shear stress at the shear plane. In contrast, **Taylor's equation ($VT^n=C$), notwithstanding its practical utility, does <u>not</u> constitute a cutting process model** since it attempts to link the input parameter (*V*) directly to the output parameter (*T*) without invoking any process parameters.

7. Process parameters ([P])

What constitutes [P]? The cutting process suddenly manifests itself when the tool touches the workpiece in the environment dictated by {I}.

process model since it attempts to link the input parameter (*V*) directly to the output parameter (*T*) without invoking any process parameters.

7. Process parameters ([P])

What constitutes [P]? The cutting process suddenly manifests itself when the tool touches the workpiece in the environment dictated by {I}. A host of process parameters (e.g. a shear angle, a mean rake temperature, a flank wear rate, a chip curl radius) appear suddenly. The modeller then decides (we seem to be prisoners of the schools of thought we belong to in doing this) which of these process parameters he/she needs to include in his/her quest for predicting the desired output parameters. [P] consists of those parameters which the modeller decides to include. **(There may be a need for the Working Group to arrive at a view on the process parameters of greater importance.)**

A source of confusion arising from the idealization in Fig. 3 with regard to [P] and {O} needs to be noted. For instance chip formation geometry (chip thickness, etc.) is a subset of {O}. Likewise, cutting forces are a subset of {O}. However, in many cutting models, an estimation of cutting forces requires *a priori* knowledge of chip formation geometry. Thus, depending on the scope of a particular model, cutting forces may appear as {I}, [P] or {O}. This confusion may be resolved by viewing cutting process modeling as follows:

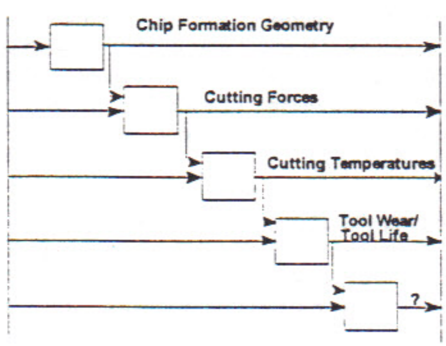

Fig. 4

8. Idealized and Simplified Machining Operations versus Practical Machining Operations

A review of scientific papers on metal cutting reveals that the majority of them have focused on *idealized* operations (such as 'classical' orthogonal cutting) and not on practical operations. The "golden age" of metal cutting was largely devoted to analyses of these idealized operations. The understanding thus gained has indeed provided us with the much needed foundation for modeling practical machining operations.

Fig. 5 shows the classification of these idealized operations processes as perceived by Venuvinod [Venu '95]:

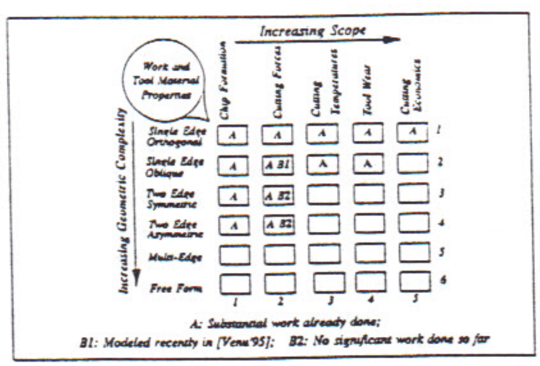

Fig. 5 Classification of Idealized Operations [Venu '95]

However, we believe that the time for changing our focus has come. Presently, we are able to quantitatively predict only a few of the output parameters for only a few of the practical machining operations. This is a dismal record when compared with other engineering disciplines. **We believe that the Working Group should redirect attention away from idealized operations and towards practical operations.**

9. Idealized Machining Operations as Basic Cutting Tests

We have already argued in section 5 that purely empirical models (i.e. those which do not invoke any process parameters while transforming {I} to {O}) such as Taylor's equation should be outside the Working Group's agenda.

operation. However, the use of this approach has resulted in very tedious models. Further, these models (e.g. Shirakashi's methodology — see Apendix 7) require materials data at high strains, strain rates and temperatures of relevance to machining which can either not be achieved without data/curve extrapolation or only obtained through the use of highly specialized equipment. In fact 'classical' orthogonal cutting tests together with a process model have been used to establish and extend the 'empirical' stress-strain curves at the required strains, strain rates, etc. i.e. the idealized machining operation has been used as an alternative to the more conventional material test rigs. The dearth of 'empirical' stress-strain equations at the appropriate strain values and temperatures as well as the complexity involved in obtaining such data seriously limit the use of such models.

The friction phenomenon at the tool-chip interface has provided a further problem which has occupied the minds of many research workers. The prevailing conditions at the tool-chip interface preclude the use of the 'empirical' values of the coefficient of friction found from ordinary sliding test conditions. While numerous papers have been reported to quantitatively explain the variable and high values of friction at the rake face none have provided reliable quantitative predictive models which are devoid of experimental testing.

A further complication is the existence of a concentrated 'edge force' acting at the cutting edge noted by research workers for decades. This force has been attributed to rubbing and ploughing phenomena due to the rounded (rather than theoretically sharp) cutting edge. Again no reliable theoretical and predictive model for the edge forces has been established although these forces can be readily estimated from cutting test data and statistical analysis.

By contrast some workers (including the present authors) have long taken the view that it is necessary to recognize the idealized or 'classical' machining operations as 'basic cutting tests' in their own right. In this approach cutting tests are carried out for a wide range of cutting conditions using an idealized ,machining operation i.e. either 'classical' orthogonal or oblique cutting tests. These tests enable 'basic cutting parameter' values such as the shear stress on the shear plane, the frictional angle at the rake face and the edge force coefficients to be estimated. In some investigations these basic cutting parameters have been related to the cutting conditions by 'empirical' equations, The basic cutting quantities so obtained have been utilized in modeling other idealized and practical machining operations [Venu '95, Arma '95].

It is useful if the Working Group arrives at a firm view on the desirability of using the 'classical' machining operations as 'basic cutting tests' in their own right.

10. Fine Brush Models

Equations (1) and (2) represent an extremely broad-brush view of modeling. In fine-brush modeling the transformation triplet [P_i] [P] [P_o] may have to be repeated several times before {I} transformed to {O}:

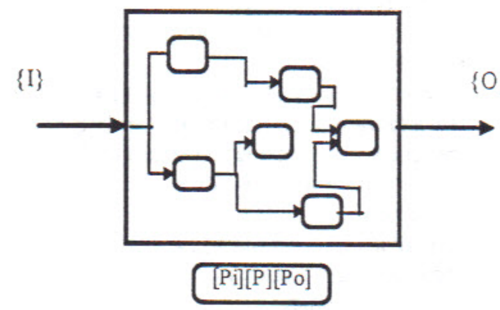

Fig. 6

While there are many workers who have modeled specific parts of specific input-output chains, very few seem to have systematically addressed complete chains. The schools of Armarego, Oxley, Shirakashi, Ueda, and Rubenstein & Venuvinod are amongst the few who have addresses complete chains (see Appendices 5-9 for details). However, amongst these, only Armarego and Oxley have paid particular attention to the the modeling of practical machining operations.

It is therefore suggested that the Working Group focus on modeling of practical machining operations

- **using such strategies as to enable the prediction of {O} from a given {I} (i.e. complete the I/O chain)**
- **while providing significant understanding of the cutting process**
- **by including the more important process parameters, [P], within the I/O chain.**

11. How can we judge or rate a machining operation model?

We may use one or more of the following criteria:

- *prediction ability*
  - prediction accuracy (as judged against empirical data)
  - prediction scope: range of input (or input variables over which the predictions are found to be valid (Note that Merchant's orthogonal cutting model has little predictive ability since the friction coefficient at the rake surface cannot be known *a priori* [Merc '44]. In contrast, Rubenstein's model [Rube '72] is free of this limitation.)
- *complexity*
  - the number of input, process, and output variables included
  - the complexity of [P} (mathematical or otherwise)
- *computability, computational speed*
- *scientific utility*:
  the extent to which the model has helped us advance a logical understanding of the process, or is it likely to contribute to such understanding in the future.
- *robustness*
  the ability to continue to be effective in new cutting situations
- *engineering utility*:
  the potential of the model with regard to the model's contribution to the solution of solve concrete practical problems (overlaps with prediction ability)
- ?

Engaging in such rating could be one of the tasks of this Working Group.

(Imagine that STC C has been given an opportunity to offer 500 words to be included in a time capsule. What will we include? Merchant's model? ? ..? ...? Or, the basic principles in which we have great trust: such as "the principle of chip equilibrium"? "the principle of force-velocity collinearity"?)

12. Database: The classification (or labeling) of cutting process models

This Working Group aims to review the current status of modeling of machining operations. This would require us to compile a computer database of a representatively large collection of published material on machining operations.

The authors are presently developing a database program capable of storing a set of labels to characterize the nature and contribution of each paper. The availability of such labels will facilitate subsequent analysis of the database to come to meaningful conclusions regarding the current status of machining modeling.

What should be these labels? In the following we give a partial list of such labels organized into appropriate groups.

⇒ Model Nature
- Scientific or Engineering Model
  Deterministic, Non-deterministic (e.g. Fuzzy), Statistical, and knowledge-based

- Classical Mechanics Based (e.g. [Merc '44])
  → Numerical
    ♦ Finite Difference
    ♦ Finite Element
    ♦ Boundary Element
    ♦ ?
  → ?
  → ?
- Other
  → using Chaos Theory (see Appendix 12)
  → using ANNs (aee Appendix 12)
  → ?
  → ?
- ?
- ?

⇒ Model Detail
- Degree of Brush on a scale of 1 to 5 (1: Very Broad Brush, 5: Very Fine Brush)
- ?
- ?

⇒ Outputs
- As listed in section 4
- ?
- ?

⇒ Geographical Source
- USA, UK, Germany, USSR (former) China, Japan, India, Australia, etc....
- ?
- ?

⇒ ?

⇒ ?

Notes

a) *Scientific and Engineering Models*:

This distinction was suggested by Chandrasekharan [Lutt '95] who says models for future development are scientific models whereas those for end user use are engineering models. We like this terminology but would like to be more rigorous in defining them.

Scientific models are generic in the sense that they are applicable to a wide variety machining operations such as turning, milling, etc. For instance, Merchant's model does not make any direct reference to a specific cutting operation but it is applicable to many. Scientific models lead to a basic and fundamental understanding of the cutting process in general. But, they need to be further refined and adapted to different practical operations while creating the operation-specific models. In [Arma '95], Armarego refers to a large program in progress at Melbourne University which is aiming to systematically develop engineering models for different machining operations including turning, drilling, end milling, and face milling.

b) *Classification of Scientific Models*:

We may adopt Venuvinod's classification for the scientific cutting process models (see Fig. 5). However, we may have to recognize rotary cutting as a separate scientific class in view of its unusual kinematic complexity. Note from Fig. 5 that the majority of scientific modeling tasks are still waiting to be addressed.

c) *Classification of Engineering Models*:

This is straight forward. We can use the classification suggested in Appendix 2.

d) *Geographical Origin*:
This may be on the country of the first author. We must include as many countries as possible.

13. What should be *in* and what should be *out*?

Page 10 of [Lutt '95] has already outlined what should be *in*. Note that we are only concerned with cutting with tools with *defined cutting edges*. Hence processes such as grinding, lapping, polishing are *out* (since their cutting tips do not have defined cutting edges). Likewise, unconventional processes such as EDM, ECM, and laser cutting are also *out*.

Do we include everything related to cutting with defined edges?. Obviously, we can't and we shouldn't. Otherwise, our task would become too unwieldy. Our area of concern is clearly a subset of cutting in general. But, what are the subset's boundaries? We need to be very clear about this.

Does the litmus test mentioned above provide an answer? A paper on cutting may be included only if it includes some modeling in terms of some process parameters to some significant degree. By this test, the following are *out*:

⇒ purely empirical models relating input variables directly to output variables without any process variables (hence Taylor's equation is *out)*.

⇒ works using neural nets, expert systems, etc., without throwing any (new) light on the process itself (see Appendix 120. **This is an important issue for discussion by the Working Group** particularly in the light of the following comment made by Usui as reecently as in 1988: "[Many cuting models have been] developed so as to have a predictive nature for practical use. The progress of the predictive theories, however, is slow and is far from being completed To cope with the urgent demand of establishing the automated machining process, an expert systems in which A.I. inferencing and the algorithms of the existing metal cutting theories are combined should be developed, though exertion for the predictive theory has to be continued." [Usui '88].

⇒ pure sensing and monitoring without relating these exercises to some process parameters.

⇒ pure control oriented works which are equally effective with or without any reference to the process itself and the associated process parameters.

⇒ ?

⇒ ?

14. Literature Review

The Working Group needs to collectively undertake a review of machining literature in the light of the above discussion. In order to facilitate the intiation of such a review, summaries of the modeling efforts of some prominent groups/schools are given Appendices 5 to 11.

Appendix 1
The Locus of Cutting Process Modeling

There are of course some historical reviews of metal cutting already available, for example, Finnie's "Review of the Metal Cutting Analysis of the Past Hundred Years" [Finnie '56], Shaw's "Historical Aspects Concerning Removal Operations on Metals" [Shaw '68], and Komanduri's "Machining and Grinding: A Historical Review of the Classical Papers". In 1988, Usui reviewed the progress on predictive theories in metal cutting in JSME [Usui '88].

More recently Merchant has briefly reviewed the impact of emerging manufacturing technologies on cutting process modeling [Merc '93]. He makes several useful observations:

- "[A]lthough the publication dates of the classical papers range from 1798 to 1982, the bulk of them lie in the period of the 1940's and 1950's — a period referred to by some as the "golden age" of metal cutting research. "
- "What transpired in that age stemmed, in large part, from the careful observation and identification of the actual mechanisms by which metal cutting chip formation takes place. [A] mathematical analytical model of the metal cutting process began to emerge, and the process of developing a scientific basis for the engineering of machining operations, supplementing the formerly wholly empirical basis, was initiated."
- "The following two decades, those of the 1940's and 50's were an exciting [t]ime. For most of it, there was little else happening in the way of technological changes in the field of manufacturing of sufficient challenge to distract from concentrating on developing further capability to understand and engineer the machining process as such."
- "However, during the latter part of the second decade, a technological event took place which was destined both to change the emphasis of such research and to broaden its perspective. This was the invention and development of the numerical control machine tools".
- On the other hand, these technological changes made us realize that machining time constitutes a small proportion of the total cycle time. "As a result, research emphasis shifted significantly away from machining technology." Hence the decreased number of classical papers on machining in 1960's and 70's."
- "The situation is now reversing because "the results of the research aimed at improving the efficiency of utilization of the machining process have now produced such large increases in the utilization that the payoffs potentially derivable from improving the efficiency of the machining process itself have once again become quite significant."
- "There is now growing emphasis on research to increase the quality-determining capabilities (accuracy, uniformity, surface finish, surface integrity, etc.) of the various machining processes."
- "There is now a steadily emphasis on research in process modeling of machining and grinding research to create more and more accurate and realistic models" to support the growing role of computer technology in manufacturing.

The contributions of CIRP to the development of cutting process modeling have been summarized in its publication "Forty Years of CIRP" in 1991 [CIRP '91]. The following quotes are taken from the section on STC Cutting in the book:

- "In November 1959, a first meeting was called together by Nicolau in Aachen ... to the effect that STC could formulate a research proposal. [T]he final proposal was submitted in January 1960. [E]xperts ... proposed to use industrial tool shapes and methods for the data and orthogonal tests for fundamental and scientific questions. [A] number of sub groups were formed. [S]haw (took) surface roughness and quality aspects. [B]odart took HSS tools, Opitz the carbide tools, forces and dynamometers were dealt with by Eugene and Svahn. [P]omey took metallurgical aspects. [B]ickel looked into temperatures; Tobias into the influence of vibrations and Gladman - later Lorenz - dealt with statistical evaluation techniques. [v]an Luttervelt especially [p]layed an important role, when ISO (TC29) W.G.22, "testing in machining" came into action."
- "Understanding the cutting process better was certainly one of the main results. To understand the relationship between the built-up edge and built-up layer took a long time, but explained many strange effects in wear and in surface roughness. [I]t brought to light the great unknown factor of the temperature. [A]s a consequence of this, a much better understanding of the wear phenomena developed" [CIRP '91, Bick '63, Lenz '64, Lenz '65, and Tuin '65].
- "Another important point was the study of chip formation and the explanation for the different forms of chips. The ultimate goal was of course to be able to control the chip

forms to the extent that one could get the preferred shape and form by controlling the cutting conditions" [Peke '63].

- "In 1965 Opitz [r]eported on hot machining and adaptive control."
- "[i]n 1967 [a]ll ideas on short or accelerated tests of tools was abandoned as totally unacceptable."
- In 1967, Opitz "emphasized the importance of automation, computer languages for NC."
- "Another everlasting problem of great importance was over chip breaking and control, especially in relation to automation."
- "(In 1972) Another means to try and get more interest from industry was AMRI, a sub-group of STC C to promote the "Application of Machining Research in Industry". [v]an Luttervelt especially was very active in assisting the group to arrive at results".
- "[o]ne of the [r]esults (after 1974) was the discovery that in milling the exit of the tooth [w]as more disastrous than the entry" [Peke '78]).
- "Over the last ten years the STC has done more of the same."
- "Chip formation and chip clearance have become topics" [once again].
- "[m]achining with very small chip dimensions and diamond tools is a focal point again."
- "[t]he fundamentals of cutting are still asking for a mastermind to answer the basic questions that have not been answered in the forty years of consequent study by CIRP members" !

Another recent CIRP milestone is the activity of STC C's Chip Control Working Group in the period 1990-93 [Jawa' 93a].

Appendix 2
Classification of machining operations

Machining operations may be classified into two broad groups with regard to the continuity of contact between the tool point (or one of the tool points) and the workpiece during one operation:

- continuous cutting
- interrupted cutting.

A partial list of continuous cutting operations is:

- turning (1)
- facing (2)
- grooving, thread cutting (3)
- drilling
  - with facet point drills (4)
  - with point thinning modifications (5)
  - with stepped drills (6)
  - with Hosai drills (7)
  - with spade drills (8)
- reaming (9)
- boring (10)
- parting (11)
- broaching (12)

A partial list of interrupted cutting operations is:

- Milling:
  - peripheral milling (13)
  - face milling (14)
  - end milling (15)
- tapping (16)
- sawing (17)
- ?
- ?

The second way of classifying operations is related to whether is generally intended to produce the final dimension on the workpiece:

1. rough cutting,
2. finish cutting.

This is a fuzzy classification since the input conditions to each class under different situations may be substantially overlapping. The classification is context dependent.

The third way of classifying operations relates to the process capability in terms of precision, i.e. the dimensional tolerance the operation is capable of achieving. On this basis, a machining operation may be classified as

1. rough
2. finishing
3. precision
4. ultra-precision
5. nano.

Finally, machining operations may be classified on the basis of the geometry of the cutting wedge (insert) used:

1. All faces of the wedge are plane (leading to straight cutting edges).
2. One or more of the clearance faces are curved while the rake face is plane (leading to curved cutting edges.
3. The rake face has "bumps and troughs" of conventional and complex forms for the purpose of controlling the chip form.

Appendix 3

The importance of being able to predict machining performance information

The following information is worth noting:

- "In the mid 1970's [Merc '74], and again in the 1980's [Ever '84] it has been reported that in conventional (manual) manufacturing systems components only spend about 6% t 10% of the total available production time on machines being processed. By contrast, it has been estimated that the percentage ... would increase to 65%-80% in modern computer-based manufacturing" [Arma '95].
- A recent survey by a leading cutting tool manufacturer (Kennametal Inc.) indicates that in the U.S.A. the correct cutting tool is selected less than 50% of the time, the tool is used at the rated cutting speed only 58% of the time, and only 38% of the tools are used up to their full tool-life capability. One of the reasons for this poor performance is the lack of predictive models for machining.
- "[D]ue to the high investment costs in the use of expensive CNC machine tools the cost per component function becomes more sensitive to the selected cutting conditions [s]o that deviations from optimal cutting conditions can result in high cost penalties. [T]his problem becomes even more critical when the effective operating time is increased to 65% or 80% estimated" [Arma '95].
- "While the need for reliable quantitative machining performance information has long been recognized, the pressing need for this information has been re-emphasized in a recent survey carried out by [C]IRP [Kahl '87]." [Arma '95].
- We may use two approaches in obtaining this quantitative machining performance information: `Empirical' and `Fundamental'. The `Empirical' approach suffers from the following disadvantages: "[the] number of variables have to be limited, [o]therwise the amount of testing would be [illegible] information in the form of empirical equations is often not reported in sufficient detail in the literature and often difficult to find." [Arma '95]
- "More recently fundamental approaches, based on mechanics cutting models, have been introduced [at the University of Melbourne] and appear to be promising for prediction purposes." [Arma '95]
- "With the aid of computers, it appears that a more comprehensive approach to machining research to quantify and optimize the technological and economic performance of machining processes [i]s both possible and necessary for modern computer-based manufacturing." [Arma '95]

Appendix 4

Machining Performance Information and Factors Affecting Performance [Arma '95]

Table 4.1 lists the various machining performance measures and criteria or desired levels for 'high' performance. It is noted that the machining performance measures may be classified as 'technological' and 'economic' with the former affecting the latter when incorporated in constrained optimization analyses for the various single or multipass machining operations. It is also evident that ideally the desired level of each performance measure is either nil (zero) or infinity which can explain why continual research and development has been carried out in order to improve machining performance.

Table A4.1

Technological Machining Performance Measures	Criterion/Desired Level: Actual	Criterion/Desired Level: Ideal
Forces, Torque	Min.	Nil
Power	Min.	Nil
Tool Wear	Min.	Nil
Tool Life (time vol. removed)	Max.	Infnite
Material Removal Rate	Max.	Infinite
Surface Roughness	Min.	Nil
Component Dim. Errors	Min.	Nil
Chip Formn/Control	Continuous/Disposable	
[illegible] Measures	Actual	Ideal
Time per component	Min.	Nil
Cost per Component	Min/	Nil
Profit Rate	Max.	Infinite
Rate of Return	Max.	Infinite

The many factors affecting the technological machining performance measures are listed in Table A4.2.

Table A4.2

Factors Affecting the Technological Machining Performance Measures
WORK MATERIAL
Various properties and characteristics (strength, hardness, composition, thermal conductivity)
TOOL MATERIAL
Various properties and characteristics (strength, hot hardness, toughness, wear resistance, thermal conductivity)
TOOL GEOMETRY
Various cutting part and tool features (rake, clearance and inclination angles, number of teeth)
CUTTING CONDITIONS
Various practical process variables (feed, speed, depth of cut)
CUTTING FLUIDS
Types, method of application, flow rates
MACHINE TOOL
Design specification, rigidity, vibration stability

Appendix 5
A summary of modeling work by Armarego's school

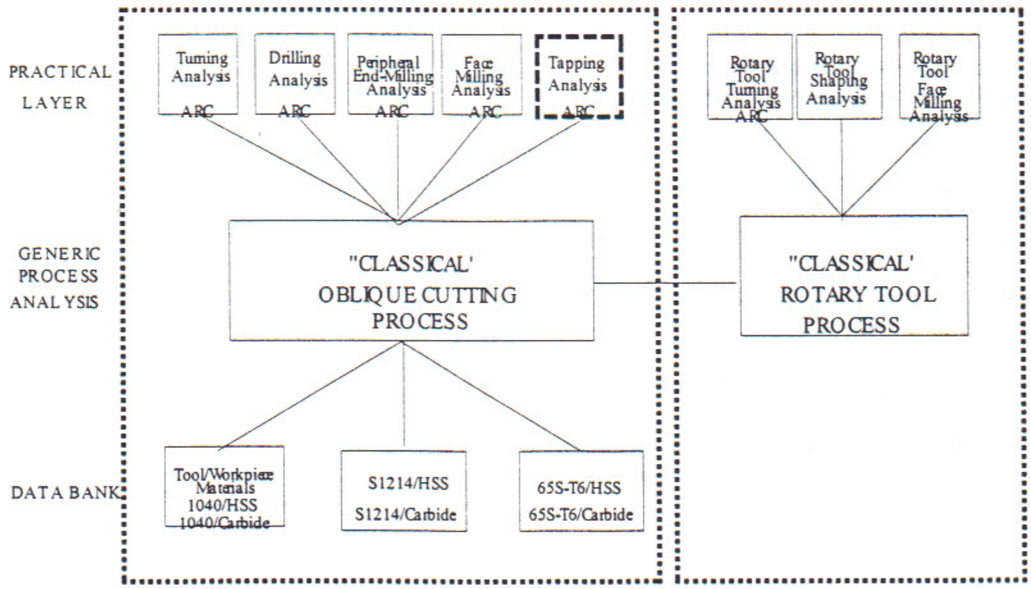

Fig. A5.1 Unified Mechanics of Cutting Approach and Software Structure for Chip Flow, Force and Power Prediction in Conventional and Rotary Tool Practical Machining

The main objective of the research group at the University of Melbourne over the past four decades has been to establish machining on a sound scientific, mathematical, predictive and quantitative basis. As such the research effort has been directed at gaining an understanding of the cutting process and the associated phenomena with a view to developing comprehensive mathematical models for quantitative prediction of the various technological performance measures for the wide spectrum of practical machining processes used in manufacturing industry. In addition constrained optimization studies for maximizing the economic performance of various practical machining operations have been carried out. These latter economic optimization models will not be considered in this appendix since these lie beyond the agreed scope of this STC Working Group [Lutt' '95].

It became evident, even in the 1960's, that fundamental studies of the mechanics of the cutting process dating back to late last century [Finn '56] have been limited to the specially designed and geometrically simple machining operations. These operations, using single straight cutting edge wedge tools removing rectangular areas of cut at uniform resultant cutting velocities, have been referred to as 'classical' orthogonal and oblique cutting operations by the Melbourne Group to highlight the early origins and simplified geometrical and kinematic configurations of these operations. By contrast investigations of the geometrically more complex practical machining operations such as turning and drilling have focused on 'empirical' (experimental) approaches for estimating the various technological machining performance measures, such as forces, power and tool-life, of importance in practice. These experimental studies considered each practical operation in isolation and related the practical or technological input variables such as feed and speed to the experimental values of the required technological performance measures by curve fitted 'empirical' equations. Notable early examples of this approach are the tool-life equation proposed by Taylor and empirical force equations by Boston [Tayl '07, Bost '36]. Thus fundamental studies and mathematical analyses of the cutting process were restricted to the simpler 'classical' orthogonal and, to a lesser extent, oblique cutting operations while the estimation of machining performance of the various practical machining operations was based on empirical testing which resulted in a wide chasm between the theory and the practice of machining.

In order to meet the above objective and hence bridge the gap between theory and practice a long series of investigations have been carried out by Armarego and his coworkers leading to the development of the "Unified or Generalized Mechanics of Cutting Approach" to performance prediction and the associated modular CAD/CAM package shown in Fig. 2.5A [Arma '95].

As an essential first stage of this on-going research program predictive mechanics of cutting analyses for the 'classical' orthogonal and oblique cutting operations have been developed and experimentally verified. These mathematical analyses have been based on modified thin shear zone (plane) deformation models which incorporated 'edge forces' due to rubbing and ploughing at the cutting edge ignored in many earlier (e.g. [Merc '44] and more recent [Oxle '89, Shir '95] models. It has been shown that provided a data bank of basic cutting parameter values such as the work material shear stress (τ), the friction angle (β) or ratio (μ) at the rake face and the chip length ratio (r_l) obtained from comprehensive 'classical' orthogonal cutting tests were available, all the force components, the power, the deformation and chip flow angle in the more general 'classical' oblique cutting operation could be quantitatively predicted from the developed oblique cutting analyses (without the need for further experimental testing). The implications of these mathematical models for the development of predictive models for the forces, power and chip flow in the various practical machining operations such as turning or drilling has been reported [Arma '83] and implemented in the next stage of the research program.

From detailed studies of the tool geometry and specification, kinematics, tool-workpiece interference and cutting action of individual practical machining operations such as turning, milling, and drilling it has been possible to develop mechanics of cutting analyses for each operation based on the 'classical' oblique cutting process. This involved the identification of the controllable input variables of each practical machining operation and their transformation to the corresponding cutting parameters of the 'classical' oblique cutting analysis for the prediction of the forces, power and chip flow followed by a further transformation for establishing equations for the force components, torque, power and chip flow of the relevant practical machining operation being modeled. In order to quantitatively predict these performance measures for the required practical operation a data bank of the basic cutting parameter values (τ, β, r_l) for the tool-workpiece material combination used was required. Thus the 'classical' oblique cutting process represented the generic process common to a variety of practical machining operations and whose analysis could be extended to establish predictive models for these practical operations. It was also clear that the data bank for each tool-workpiece material combination required must be applicable to all modeled practical machining operations. However each practical machining operation had to be individually modeled and verified by extensive testing. Similarly each new tool-workpiece material used had to have the corresponding data bank established.

These investigations have enabled the predictive models for the different practical machining operations to be integrated into the modular CAD/CAM package centered around the generic 'classical' oblique cutting process analysis with modules for each practical machining operation and tool-workpiece material data bank. New modules can be added as these are established and proven. Modules for turning and drilling (with a variety of drill point designs) as well as the different milling and slotting operations have been established, many of which have been reported in the Annals of CIRP. Modules for tapping operations as well as the novel self-propelled rotary tool turning operations are currently being developed. It should be noted that earlier studies of the geometrically simpler or 'classical' rotary tool cutting operations have been analyzed and tested and shown to be mathematically related to the generic 'classical' oblique cutting operation and the relevant data bank of basic cutting parameter values.

The ongoing research program also includes basic investigations of the cutting action and mathematical modeling of machining with plane faced multi-edge form tools. Triangular and circular profiled form tools taking a variety of area of cut shapes and sizes have been studied and modeled. New and generalized definitions for identifying two dimensional (orthogonal) and three dimensional (oblique) chip formation models have been established. These were based on the angular relationship between the resultant cutting velocity vector and the vector joining the extreme points of the tool active cutting edges which produce one chip. Generalized definitions for the tool and cut geometry as well as predictive cutting models for machining with form tools have been developed [Arma '83b]. Research to link the 'classical' orthogonal cutting data bank to the predictive models for form tool operations is under way.

Apart from the development of predictive force models, an important feature of these investigations has been the deeper understanding achieved of the geometrical design, specification, manufacture and 'as produced' geometrical variability of the various practical cutting tools and their effects on the cutting process and performance. This knowledge has proved very useful in developing national and international standards on the geometry and specification of practical cutting tools.

Appendix 6

A summary of modeling work by Oxley's school

Significant contributions to the understanding and modeling of the metal cutting process for the 'classical' orthogonal operation and an extension to a few practical machining operations have been made by Oxley and his co-workers since the late 1950's in England and from 1960's in Australia. Details of Oxley's theoretical and experimental investigations may be found in the many technical papers culminating in an advanced text book on machining published in 1989 [Oxle '89]. This book summarizes the key findings and computer-aided predictive models of this group's work to 1989. Active research programs on the various aspects of machining as well as friction and wear are currently being undertaken by Oxley's group at the University of New South Wales, Australia.

A major portion of Oxley's work on machining to the late 1970's has focused on the 'classical' orthogonal cutting operation. Particular attention has been paid to the effects of the mechanical properties of the work material at the high strains, strain rates and temperatures on the deformation process in the shear zone region and friction process at the tool-chip interface. A major objective of this work was to develop a comprehensive predictive model for the forces, power, deformation and salient temperatures in 'classical' orthogonal cutting operations from the given cutting conditions (speed, width of cut, cut thickness), tool geometry (rake angle) and the tool and workpiece mechanical and thermal properties.

The early work on the 'classical' orthogonal cutting process in 1959 applied the slip line field theory of plasticity to the shear zone and Hertzian contact between the curved chip and tool rake face to describe the tool-chip friction. This early model considered the shear zone to be thick, the chip curved and no contact between the tool cutting edge and both the chip and the workpiece. A very significant contribution of this work was the introduction of strain hardening effects in the slip line theory of plasticity by modifying the Hencky plasticity equations.

In the following investigations Oxley assumed, and later experimentally verified, that the thickness of the shear zone was indeed thin and he progressively developed more refined mathematical and predictive models of the orthogonal cutting process allowing for the variable mechanical properties of the workpiece material. Considerable effort has been placed in relating the stresses, strains, strain rates and temperatures found from machining to those obtained from conventional 'static' and high strain rate mechanical tests using 'empirical' curve fitting techniques. Thus an important outcome of this fundamental machining research has been to relate and extend the 'empirical' stress-strain equations commonly used as the basis for modeling mechanics of solids and plasticity problems in practice.

A more recent predictive model for the 'classical' orthogonal cutting operation is given in Oxley's book [Oxle '89]. This model assumes a thin shear zone, chip equilibrium, a uniform shear stress in the secondary deformation zone at the tool-chip interface, a sharp cutting edge with no concentrated edge force acting at the cutting edge, and that minimum energy applies in