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Concurrent Evaluation of Machinability during Product Design

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Concurrent Evaluation of Machinability during Product Design*

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Abstract

This paper presents a new methodology for evaluating the machinability of a machined part during the design stage of the product development cycle, so that problems related to machining can be recognized and corrected while the product is being designed. Our basic approach is to perform a systematic evaluation of machining alternatives throughout each step in the design stage. This involves three basic steps: (1) generate alternative interpretations of the design as different collections of machinable features, (2) generate the various possible sequences of machining operations capable of producing each interpretation, and (3) evaluate each operation sequence, to determine the relevant information on achievable quality and associated costs. The information provided by this analysis can be used not only to give feedback to the designer about problems that might arise with the machining, but also to provide information to the manufacturing engineer about alternative ways in which the part might be machined.

Keywords: manufacturing, production automation, concurrent engineering, computer-aided design, machinability evaluation, form features, tolerance, geometric reasoning.

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1 Introduction

It is becoming widely understood that decisions made during the design of a product can have significant effects on product cost, quality, and lead time. This is especially important for flexible manufacturing systems:[1] the need to respond quickly to changing demands and opportunities in the marketplace requires that new product designs be generated and analyzed quickly in order to decide how or even whether to manufacture them.

Such considerations have led to the evolution of the philosophy of *design for manufacture*, which involves identification of design elements that pose problems for manufacturing and quality control, and changing the design if possible to overcome these problems during the design stage. Although this approach is extremely attractive, there are still a number of problems in producing a large scale implementation.

One of the missing links is the virtual absence of theoretical groundwork for the generation of manufacturing alternatives. In absence of such work, most attempts to implement design for manufacture consider a single manufacturing plan (supposedly the best one), and recommend design changes based on this plan. But in general, there may be several alternative ways to manufacture a given design—and all of these alternatives should be generated and examined, to determine how well each one balances the need for a quality product against the need for efficient machining.

In this paper, we describe how to address the above task in the domain of rotational machined parts. Even in this restricted domain, the task is a difficult one. For machining purposes, the part is often considered as a collection of machinable features [3, 8], but there can be several different interpretations of the part as several different collections of machinable features. Different features require different machining steps, so different feature interpretations will yield different plans for machining the part. To evaluate how well each machining step can do at creating the corresponding feature, we must take into account the feature geometry, tolerance requirements, surface finish requirements, and statistical variations in the process capabilities.

In developing a process plan for a part, most human process planners would not consider more then two or three possible operation sequences. This is because human process planners reject many geometrically feasible interpretations up front, because of common machining practices, fixturing

[1] The term "flexible manufacturing" seems to have different meanings to different people. We use it to refer to manufacturing systems which can be reconfigured very quickly to manufacture different products, to respond quickly to changing demands.

considerations, tolerance requirement, plant facilities, etc. As a first thought, one might propose a similar architecture for an automated system. However, this is not possible at present, for three main reasons.

1. The task of generating a feature based model is very complex, and significant research is still needed to develop a general feature recognition system capable of handling all types of complex feature interactions. Integrating a vast amount of machining information into a single module would make the system difficult to develop and maintain. Moreover, changes in machining practice would require major upgrades to the system.

2. If some of the candidate interpretations are rejected in the beginning itself, one can never be sure whether they have been rejected correctly.

3. With rapidly changing products and market demands, the criteria for what is constitutes good process plan may often change. One cannot always say in advance that the fastest plan (or the least costly plan, or the one that maximizes the profit) is the best one. This eliminates the possibility of choosing a single feature interpretation up front, because this single interpretation may not lead to the best plan if the evaluation criteria change.

Thus, we instead use a generate-and-test approach, consisting of three fundamental steps:

1. Generate alternative interpretations of the design as different collections of machinable features.

2. For each interpretation, generate the various possible sequences of machining operations capable of producing that interpretation.

3. Evaluate each operation sequence, to determine whether it is capable of meeting the desired tolerance and surfaces requirements, and if so, what the associated machining costs and times will be.

This approach will produce a large number of alternative operation sequences, and then eliminate most of them based on machining considerations.

The information provided by this analysis will enable us to provide information to the manufacturing engineer about what processes and process parameters are most desirable over all feature interpretations of the design, and feedback to the designer about the machinability of the design, and how the design might be changed to improve its machinability.[2]

This paper is organized as follows. Section 2 discusses related work, and Section 3 contains basic mathematical definitions. Section 4 discusses the generation of alternative feature interpretations of a design, and Section 5 discusses the generation of alternative operation sequences from each feature interpretation. Section 6 discuss the evaluation of the tolerances and costs associated with each operation sequence. Section 7 discusses how this analysis can be used to give feedback to the designer about problems in the design, and Section 8 gives concluding remarks.

2 Related Work

Hayes [2] has built a program called Machinist, which captures some of the knowledge used by machinists during process planning. This program has the capability to identify certain kinds of feature interactions that affect how an object should be machined. Hayes defines an interaction to occur when one of the results of making one feature is to destroy one of the preconditions required in order to make another feature. The machining expertise captured by the Machinist program is very useful. However, its representation of features is not adequate for our purposes, because it does not use an unambiguous representation of solid objects. For example, if the Machinist program decides that some hole h needs to be made before some slot s, it does not recognize that this requires machining a hole of different dimensions than if h were machined after s—and yet such information may be necessary in order to know whether it is possible to machine h.

Vandenbrande [9] has developed a system that combines techniques from artificial intelligence and solid modeling. The program uses hints or clues to identify potential features in the boundary representation of the part. The system is capable of identifying interacting features (e.g., two intersecting slots). This program also produces alternative feature interpretations in certain cases. But since there is no formalization available regarding the kinds of interactions it handles, it is hard to determine what all the interpretations it produces are.

The first systematic work in the direction of generation of alternative interpretations was done by Karinthi and Nau [4]. This paper describes an approach for producing alternative interpretations of the same object as different collections of machining features as the result of algebraic operations on the features, and a system for generating alternative interpretations by performing these algebraic

[2] By the machinability of a part, we mean how easy it will be to achieve the required machining accuracy. This is somewhat broader than the usual usage of "machinability."

operations. The methodology is general enough to include practically all shapes of interest to machining, but the capabilities of the implemented system are quite limited. The system uses only a few of the features defined in the algebra, and the ones it uses do not always correspond directly to machining operations. Moreover, this program does not make use of any common machining considerations, so some of the interpretations generated by this program are not feasible from the machining point of view.

Because of the need for quality assurance on the shop floor, extensive research has been done on evaluating of machinability for a given design. Much of the data relevant for machining operation planning is available in machining data handbooks such as [5]. In addition, mechanistic models have been developed to provide quantitative mappings between machining parameters (such as cutting speed, feed, and depth of cut), to the performance measures of interest (such as surface finish and dimensional accuracy) [12]. Research on machining economics has produced quantitative models for evaluating costs related to machining operations [10]. Optimization techniques have been applied to these quantitative models to seek the machining parameters which minimize the variable cost, or maximize the production rate and profit rate associated with machining operattions.

3 Definitions

A *machined part* (or just a *part*) is the finished component to be produced as a result of a set of machining operations on a piece of *stock*, i.e., the raw material from which the part is to be machined. For example, Fig. 1 shows a piece of stock, and a part to be made from the stock by machining the surfaces H1 through H5.

We will represent both the part and the stock as geometric solids. For our purposes, a *solid* is any regular, semi-analytic set. In CAD systems, solids may be represented using any of several techniques, such as constructive solid geometry or boundary representations [7]. If R is any solid, then $b(R)$ is the *boundary* of R and $i(R)$ is the *interior* of R. Note that $R = i(R) \cup b(R)$ and that $i(R) \cap b(R) = \emptyset$. A *patch* of R is a regular, semi-analytic subset of the boundary $b(R)$.

Throughout the rest of this paper, we will let P be a solid representing a part, and S be a solid representing the stock from which P is to be made. The *delta volume* (i.e., the volume to be machined), is the solid $\Delta = S - P$. For example, in Fig. 1(b), the shaded portion of the figure is the part, and the unshaded portion is the delta volume.

A *machining feature* is the volume removed from the stock by a single machining operation. We will represent each machining feature by the solid V that corresponds to the volume of material removed. For example, in Fig. 1, we can create the surfaces H1 through H5 by making the four machinable features h_{11} through h_{41} shown in Interpretation 1 of Fig. 2.[3]

In addition to the solid representing the volume occupied by a machining feature, machining features are also characterized by properties of the surfaces that bound it. We will be interested in the following properties:

Accessibility. Let F be a feature, and p be a patch of F. If p separates air from metal, say that p is *blocked*. If p separates air from air, then we say that p is *unblocked*.

Relation to the part and the stock. A *part patch* is a patch of V that is also a portion of the part's boundary; i.e., if p is a part patch then $p \subseteq b(V)$ and $p \subseteq b(P)$. A *stock patch* is a patch of V that is also a portion of the stock's boundary; i.e., if p is a stock patch then $p \subseteq b(V)$ and $p \subseteq b(S)$. A *construction patch* is is a patch of V that is not a portion of either the part's boundary or stock's boundary; i.e., if p is a construction patch, then $p \subseteq b(V)$ and $i(p) \cap b(P) = i(p) \cap b(S) = \emptyset$.

Note that every part patch is blocked, and every stock patch is unblocked. Whether a construction patch is blocked or unblocked depends on the order in which the features are made.

In this paper, we are only considering rotational parts, so we will only consider rotational machining features. These can be defined mathematically using a cylindrical coordinate system (r, θ, z). Let f be any semi-analytic function, and let r_0, r_1, z_0, z_1 be any nonnegative numbers such that $0 < r_0 < r_1$ and $z_0 < z_1$. Then a rotational machining feature may be any of the following solids:

1. An *inner radial feature* is the set of all points (r, θ, z) such that $z_0 \leq z \leq z_1$ and $r_0 \leq r \leq f(z)$. This solid has four faces: a cylindrical face $r = r_0$, which must be unblocked; two planar faces $z = z_0$ and $z = z_1$, which need not necessarily be blocked or unblocked; and a face $r = f(z)$, which must be at least partially blocked.

   In Fig. 2, the following are inner radial features: the recesses h_{11}, h_{12}, h_{13}, and h_{14}, and the enlarged holes h_{23}, h_{24}, and h_{34}. Fig. 3 gives some other examples of inner radial features.

2. An *outer radial feature* is the set of all points (r, θ, z) such that $z_0 \leq z \leq z_1$ and $f(z) \leq r \leq r_0$. This solid has four faces: a cylindrical face $r = r_0$, which must be unblocked; two planar faces

[3] Although this is a possible way to create the surfaces, it is not a good one. The reason why we consider Interpretation 1 at all is because we generate all possible interpretations, and eliminate the undesirable ones later, based on the machining considerations described in Sections 6.1 and 6.2.

$z = z_0$ and $z = z_1$, which need not necessarily be blocked or unblocked; and a face $r = f(z)$, which must be at least partially blocked.

Fig. 2 contains no examples of outer radial features, but Fig. 4 gives some examples.

3. An *axial feature* is the set of all points (r, θ, z) such that $r_0 \leq r \leq r_1$ and $z_0 \leq z \leq f(r)$. This solid has four faces: a planar face $z = z_0$, which must be unblocked; two cylindrical faces $r = r_0$ and $r = r_1$, which must be at least partially blocked; and a face $z = f(r)$, which must be at least partially blocked.

   Fig. 2 contains no examples of axial features, but Fig. 5 gives an example.

4. A *hole* is the set of all points (r, θ, z) such that $0 \leq r \leq r_1$ and $z_0 \leq z \leq f(r)$. This solid has three faces: a planar face $z = z_0$, which must be unblocked; a cylindrical face $r = r_1$, which must be at least partially blocked; and a face $z = f(r)$, which need not necessarily be blocked or unblocked.

   In Fig. 2, h_{41}, h_{42}, h_{43}, and h_{44} are holes. Fig. 6 gives some other examples of holes.

Let P be any part and S be any stock. Then a *feature-based model* (or FBM) of P and S is any set of features M having the following properties:

1. For any two features $F_1, F_2 \in M$, $F_1 \cap F_2 = \emptyset$.

2. The union of all the features in M is the delta volume $\Delta = S - P$.

Intuitively, an FBM is an interpretation of the delta volume as a set of machining features. For example, the set $\{h_{11}, h_{21}, h_{31}, h_{41}\}$ shown in Interpretation 1 of Fig. 2 is an FBM of the part shown in Fig. 1.

An FBM M is *maximal* if every feature in M is maximal; i.e., if for every pair of features $F_1, F_2 \in M$, $F_1 \cup f_2$ is not a feature. For example, all of the features in Fig. 2 are maximal.

Two FBM's M and M' are *equivalent* if they represent the same part and stock.

Let M be an FBM, and F_1 and F_2 be any two features in M. Then it follows that $i(f_1) \cap i(f_2) = \emptyset$. We say that F_1 and F_2 are *adjacent* if $b(F_1) \cap b(F_2) \neq \emptyset$. If F_1 and F_2 are adjacent, then it follows that the patch $p = b(F_1) \cap b(F_2)$ is a construction patch.

Let F_1 and F_2 be any two adjacent features in an FBM M, and suppose there is a feature F having the following properties:

1. F_1 is a proper subset of F;

2. $F_2 - F$ is a feature or collection of features;

3. there is no feature G such that F is a proper subset of G and $F_2 - G$ is a feature or collection of features.

Then we say that F is an *extension* of F_1 into F_2. It follows from our definitions that there is at most one extension of F_1 into F_2, and that if F is this extension, then the set of features M' produced by removing F_1 and F_2 from M and replacing them with F and $F_2 - F$ is an equivalent FBM. We say that M' is a *reinterpretation* of M.

4 Generating Alternative Feature Interpretations

In this section we desribe our methodology for generating alternative feature interpretations for rotational parts.

First, we need to obtain an initial feature interpretation from the CAD model. There are three primary approaches for this task. In *human-supervised feature recognition*, a human user examines an existing CAD model to determine what the manufacturing features are [1]. In *automatic feature recognition*, the same feature recognition task is performed by a computer system [9]. In *design by features*, the designer specifies the initial CAD model in terms of various form features which translate directly into the relevant manufacturing features[8].

Let P be a part, S be a stock, and $\mathcal{M}$ be the set of all maximal FBM's for P and S. Let G be the digraph whose node set is $\mathcal{M}$ and whose edge set is

$$E = \{(M, M') | M' \text{ is a reinterpretation of } M\}.$$

We call this digraph the *interpretation space* for P and S. As an example, Fig. 2 shows the interpretation space for the part shown in Fig. 1.

By starting with a single FBM M of P and S and performing successive reinterpretations, it is possible to produce all of the maximal FBM's of P and S. Below is an algorithm that does this.

procedure FIND-MAXIMAL-MODELS(M):

OPEN := $\{M\}$

CLOSED := $\emptyset$

while OPEN $\neq \emptyset$ do

let M be any model in OPEN

for every pair of features F_1 and F_2 in M

if F_1 is extendable into F_2 then

let F be the extension of F_1 into F_2

let M' be the model produced by removing F_1 and F_2

from M, and replacing them with F and $F_2 - F$

if M' is not in OPEN or CLOSED then insert M' into OPEN

remove M from OPEN and insert it into CLOSED

end

return CLOSED

Most of the FBM's of interest for machining purposes are maximal, but not all of them. In particular, suppose a model contains a through hole. Normally, we would make the hole in a single machining operation, as shown in Fig. 7(a). However, if the hole is too long to be machined in this way, it may be necessary to make it using two machining operations, as shown in Fig. 7(b). Thus, if the part P contains a through hole, then each maximal model of P corresponds to two or more non-maximal models. For example, Fig. 8 shows some of the non-maximal models that can be obtained from the fourth interpretation shown in Fig. 2.

Given a maximal model M of a part that contains a through hole, the following procedure will produce all of the non-maximal models corresponding to M.

procedure FIND-MODELS(M):

MODELS := $\{M\}$

if M contains a through hole h then

for every possible way to split h into holes h_1 and h_2 do

insert $(M - \{h\}) \cup \{h_1, h_2\}$ into MODELS

end

return MODELS

5 Generating Operation Sequences

This section describes our approach for generating alternative operation sequences for each feature interpretation of a part.

Due to accessibility [6] and setup constraints [2], the set of features that comprise an object cannot necessarily be machined in any arbitrary sequence. Instead, these constraints will require that some features be machined before or after other features. However, for a given set of features, usually there will be more than one order in which the features can be machined.

As an example, consider Interpretation 4 of Fig. 2. In this interpretation, h_{14}, h_{24}, and h_{34} must all be made after the hole h_{44}. However, once we have made h_{44}, we can make h_{14}, h_{24}, and h_{34} in any order. Thus, there are six possible orderings for h_{14}, h_{24}, and h_{34}, so Interpretation 4 corresponds to six possible orders in which to make the features.

Let M be an FBM and F be any feature in M, and suppose that F has no stock faces. Then F cannot be machined at all unless it has at least one construction face. For every construction face f of F, there are two possible cases:

1. f is also a subface of some other feature F'. Then F will be accessible once F' has been created, so it will be possible to machine F any time after F' has been machined.

2. f can be partitioned into subfaces f_1 and f_2 that are subfaces of some other features F_1' and F_2', respectively. (The only way this can happen is if F_1' and F_2' were created by splitting a through hole, as described in Section 4.) This means that f will be accessible once F_1' and F_2' have been created, so it will be possible to machine F any time after both F_1' and F_2' have been machined.

The *time-order graph* for M is the hypergraph (M, A), where A is the set containing all hyperarcs $(\{F'\}, F)$ such that F and F' satisfy Case 1 above, and all hyperarcs $(\{F_1', F_2'\}, F)$ such that F, F_1', and F_2' satisfy Case 2 above. The time-order graph for M represents all possible time orderings in which the features might be machined.

As an example, Fig. 9a gives the time-order graphs for Interpretation 4 of Fig. 2. There are six time orderings consistent with this graph:

Time Order 4.1: $h_{44} \Rightarrow h_{14} \Rightarrow h_{24} \Rightarrow h_{34}$;

Time Order 4.2: $h_{44} \Rightarrow h_{14} \Rightarrow h_{34} \Rightarrow h_{24}$;

Time Order 4.3: $h_{44} \Rightarrow h_{24} \Rightarrow h_{14} \Rightarrow h_{34}$;

Time Order 4.4: $h_{44} \Rightarrow h_{24} \Rightarrow h_{34} \Rightarrow h_{14}$;

Time Order 4.5: $h_{44} \Rightarrow h_{34} \Rightarrow h_{14} \Rightarrow h_{24}$;

Time Order 4.6: $h_{44} \Rightarrow h_{34} \Rightarrow h_{24} \Rightarrow h_{14}$.

Fig. 9b gives the time-order graphs for Interpretation 5 of Fig. 8. There are eight time orderings consistent with this graph:

Time Order 5.1: $h_{55} \Rightarrow h_{25} \Rightarrow h_{45} \Rightarrow h_{35} \Rightarrow h_{15}$;

Time Order 5.2: $h_{55} \Rightarrow h_{25} \Rightarrow h_{45} \Rightarrow h_{15} \Rightarrow h_{35}$;

Time Order 5.3: $h_{55} \Rightarrow h_{45} \Rightarrow h_{25} \Rightarrow h_{35} \Rightarrow h_{15}$;

Time Order 5.4: $h_{55} \Rightarrow h_{45} \Rightarrow h_{25} \Rightarrow h_{15} \Rightarrow h_{35}$;

Time Order 5.5: $h_{55} \Rightarrow h_{45} \Rightarrow h_{35} \Rightarrow h_{25} \Rightarrow h_{15}$;

Time Order 5.6: $h_{55} \Rightarrow h_{45} \Rightarrow h_{35} \Rightarrow h_{15} \Rightarrow h_{25}$;

Time Order 5.7: $h_{45} \Rightarrow h_{35} \Rightarrow h_{55} \Rightarrow h_{25} \Rightarrow h_{15}$;

Time Order 5.8: $h_{45} \Rightarrow h_{35} \Rightarrow h_{55} \Rightarrow h_{15} \Rightarrow h_{25}$.

Given a time order graph of an FBM, the following nondeterministic procedure (which can be implemented deterministically as a backtracking procedure) will generate all possible time orderings consistent with the time-order graph. In this procedure, the in-degree of a feature $F \in M$ is the number of hyperarcs $(P, Q) \in A$ such that $Q = F$.

```
procedure FIND-TIME-ORDERINGS(M, A):
    SEQUENCE := NIL
    OPEN := {all features in M whose in-degree is 0}
    while OPEN ≠ ∅ do
        nondeterministically choose a feature F in OPEN
        remove F from OPEN, and append it to the end of SEQUENCE
        for every hyperarc (P, G) ∈ A such that every feature in P is also in SEQUENCE do
            insert G into OPEN
            remove from A all hyperarcs (Q, H) such that H = G
        end
    end
    return SEQUENCE
```

If each feature could be created in a single machining operation, then FIND-TIME-ORDERINGS(M, A) would provide us with all possible orderings for these operations. However, in order to create a feature, sometimes we will need not just one machining operation, but several: a *roughing* operation followed by one or more *finishing* operations. In this case, the time-order graph only gives us the precedence constraints for the roughing operations. For example, here is one possible sequence of roughing operations corresponding to Time Order 4.3 above:

drill $h_{44} \Rightarrow$ drill $h_{24} \Rightarrow$ bore $h_{14} \Rightarrow$ bore h_{34}.

Similarly, here is one possible sequence of roughing operations corresponding to Time Order 5.1 above:

drill $h_{55} \Rightarrow$ drill $h_{25} \Rightarrow$ drill $h_{45} \Rightarrow$ drill $h_{35} \Rightarrow$ bore h_{15}.

For the finishing operations, the constraints given in the time-order graph do not apply; the constraints on the finishing instead involve the nature of the machining operations themselves, such as how the part will be fixtured (i.e., held in place) during each operation, how many setups (i.e., changes of fixturing) will be needed, etc.). A discussion of these issues is beyond the scope of this paper—but as an example, here is one way to augment the above two sequences of roughing operations, to include finishing operations as well:

Operation Sequence 1:
drill $h_{44} \Rightarrow$ drill $h_{24} \Rightarrow$ bore $h_{24} \Rightarrow$ bore $h_{44} \Rightarrow$ bore $h_{14} \Rightarrow$ bore h_{34}.

Operation Sequence 2:
drill $h_{55} \Rightarrow$ drill $h_{25} \Rightarrow$ change setup $\Rightarrow$ bore $h_{25} \Rightarrow$ drill $h_{45} \Rightarrow$ drill $h_{35} \Rightarrow$ bore $h_{35} \Rightarrow$ bore h_{15}.

These two operation sequences are illustrated in Figs. 10 and 11, respectively.

6 Machinability Evaluation

Below, we discuss how to estimate the costs incurred by the machining operations, and the tolerances produced by these operations.

6.1 Estimating the Achievable Tolerance

Each machining operation creates a feature which has certain geometric variations compared to its nominal geometry. Designers normally give tolerance specifications on the nominal geometry, to specify how large these variations are allowed to be.

Given a candidate operation sequence, the machining data for that sequence, the feature's dimensions, and the material from which the part is to be made, we want to evaluate whether or not it can satisfactorily achieve the tolerance specifications. The capabilities of the machining process depend on the following factors:

1. The machining system parameters, such as the feed rate, cutting speed, depth of cut, and structural dynamics. Their effects on the process capabilities can be modeled and evaluated deterministically [5, 6].

2. The natural and external variations in the machining process. For example, variations in hardness in the material being machined cause random vibration, which is one of the major factors affecting the surface quality. Such variations are unavoidable in practice, and are best dealt with statistically. [11, 12, 6].

Methodology to compute the achievable tolerance is described in detail in [6]. Some of the more important formulas from [12, 6] are reproduced in Appendix A.

6.2 Estimating the Costs

The total cost of a machining operation consists of two components, the fixed cost and the variable cost. Both of these costs serve as a basis for the economics of machining operation planning. The fixed cost mainly consists of depreciation of machining equipment, maintenance disbursements, and administrative expenses. The variable cost consists of the costs which vary in accordance with the level of production activity. Typical examples of variable cost would be the cost related to the machining activities, tooling, and auxiliary activities. Note that the fixed cost is the part of the total cost which remains at a constant level even when different operation sequences are used.

Extensive research has been reported dealing with estimating the costs for the machining operations; we discuss the details in [10, 6]. Some of the more important formulas from[10, 6] are reproduced in Appendix B.

6.3 Examples

In the part shown in Fig. 1, suppose that the dimensions are as follows: $D_1 = 40$, $D_2 = 60$, $D_3 = 60$, $L_1 = 30$, $L_2 = 40$, and $L_3 = 80$. In Section 5, we presented two possible operation sequences for making this part:

Operation Sequence 1:
drill h_{44} $\Rightarrow$ drill h_{24} $\Rightarrow$ bore h_{24} $\Rightarrow$ bore h_{44} $\Rightarrow$ bore h_{14} $\Rightarrow$ bore h_{34}.

Operation Sequence 2:
drill h_{55} $\Rightarrow$ drill h_{25} $\Rightarrow$ change setup $\Rightarrow$ bore h_{25} $\Rightarrow$ drill h_{45} $\Rightarrow$ drill h_{35} $\Rightarrow$ bore h_{35} $\Rightarrow$ bore h_{15}.

Figs. 10 and 11, respectively, give graphical representations of Operation Sequences 1 and 2, and the machining tolerances produced by each step in these sequences.

Calculation of Machining Tolerances Below, we illustrate how these machining tolerances were calculated (using the formulas from Appendix A) for some of the steps of Operation Sequence 1.

For drilling h_{44}, it follows from Eqs. 2 and 3 that the upper and lower limits on the achievable tolerance for H1 are

$$\begin{aligned} \text{upper limit} &= \text{incremental increase} + \Delta d_{max} \times \text{MF1} \times \text{MF2} \\ &= 0.20 + 0.25 \times 0.8 \times 1.0 \\ &= 0.40 \quad \text{(mm)} \end{aligned}$$

and

$$\begin{aligned} \text{lower limit} &= \frac{L - L_1}{L} \Delta d_{max} \\ &= \frac{260 - 230}{260} \times 0.25 \\ &= 0.03 \quad \text{(mm)} \end{aligned}$$

It should be pointed out that the achievable tolerance for H1 is

$$\text{upper limit} - \text{lower limit} = 0.40\text{mm} - 0.03\text{mm} = 0.37\text{mm}.$$

In the second operation (drilling h_{24}), it follows from Eqs. 2 and 3 that the achievable tolerance is $[0.22, 0.00]$. This achievable tolerance is tighter than that in the first operation, due the higher rigidity of the drill.

The concentricity error is calculated from the first term in Eq. 4, resulting in a concentricity error value of 0.08. The second term of the equation is considered to be zero since the workpiece (i.e., the partially machined part) remains at an identical position during the two drilling operations.

Calculation of Machining Costs Table 1 presents the cost data for Operation Sequence 2, as calculated using the formulas from Appendix B. Each row lists the estimated cost components for individual machining operation. By summing up the seven individual production costs, the total production cost associated with this process plan is \$36.18 as indicated in Table 1. By examining the production costs associated with the two operations of drilling H1 and H2, they are listed as \$6.54 and \$7.87, or a combined cost of \$14.41.

Table 1: Cost Analysis of the Machining Operations

Machining op.	Spindle speed (rpm)	Feed (mm/rev)	Machining time (min)	Aux. time (min)	Machining cost	Tooling cost	Aux. cost	Tot. cost	Fixed cost	Production cost
drill H1	250	0.30	3.46	3	$1.73	$2.31	$1.50	$5.54	$1.00	$6.54
drill H4	200	0.15	1.00	3	0.50	1.40	1.50	3.40	1.00	4.40
bore H4	400	0.10	0.75	3	0.60	1.29	2.40	4.29	2.00	6.29
drill H2	250	0.30	4.60	3	2.30	3.07	1.50	6.87	1.00	7.87
drill H5	200	0.15	1.00	3	0.50	1.40	1.50	3.40	1.00	4.40
bore H5	400	0.10	0.75	3	0.60	1.29	2.40	4.29	2.00	6.29
bore H3	400	0.10	1.00	3	0.80	1.72	2.40	4.92	2.00	6.92
									Total Cost:	$36.18

Tradeoffs From the above calculations, it is clear that which of the two operation sequences is preferable will depend on the machining tolerances and cost objectives.

In Operation Sequence 1, h_{14} through h_{44} will be made in one setup as shown in Fig. 10, offering an opportunity to achieve high machining accuracy. Thus, this operation sequence will be preferable when the specifications of the tolerances of the two holes and the concentricity between them are tight. It is a common practice to apply drilling operations for making holes and to apply boring operations to enlarge the drilled holes for tight tolerance and concentricity control.

To achieve its high degree of dimensional accuracy and concentricity, Operation Sequence 1 requires one more boring process than Operation Sequence 2. This boring process would result in a much higher cost than Operation Sequence 2's combined cost of $14.41. Consequently, a higher production cost can be expected in Operation Sequence 1 than in Operation Sequence 2. When the concentricity tolerance between H4 and H5 is not tight, the main objective in process planning may be to achieve a low cost while maintaining an acceptable machining accuracy. Under such circumstances, Operation Sequence 2 may be used to machine the part.

7 Identifying Problems in the Design

The analysis described in the previous sections will enable us to provide feedback to the designer, by generating and examining the alternative ways in which the proposed design might be machined, and identifying what problems will arise with the machining. By comparing the tolerances achievable by various machining operations with the designer's tolerance requirements, we should be able to discover cases in which the design cannot be made without specialized (and thus expensive) machining processes and fixtures. In this case, we can give the designer the option of leaving the design unchanged (and thus incurring a high machining cost), or else making possible changes to the design in order to make it easier (or even feasible) to machine.

For example, in the part shown in Fig. 1, consider the problem of making the surfaces H1 and H2. As we have seen in Figs. 2 and 8, there are many interpretations for the part; but we can divide them into classes: (1) interpretations in which H1 and H2 are made as part of a single long hole, and (2) interpretations in which H1 H2 are made as two shorter holes. Suppose that our analysis tells us that:

- in case (1) above, the hole is too long to be made in an inexpensive drilling operation such as twist-drilling.
- in case (2) above, we cannot meet the required concentricity tolerance on H1 and H2 by using an inexpensive way to hold the part (such as a three-jaw chuck).

Then there are two alternatives:

1. Use specialized production facilities. In particular, we can use a specialized machining operation such as gundrilling in case (1), or use special fixturing to hold the workpiece during the machining of the second hole in case (2).
2. Modify the design, if the designer can do so without affecting its functionality. The most obvious change would be to loosen the concentricity tolerance on H1 and H2. However, other modifications would also work. For example, the designer might consider reducing the length l enough that the hole in case (1) could be made using an inexpensive operation such as twist-drilling, or tightening the tolerance on the diameter D to increase the accuracy with which the workpiece can be held in a three-jaw chuck.

Note that if we had not considered alternative interpretations of the part, we would not have been able to do as good an analysis. For example, if we had only considered Interpretation 4 (in which which H1 and H2 are made as part of a single long hole), we would have erroneously concluded that the only options were either to use a specialized machining operation such as gundrilling, or else reduce the length l.

As another example, suppose that in the part shown in Fig. 1, the diameter D_2 is more than twice the diameter D_1. Then the surface H1 cannot be machined, because no boring bar capable of fitting within the diameter D_1 can be large enough to machine a surface of diameter D_2. In this case, the only option is for the designer either to increase D_1 or to reduce D_2.

8 Conclusions

We have presented a new approach for evaluating machinability of a machined part during design stage of the product development cycle, so that problems related to manufacturing can be recognized and corrected while the product is being designed. Our basic approach is to perform a systematic evaluation of machining alternatives throughout each step in the design stage.

We have described the details of our approach, and have also presented a case study to demonstrate how our approach can be used to suggest design changes to mitigate the deleterious effects introduced by inappropriate parameter designs.

Such an analysis can be useful in two ways:

1. to provide feedback to the designer about the machinability of the design, so the designer can modify the design if necessary to balance the need for efficient machining against the need for a quality product;

2. to provide information to the manufacturing engineer about alternative ways in which the part might be machined, for use in developing process planning alternatives depending on machine tool availability.

We anticipate that the results of our work will be useful in providing a way to evaluate new product designs quickly in order to decide how or whether to manufacture them. Such a capability will be especially useful in flexible manufacturing systems, which need to respond quickly to changing demands and opportunities in the marketplace.

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A Formulas for Estimating the Achievable Tolerances

A.1 Drilling

Achievable Dimensional Tolerance. Let the hole diameter be expressed as:

$$\text{Drill Size}\ {}^{+\text{upper limit}}_{+\text{lower limit}} \tag{1}$$

Suppose the hole is drilled from right to left, as shown in Fig. 12. Then there are three cases.

Table 2: Estimating the Incremental Increases during Drilling

Drill Diameter (mm)	Hardness of Workpiece Material (BHN)	Incremental Increase
1.0 to 5.0	100	0.05 - 0.10
1.0 to 5.0	300	0.05 - 0.20
5.0 to 20	100	0.08 - 0.15
5.0 to 20	300	0.15 - 0.25
20 to 60	100	0.12 - 0.30
20 to 60	300	0.20 - 0.35

For a complete hole, the tolerances are

$$\text{upper limit} = \begin{cases} I + \Delta d_{max} \times \mathrm{MF1} \times \mathrm{MF2} & \text{for a complete hole} \\ I + \Delta d_{max} \times \mathrm{MF1} \times \mathrm{MF2} & \text{if the right side is later removed} \\ I + [\frac{L_1}{L} \Delta d_{max}] \times \mathrm{MF1} \times \mathrm{MF2} & \text{if the left side is later removed} \end{cases} \quad (2)$$

$$\text{lower limit} = \begin{cases} 0.0 & \text{for a complete hole} \\ \frac{L-L_1}{L} \Delta d_{max} & \text{if the right side is later removed} \\ 0.0 & \text{if the left side is later removed} \end{cases} \quad (3)$$

In the above equation, I is the *incremental increase*, i.e., the difference between the hole's diameter and the drill's diameter. Table 2 lists some of the typical values used for I on the shop floor. Δd_{max} is the maximum error caused by deflection during the drilling process. MF1 is a modification factor to account for machine tool precision. MF2 is a modification factor to account for machining parameters such as spindle speed and feed rate (for example, a high spindle speed increases the runout error, and drilling at a large feed rate leaves large feed marks on the drilled surface). L is the length of the complete hole, and L_1 is the length of the portion of the hole that remains if part of it is later removed.

Fig. 13 shows a decision tree for determining Δd_{max}, MF1, and MF2. For example, if the operation is to be performed on a lathe, a value of 0.8 will be used for MF1, since a lathe is considered to be a high-precision machine tool (compared to, say, a drill press).

Achievable Concentricity Tolerance. We use the following formula to calculate the concentricity error between two drilled holes H_1 and H_2:

$$\text{concentricity error} = \frac{\frac{1}{2}(\Delta d_{max} + \Delta d_{min})_{H1} + \frac{1}{2}(\Delta d_{max} + \Delta d_{min})_{H4}}{2} \times \mathrm{MF1} \times \mathrm{MF2} + \text{errors due to multiple setups} \quad (4)$$

In the above equation, Δd_{max}, MF1, and MF2 are as before, and Δd_{min} is the minimum error caused by deflection during the drilling process.

A.2 Boring

Achievable Dimensional Tolerance. We calculate the dimensional tolerance that can be achieved by boring using the following formulas:

Let the hole diameter be expressed as:

$$\text{Boring Dia} \begin{smallmatrix} +\text{upper limit} \\ +\text{lower limit} \end{smallmatrix} \tag{5}$$

For the first pass:

$$\text{upper limit} = \Delta B \times \text{MF1} \times \text{MF2} \times \text{MF3} \tag{6}$$

$$\text{lower limit} = 0.0 \tag{7}$$

For the second pass:

$$\text{upper limit} = [\Delta B \times \text{MF1} \times \text{MF2} \times \text{MF3}] \times 0.5 \tag{8}$$

$$\text{lower limit} = 0.0 \tag{9}$$

In Eqs. 6 and 8, ΔB represents a nominal value of the machining error, and the MF's are modification factors to account for the machine tool accuracy, rigidity of the workpiece-boring bar combination, and machining parameters. In Eq. 8, the proportionality coefficient of 0.5 is used to indicate that the tolerance achievable during a finish cut is higher than the tolerance achievable during a rough or semi-finish cut.

Fig. 14 presents the basic structure of a decision tree for determining ΔB, MF1, MF2, and MF3 under various machining conditions.

Achievable Concentricity Tolerance. As a semi-finishing or finishing operation, the boring process significantly reduces the concentricity error resulting from the drilling operation. We use the following formulas to calculate the concentricity error between two bored holes H_1 and H_2.

For the first pass:

$$\begin{aligned}\text{concentricity error} &= \frac{1}{2}(\Delta B_{H1} + \Delta B_{H2}) \times \text{MF1} \times \text{MF2} \\ &\quad + \text{errors due multiple setups}\end{aligned} \tag{10}$$

For the second pass:

$$\begin{aligned}\text{concentricity error} &= [\frac{1}{2}(\Delta B_{H1} + \Delta B_{H2}) \times \text{MF1} \times \text{MF2} \times \text{MF3}] \times 0.5 \\ &\quad + \text{errors due to multiple setups}\end{aligned} \tag{11}$$

In the above equations, ΔB_{H1} and ΔB_{H2} are the values of ΔB for the holes H1 and H2, respectively.

B Formulas for Cost Estimation

$$\text{machining cost} = (\text{wage rate} + \text{overhead}) \times \text{machining time} \tag{12}$$

For drilling operations,

$$\text{machining time} = \frac{\text{travel distance}}{\text{spindle speed} \times \text{feed}} \quad (\text{min}) \tag{13}$$

For boring operations,

$$\text{machining time} = \frac{\pi(D_f + D_i)}{2} \frac{\text{travel distance}}{\text{feed}} \frac{1}{\text{Cutting Speed}} \times (\text{number of passes}) \tag{14}$$

where D_f and D_i are the diameters in mm before and after machining. The cutting speed is calculated from $\pi \times D \times$ spindle speed. The units of feed and cutting speed are mm/rev and mm/min, respectively.

$$\text{tooling cost} = \frac{\text{machining time}}{\text{tool life}} [\text{tool cost} + (\text{tool changing time})(\text{wage rate} + \text{overhead})] \tag{15}$$

$$\text{tool life} = (\frac{\text{referenced cutting speed}}{\text{selected cutting speed}})^{1/n} \times \text{referenced tool life} \tag{16}$$

where n is the tool life exponent.

$$\text{Production Cost} = \text{machining cost} + \text{tooling cost} + \text{auxiliary cost} + \text{Fixed Cost} \tag{17}$$

where the fixed cost is assumed to be constant, and

$$\text{auxiliary cost} = (\text{wage rate} + \text{overhead})(\text{auxiliary time}) \tag{18}$$

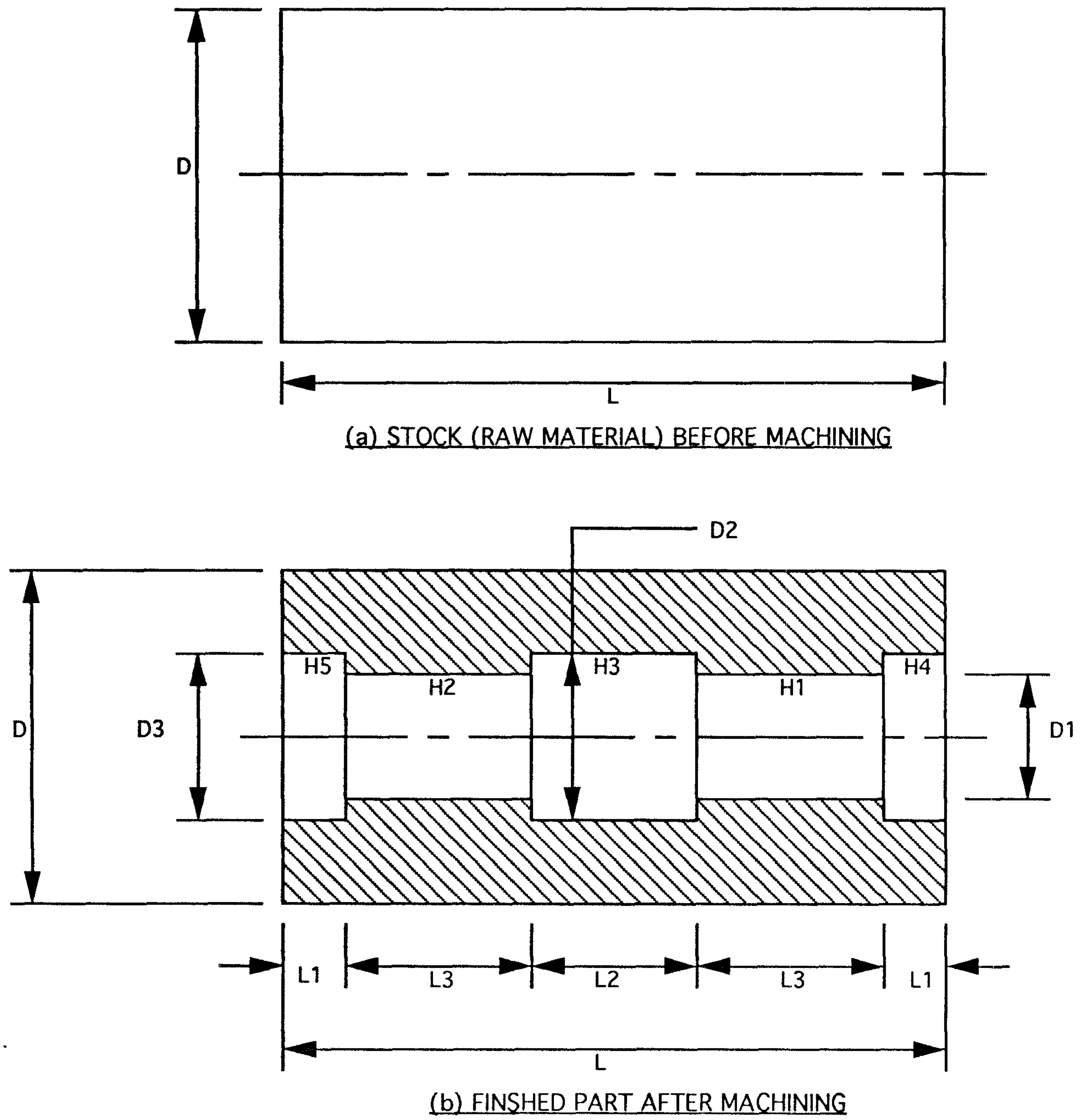
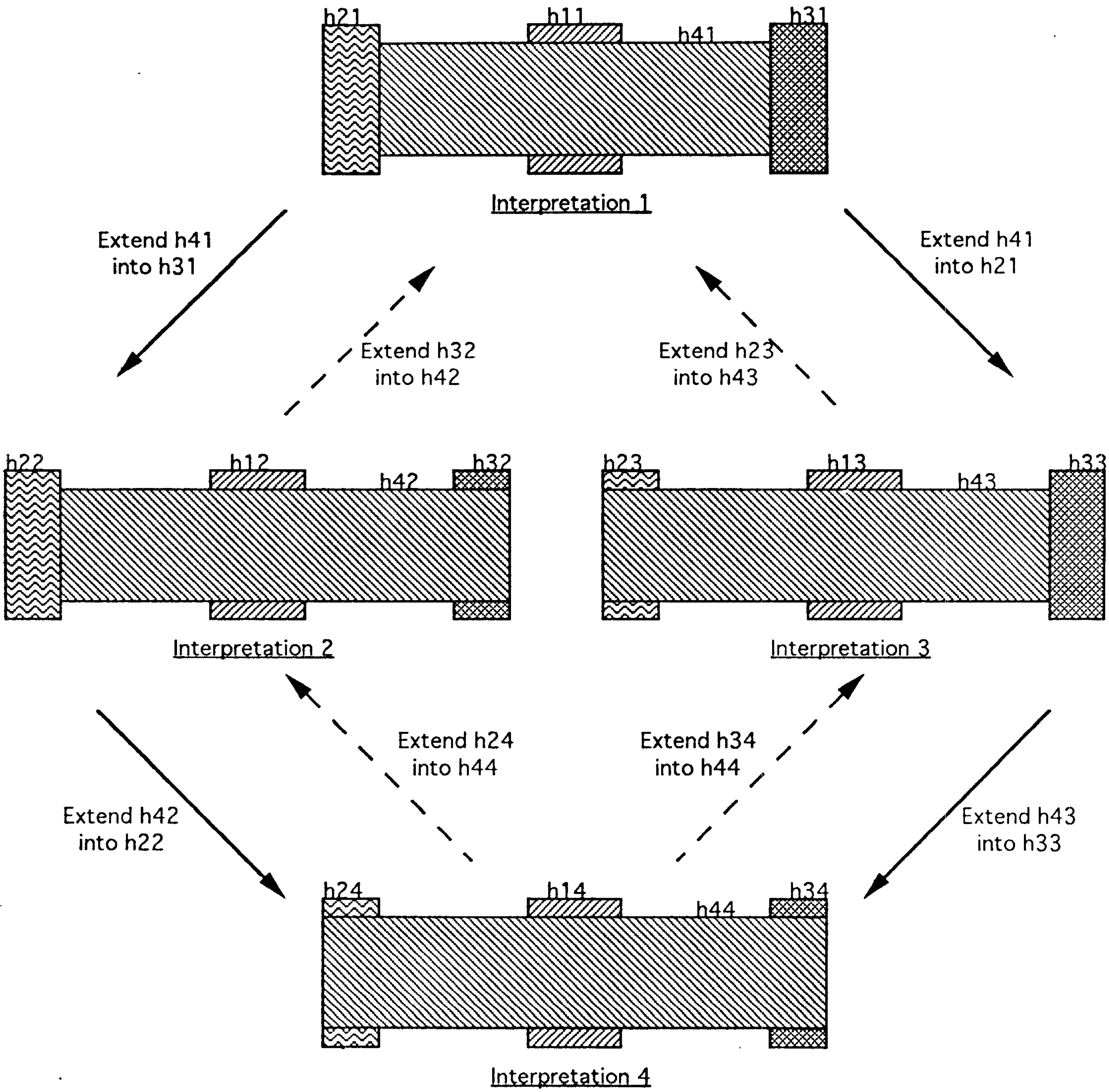
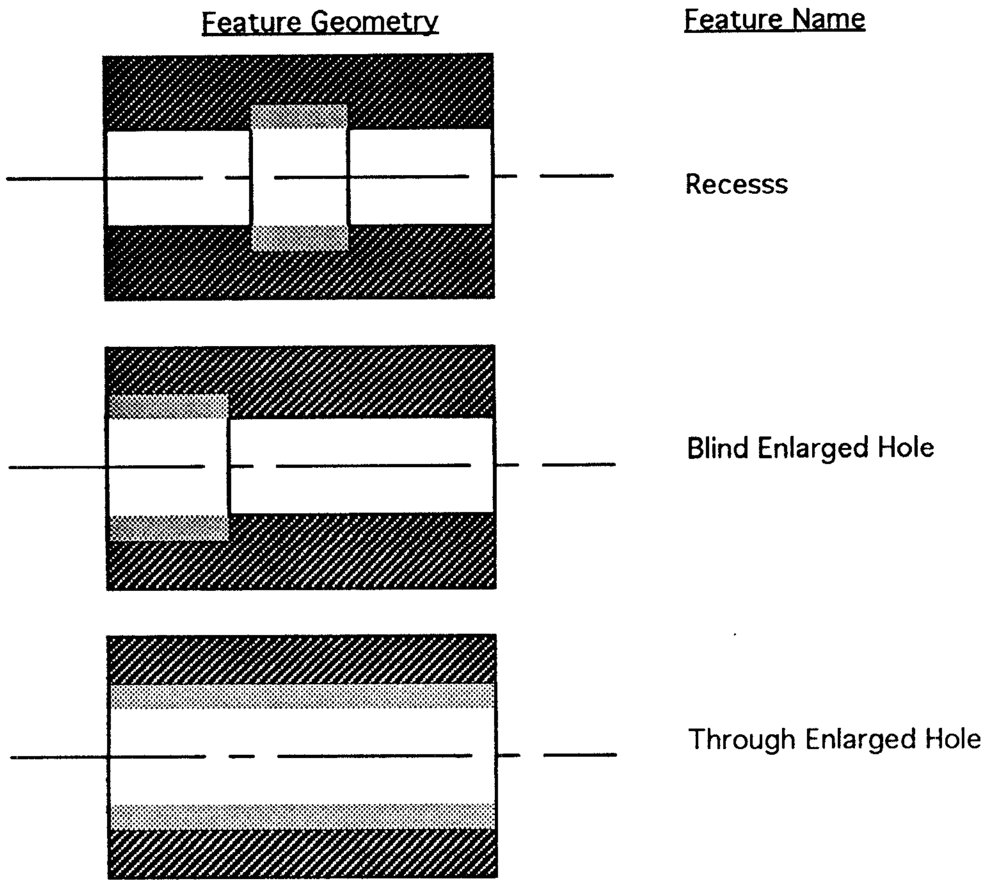

D
L
(a) STOCK (RAW MATERIAL) BEFORE MACHINING
D2
H5
H3
H4
H2
H1
D
D3
D1
L1
L3
L2
L3
L1
L
(b) FINSHED PART AFTER MACHINING

Fig. 1



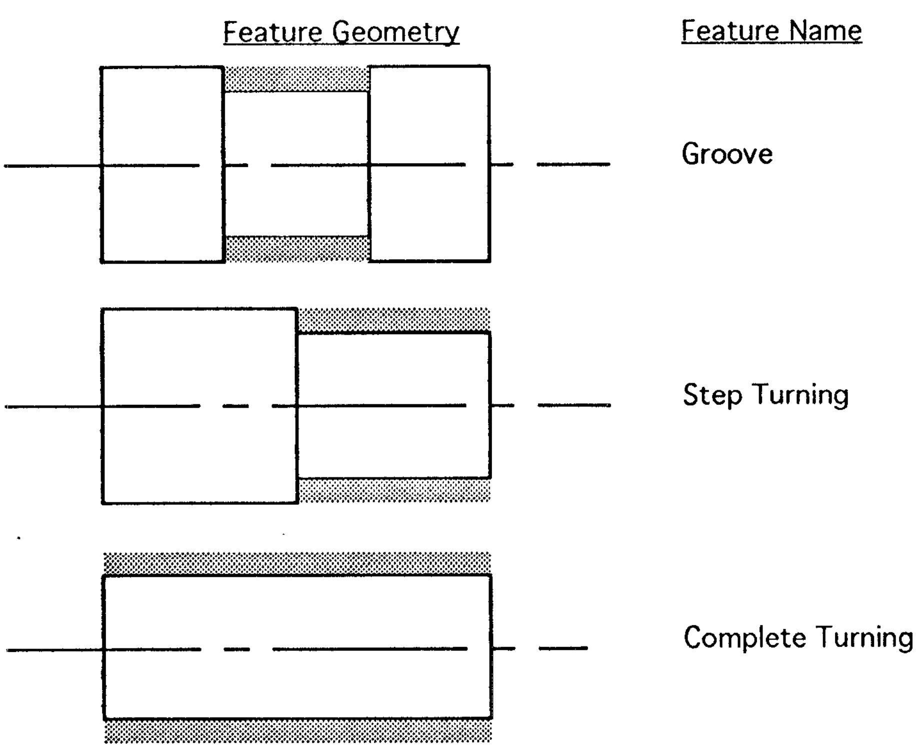
Alternative interpretations of the part shown in
Fig. 1 as different collections of machining features

Fig. 2



Inner Radial Features

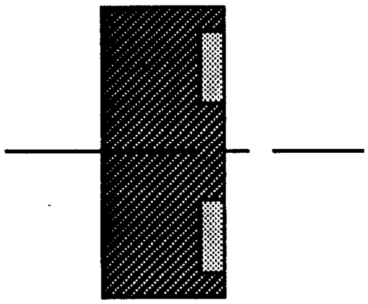
Fig. 3



Outer Radial Features

Fig. 4

Feature Geometry | Feature Name

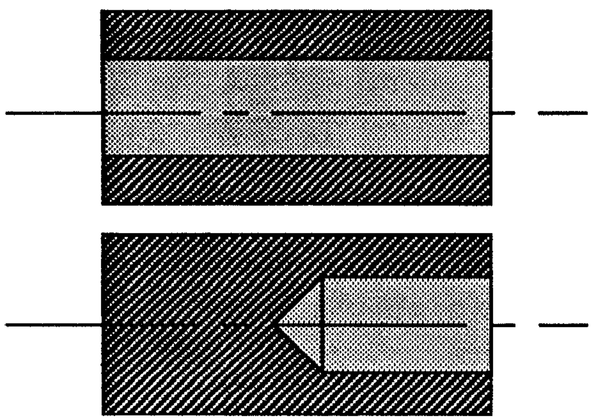


Axial Groove

Axial Feature

Fig. 5

Feature Geometry | Feature Name

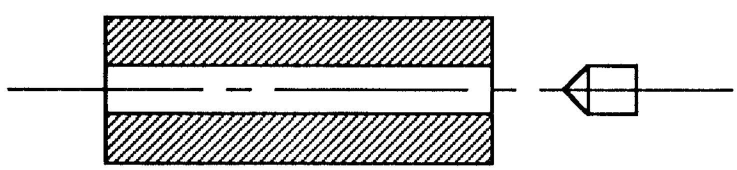


Through Hole

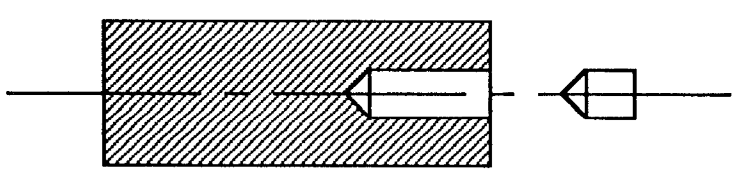
Blind Hole

Hole Features

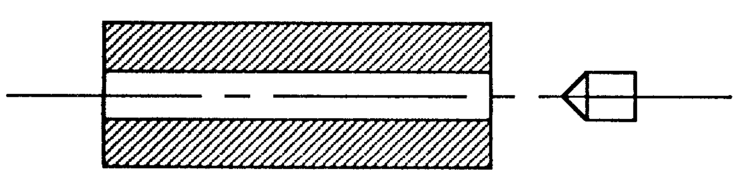
Fig. 6



(a) Drilling the complete hole from one side



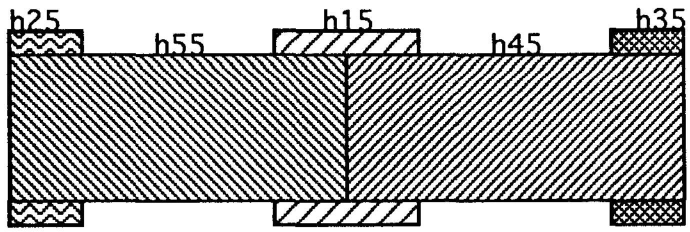
1. Drilling part of the hole from one side



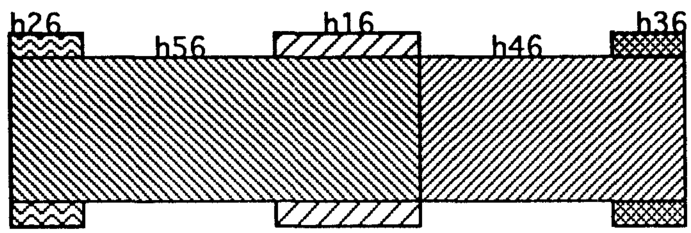
2. Drilling the rest of the hole from the other side

(b) Drilling the hole from both sides

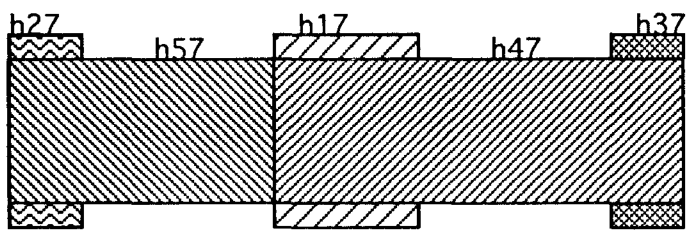
Fig. 7



Interpretation 5



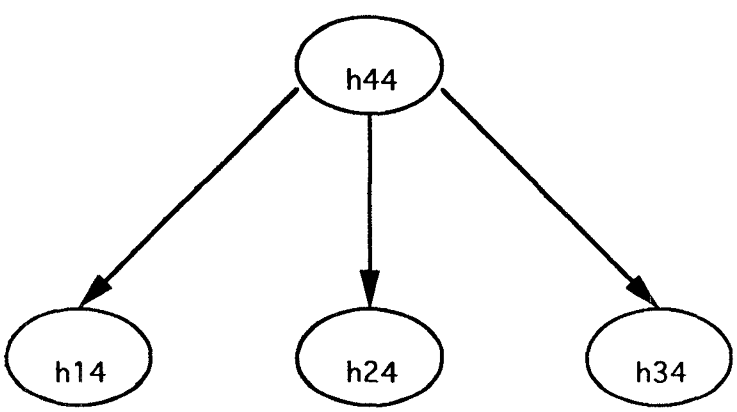
Interpretation 6



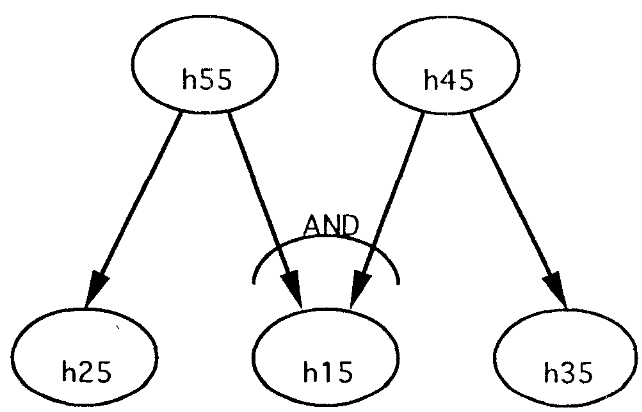
Interpretation 7

Some of the non-maximal models that can be obtained from the interpretation 4, shown in Fig. 2

Fig. 8



(a) Time Order Graph for Interpretation 4



(b) Time Order Graph for Interpretation 5

Fig. 9

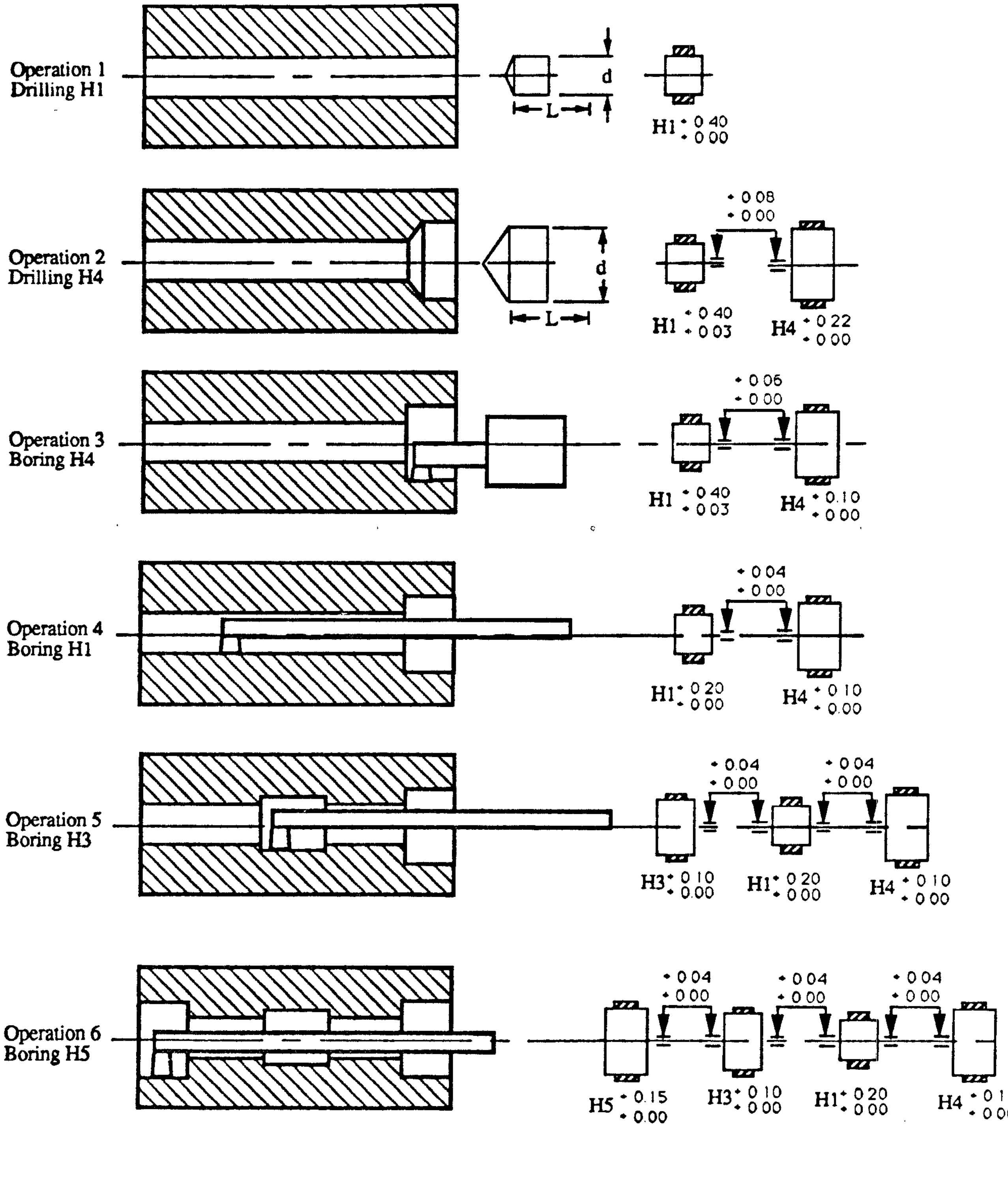


Fig. 10 Operation Sequence 1

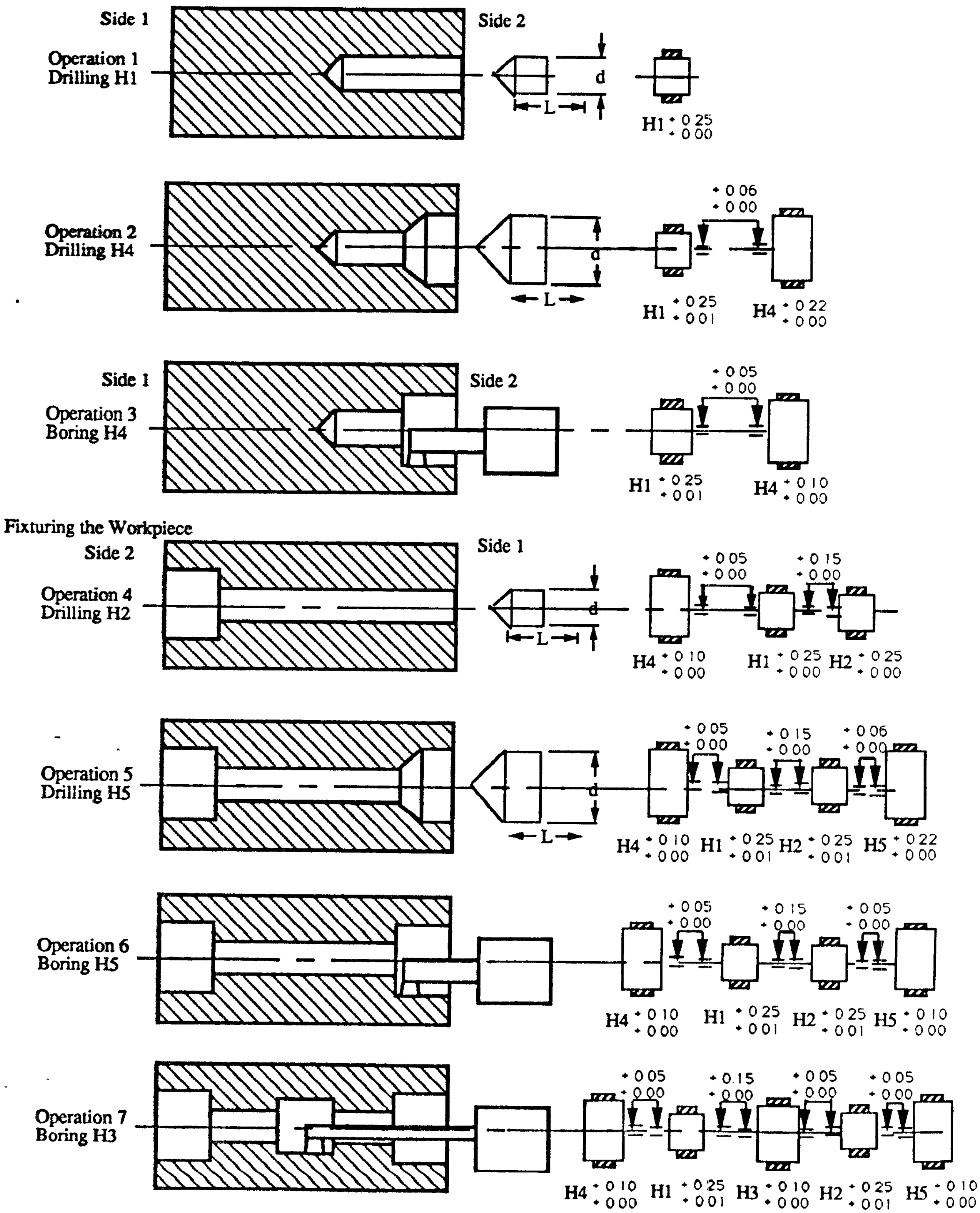


Fig. 11 Operation Sequence 2

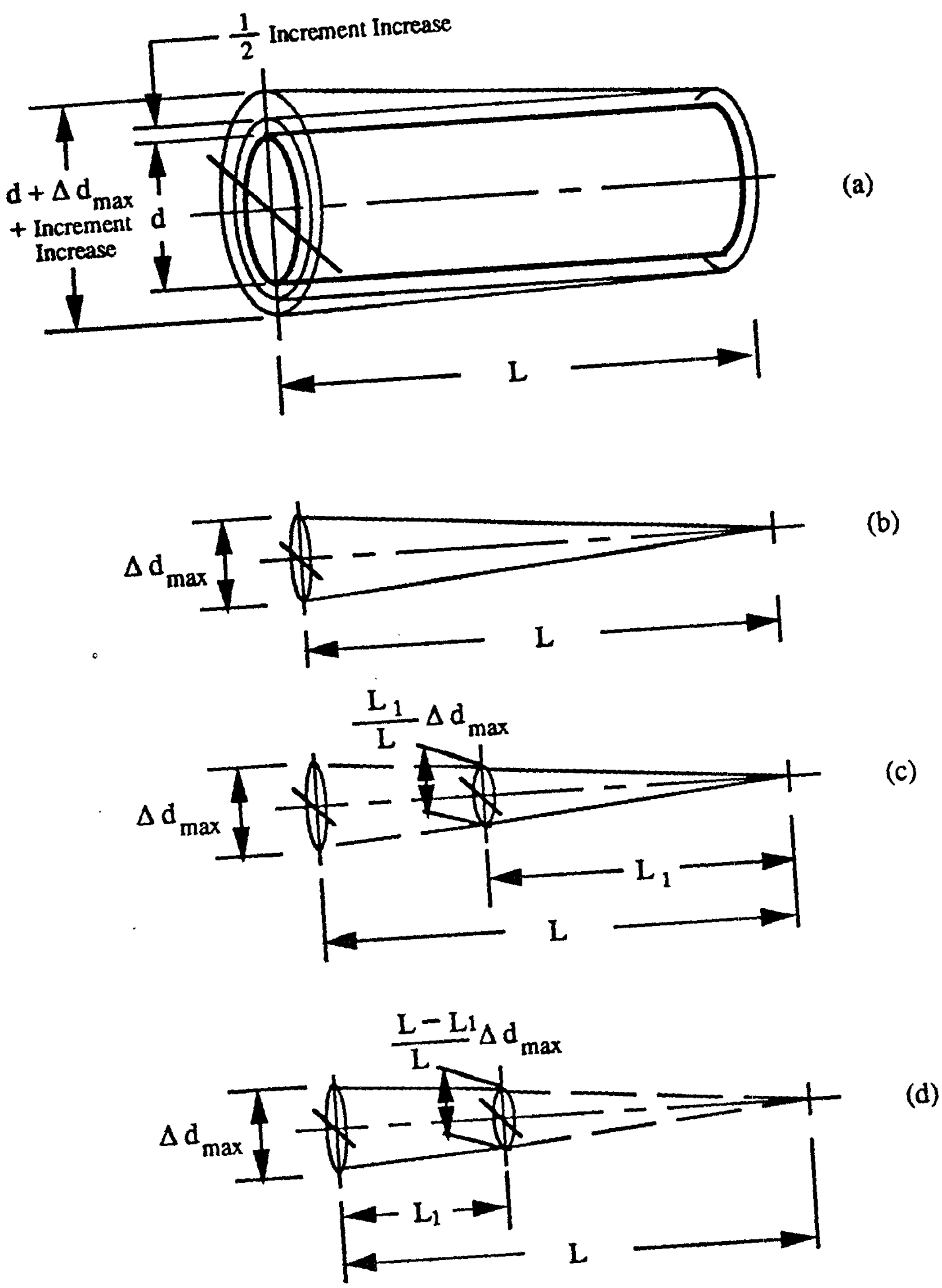


Fig. 12 Analysis of Machining Errors during Drilling Operations

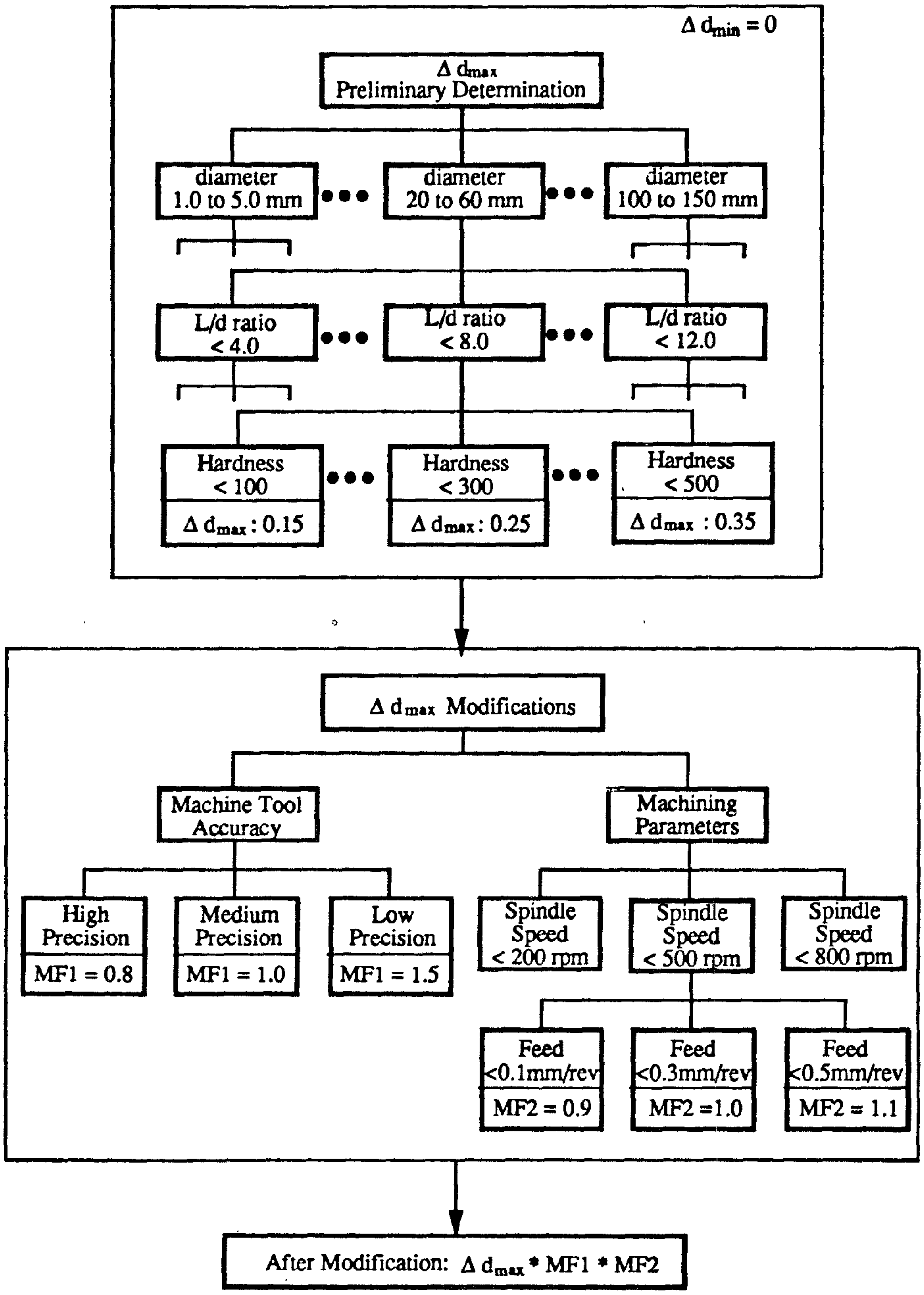


Fig. 13 Decision Tree for Drilling

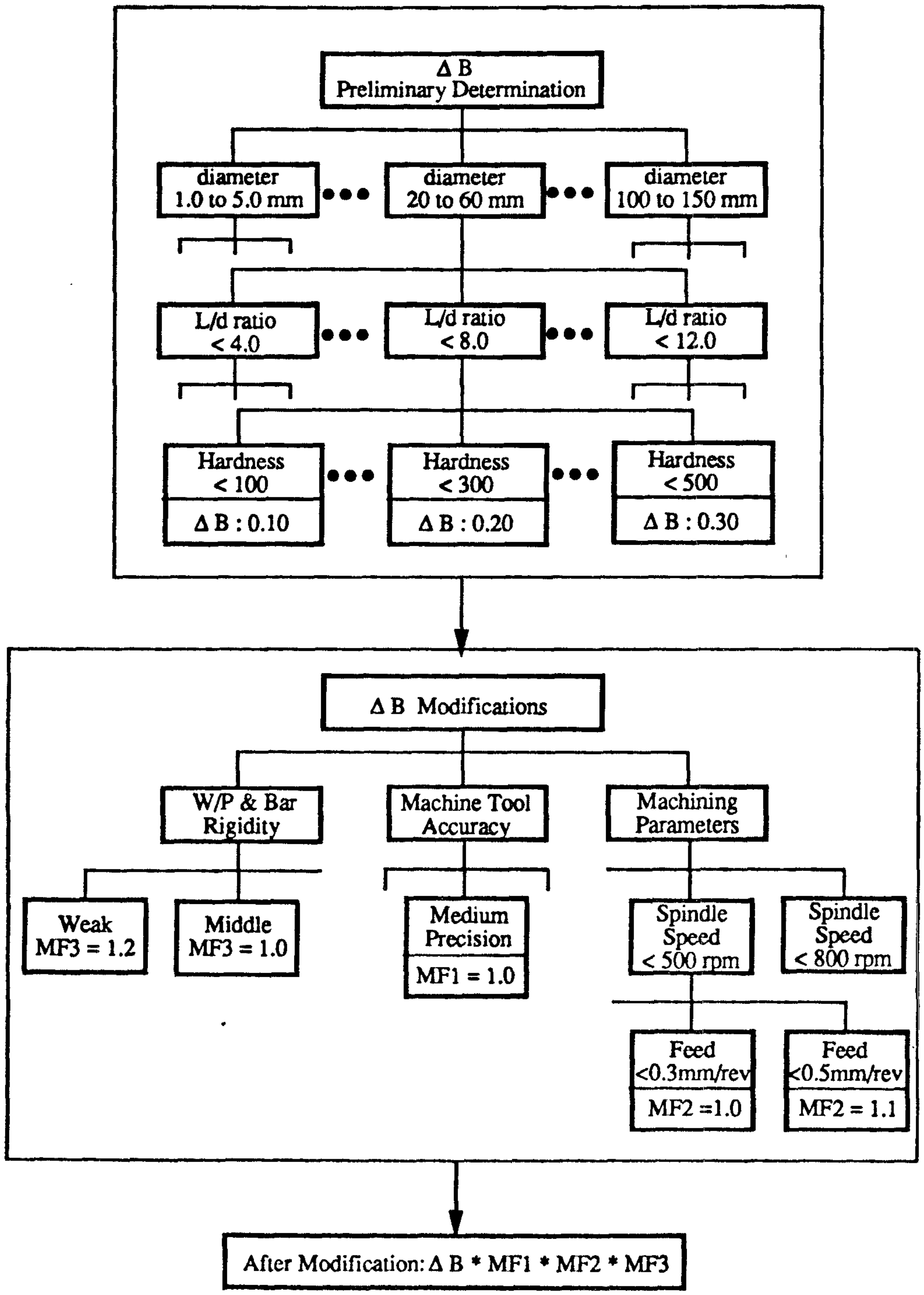


Fig. 14 Decision Tree for Boring