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A SYSTEMATIC APPROACH TO SUPPORT DESIGN FOR
MANUFACTURABILITY IN INJECTION MOLDING AND DIE CASTING

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of the Ohio State University

By

Yuh-Shan Yueh, M.S.

* * * * *

The Ohio State University

1995

Dissertation Committee:

Prof. R. A. Miller

Prof. C. H. Menq

Prof. J. Brevick

Approved by

A handwritten signature in black ink, appearing to read 'R. A. Miller', written over a horizontal line.

Adviser

Industrial and Systems Engineering
Graduate Program

UMI Number: 9544733

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To my father

Jin-Sheng Yueh

1918 - 1990

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VITA

September 7, 1960	Born in Kao-Hsiung, Taiwan, R.O.C.
1982	B.S., National Tsing Hua University, Sing-Chu, Taiwan, R.O.C.
1982-1984	Research Assistant, Department of Power Mechanical Engineering, National Tsing Hua University, Sing-Chu, Taiwan, R.O.C.
1984	M.S., National Tsing Hua University, Sing-Chu, Taiwan, R.O.C.
1984-1986	Instructor, The Chinese Navy Weapon School, Kao-Hsiung, Taiwan, R.O.C.
1986-1987	CAD/CAM Application Engineer, Metal Industries Development Center Kao-Hsiung, Taiwan, R.O.C.
1987-1990	CAD/CAM Software Engineer, Metal Industries Development Center Tai-Chung, Taiwan, R.O.C.
1990-1991	Visiting Engineer, Engineering Research Center, The Ohio State University, Columbus.
1991-present	Research Associate, Engineering Research Center, The Ohio State University, Columbus.

PUBLICATIONS

Papers:

- (1) Yueh, Y.S. and Miller, R.A. (1995), "A Systematic Approach to Support Design for Manufacturability in Injection Molding and Die Casting," Paper submitted to ASME Computers in Engineering Conference 1995, to appear.
- (2) Yueh, Y.S. (1989), "Design of Graphic Display Library," Metal Industries, Vol.23, No.4, pp. 40-48, 1989.
- (3) Yueh, Y.S. (1988), "Data Structure and Graphic Display," Metal Industries, Vol.22, No.4, pp. 6-10, 1988.
- (4) Yueh, Y.S. and Chieng, C.C. (1987), "On the Calculation of Flow and Heat Transfer Characteristics for CANDU-Type 19-Rod Fuel Bundles," ASME Transactions, Journal of Heat Transfer, Vol. 109, pp. 590-598, 1987.
- (5) Yueh, Y.S. and Hwang, W.S. (1987), "Computer Simulation of Flow Pattern in Die Casting Die," Proceeding of Chinese Foundry Society, Paper 15.1-15.13, 1987.
- (6) Fong, C.K., Huang, S.T. and Yueh, Y.S. (1987), "Die Casting Die CAD/CAM Software Application Case Study," Metal Industries, Vol.21, No.6, pp. 10-16, 1987.
- (7) Yueh, Y.S. and Chieng, C.C. (1985), "Temperature Profiles of Various Rod Power Ratios in CANDU-Type 19-Rod Fuel Bundles," Proceeding of the Third International Topical Meeting on Reactor Thermal Hydraulics, Rhode Island, 1985.

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(2) Yueh, Y.S. and Miller, R.A (1993), "DIECAST: Current Status and Research Directions," Technical Report ERC/NSM-D-93-63, Engineering Research Center for Net Shape Manufacturing, The Ohio State University, 1993.

(3) Yueh, Y.S., Rebello, A. and Miller, R.A (1992), "DIECAST: Design for Die Casting," Technical Report ERC/NSM-D-C-92-65, Engineering Research Center for Net Shape Manufacturing, The Ohio State University, 1992.

(4) Fong, C.K., Huang, S.T. and Yueh, Y.S. (1987), "Die Design of Aluminum Heater," Metal Industries Development Center, 1987.

(5) Yueh, Y.S. (1986), "Temperature Distribution of Liquid Metal Flow Through Die Casting Runner Systems," Metal Industries Development Center, 1986.

FIELDS OF STUDY

Major Field: Industrial and Systems Engineering

Major Area: Geometric Modeling and Manufacturing in CAD/CAM

Faculty Members - Dr. R. A. Miller
Dr. C. H. Menq
Dr. J. Brevick
Dr. R. Parent

Minor Area I: Database and Information Systems

Faculty Members - Dr. D. Lee
Dr. G. Perlman

Minor Area II: Artificial Intelligence

Faculty Members - Dr. J. Davis
Dr. B. Chandrasekaran
Dr. H. Adeli

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CHAPTER I

INTRODUCTION

1.1 Problem Description

Computer-aided design (CAD) systems, providing realistic images and solid modeling capability, have been widely used in designing mechanical parts. Compared with traditional blueprints, a part created in CAD systems can be easily modified and used to facilitate many additional applications such as FEA analysis and NC tooling path generation. However, the major function of current CAD systems is to perform geometric modeling and part shape description rather than to provide enough information to coordinate the whole product life-cycle.

Net shape manufacturing is defined as processes that use dies or molds to transform material which is shapeless, or of simple shape, into a near finished part (Ishii and Miller, 1992). Examples of such processes are die casting, injection molding, forging, sheet metal forming, etc. Compared with metal removal processes, the major characteristic of net shape operations is to achieve the final shape of the discrete part through the geometry of the die or mold. The required custom tooling of the dies or molds limits the applications to high-volume products. Proper design of the dies which can be used for long periods with little maintenance is extremely important.

Product design in net shape manufacturing includes part design, process selection and process design. After the material is selected and the overall part envelope is created to fit functional requirements, specific geometric details are added to address the concerns of detailed process design. In general, product design and process design are equally important and they should be closely coupled with each other (Miller, 1988; Voelcker et al, 1988; and Suh, 1988). The practice involves the incorporation of a wide variety of design expertise trade-offs. Design for net shape manufacturing is usually laborious and time consuming. In addition, the design quality may not be consistent.

This research is primarily concerned with tooling-related design problems in injection molding and die casting. These manufacturing methods use temperature dependent changes in material properties to obtain the final shapes of discrete parts to finish or near finish dimensions through the use of dies or molds. In this type of manufacturing process, liquid or viscous material is forced to fill and then solidify inside the cavity of the die or mold. Once solidified the material is removed from the die/mold.

To achieve a successful design in injection molding and die casting, designers need to consider manufacturing issues as well as functional requirements. Typical manufacturing concerns include filling, solidification, ejectability, tolerance/cosmetic considerations, need for secondary operations, die maintenance, cost, etc. Design characteristics which may affect manufacturing include uniform wall thickness with rib structures, properly rounded or filleted boundary edges for smooth fill, and suitable draft to increase ejectability. During design, a great deal of "know how" is applied to these design details by considering process-related manufacturing information such as the draw (ejection) direction, parting-line location, and gate location.

In general, process-related information depends on the particular design but processing issues also affect the design. Properly specifying the needed information not only simplifies the required dies or molds (e.g., undercut removal) but also facilitates many design details such as faces with draft and edges with round/fillet. For a given design concept, several competitive processes such as die casting, injection molding, forging or sheet metal forming may be considered to fabricate a part. Also several possible configurations may be chosen in the construction of the required dies/molds for the selected process. Figure 1.1 shows some possible shapes modified from the same design concept by considering the die/mold. As these simple examples show, dramatically different designs can result.

Figure 1.1: Parting proposals and the related design details

However, contemporary computer-based design tools generally do not directly support manufacturing-related decision making. Design decisions are therefore dependent on the designer's expertise and experience. If any of the many design details are overlooked, design modifications or changes may be necessary at later stages and are often laborious and time consuming.

1.2 Research Objective

As can be seen from the example in Figure 1.1, part design in injection molding or die casting should consider process-related information into adding geometric details for manufacturing concerns. In order to achieve a manufacturable part design with higher quality and lower cost, the required manufacturing information is usually carried by discussion with various groups of engineers and designers. The nature of these design activities is iterative and not well supported by current CAD systems. Therefore, there is potential to develop an approach which can work with current geometric modelers to increase the capability of handling the manufacture "know-how" and to support design for manufacturability.

The objective of this research is to design a custom user interface to incorporate die-related parting information with the part geometry at earlier design stage and to develop the reasoning procedures to explicitly generate the data linkage between part design and die/mold design. In this approach, manufacturing information can be strongly coupled with geometric data to form a complete part model which supports manufacturability assessment and facilitates any necessary shape transformations to achieve a manufacturable part in a concurrent manner. In this way design iterations can be controlled and development cost can be reduced.

This research explores the problems of improving the suitability of part designs for manufacture by the die casting or injection molding process, and focuses on design aids to be used by part designers and tooling engineers to efficiently evaluate the manufacturability of part and die designs, and to detect and highlight problem areas where necessary. The design aids are computer programs which augment the capabilities of computer aided design systems and together form a design for process system.

1.3 Research Issues

To develop an appropriate approach for the objective, several points should be considered: 1) the division of labor between part designers and die makers, 2) the design principles to achieve a manufacturable design, 3) the key features needed to incorporate design principles at the appropriate design phases and 4) the required functions of manufacturability assessment to enhance the capability of current CAD systems.

1.3.1 Investigation of Manufacturability Assessment

There are many manufacturing details of geometric shape which always need to be considered by designers such as undercut problems, process capability to achieve specified tolerances, draft and round/fillet requirements. When using current CAD systems, users may find that it is hard to examine the design based on the image shown on the monitor screen. A simple example is to find the face causing an undercut based on a given draw (die-opening) direction. A system with the capability of manufacturability assessment will help designers to examine current design work quickly, accurately, and completely and facilitate the creation of a manufacturable part.

In this research, a variety of functions for manufacturability assessment are investigated and typically focused on the following issues:

- 1) What strategies of design for manufacturability (DFM) systems, including their representations and evaluation tasks, are reported in the literature?
- 2) What kind of manufacturability assessment functions are required for injection molding and die casting? and
- 3) What kind of reasoning methods and representations are suitable to ensure a robust evaluation?

1.3.2 Identification of Key Features for Design Integration

Three types of process-related manufacturing information are the primary features used in this research. They are draw direction, parting-line location and the derived face groups. From the process point of view, a die casting or injection molding is produced in high volumes by the cyclical operations of dies and molds. The specific directions used for the movement of die/mold members are called draw directions. Each die/mold member has one pairs of opposite draw directions, $\mathbf{d}$ and $-\mathbf{d}$, for the opening and closure.

The mating surfaces when dies close are called the parting planes or parting surfaces, which should meet tightly to avoid the material splashing out (flashing). However, there must be clearance to allow the required motion between die members and such clearances tend to increase due to wear (NADCA, 1988). In this case, material will be forced into these clearances, leaving flash on the product surface and forming visible parting lines on the part.

Parting lines can be further divided into three categories based on their locations. They are external parting lines, internal parting lines, and parting interfaces. The first two types are caused by the two major die halves, i.e., ejector and cover dies, and parting interfaces refer to those formed by moving cores or slides.

The cavity shapes of the die/mold components, resulting from the product shape and the proposed parting locations, can be treated as the partition of the boundary of the part from the modeling point of view. For a given part, there can be more than one way of parting. That is, we could have different die/mold configurations for the same part, depending on the shape characteristics, tolerance requirements as well as the designer's experience. Each partition separates the part boundary along a different set of parting locations, as shown in Figure 1.1.

The proposed draw directions and parting line locations for one partition to establish the die/mold configuration is called a parting proposal. Associated with a parting proposal, the detailed partition of surfaces is called a set of face groups. A face group is a collection of entities, complete or partial surfaces covered by the same die/mold component, with the parting definition as the boundary information and with the draw direction as the moving information. In this approach, the part model is refined to include these face groups for the die/mold information. Therefore, the database created during part design can be extended to cover die/mold issues, and geometric reasoning about several manufacturing concerns can be explicitly addressed with respect to the generated data.

1.3.3 Development of A Framework for Manufacturability Assessment

Most computer-aided design tools, currently available, emphasize geometric modeling operations rather than providing integration capability for decision making. For example, process-related manufacturing information, such as draw direction and parting specification, is generally not integrated with the modeling operations of part creation. Therefore the database only contains geometric data which is not sufficient to directly support manufacturability assessment.

This work concentrates on augmenting the data structure and reasoning capability of CAD systems to account for parting information. The implementation of the system can be addressed in terms of custom interfaces and aggregation algorithms for the data refinement. In this system, parting line locations can be either identified by reasoning algorithms or specified by the user. The data are then used to derive corresponding face groups. Designers always have the freedom to choose the approach. The system can automatically or semi-automatically associate the parting line with geometric data extracted from CAD databases to perform manufacturability assessment or die/mold design. This approach also eliminates the limitations of splitting a part used in the earlier DIECAST (Yueh and Miller, 1993; Liou, 1990) and current commercial systems.

1.4 Research Approach

To account the typical design interactions, we can organize the design activities into several design phases. Four major phases are laid out in Figure 1.2 for injection molding

and die casting: initial/conceptual part design, detail part design, insert/cavity design, and detail die/mold design.

Figure 1.2: Design phases in injection molding and die casting

A part concept is created in Phase I based on the functional requirements. The typical process-related manufacturing information, such as the draw direction and parting-line location, is then added to the design to produce a detailed geometry in Phase II. The conceptual design is transformed into a manufacturable one by using appropriate manufacturing information.

In Phase III, the part shape is again modified and used to establish the shape of the die cavity which will be used to form the part. Generally part shrinkage and die/mold

expansion factors are applied to determine the shape and dimensions required so that the die/mold will be the correct size and shape at processing temperature to produce a part of the specified size and shape at its operating temperature. Gates, runners, overflows and vents are also added. The association between geometric data and parting information is critical at this point.

Phase IV is related to the overall mechanical structure of the die including connection of the die to the machine, mechanisms for filling (e.g. nozzle or gate placement), for cooling (e.g. cooling line locations, coolant inlet/outlet), for ejection (e.g. ejector pins and ejector plate), and for die/mold assembly.

This research is primarily concerned with the mechanism which can facilitate the development of a parting proposal by considering problems associated with Phase II where process-related information must be tightly coupled with the design concept to add geometric details. But, the key to accomplish a successful design is to incorporate the downstream information (die/mold level) into the upstream (part level) and to get the upstream process integrated with the downstream application in a concurrent manner (Webster, 1991).

The geometric details to increase manufacturability for the selected process, added in Phase II, can be treated as shape transformations and supported by manufacturability assessment. The concept is illustrated in Figure 1.3 and a design example of this paradigm is given in Figure 1.4.

Figure 1.3: Shape transformation for design details

Figure 1.4: An example of the proposed shape transformation

In this approach, manufacturing information can be strongly coupled with geometric data to form a complete part model which supports manufacturability assessment and facilitates the necessary shape transformations to achieve a manufacturable part so that design iterations can be controlled and development cost can be reduced. The representation provides the essential information in describing cavity shapes corresponding to the required die/mold members, which is also extendible to support the design activities in the die/mold level, such as the starting point for die/mold insert design, as well as for spatial reasoning and numerical simulation.

1.5 Dissertation Organization

The dissertation is organized into seven chapters. Chapter II reviews reported approaches to support DFM activities including the system functions and the evaluation methodologies. Since design-by features has been widely used, this chapter will also study the feasibility to applying this approach in injection molding and die casting types of applications.

Chapter III will focus on the development of a system to support DFM, including a review of reasoning algorithms which can extract the process-related data, scope of design guidelines, and the system architecture. The following three chapters will go to the details of the three subsystems. The discussion will cover major issues of system design strategy, user interface, internal data representation, reasoning procedures, and manufacturability assessment based on the refined part model. The last chapter gives a summary and conclusions. Some directions of future work about DFM assessment and possible extension from current system are outlined as well.

CHAPTER II

DESIGN FOR MANUFACTURABILITY AND FEATURES TECHNOLOGY

Features were originally thought of as geometric regions associated with specific operations. However, the term "features" is being widely used to represent high-level, meaningful entities related to design and manufacturing applications at the present time. This chapter will briefly review features research and investigate the feasibility of features technology, from a design for manufacturing perspective, in injection molding and die casting.

2.1 Design for Manufacturability

Design is a sophisticated process of transforming conceptual meaning of functional requirements into a set of design parameters or attributes of a physical object (Yoshikawa, 1982). Modern, industrialized design should utilize an explicitly organized, rational and systematic approach to facilitate this creative process by using both intuitive and non-intuitive design knowledge.

From the engineering point of view, one of the most important checks in design activities is that designed products should be manufacturable. DFM is the philosophy for this

purpose. It is concerned with the methodologies which can be used at earlier design stages to ensure a designed part produced more easily and more economically.

Jansson and others (Jansson et al, 1990) reported six generalized indices for measuring manufacturability quantitatively, including compatibility, bug index, availability, complexity, standardization, and efficiency. In their framework, compatibility is used to evaluate a complete design specification in terms of six factors - processibility of the material, production volume, overall size, overall shape, desired strength and stiffness, and surface finish and tolerance - from three aspects (i.e., design configuration, material, and manufacturing process). Potential problems in the manufacturing or assembly process is indicated by the bug index, e.g., core shift or sink marks in injection molding. Availability is concerned with different machine parameters such as clamping force and shot size. Information about expensive tooling or operations is pointed out by complexity, while standard components and tools are measured by standardization index. The efficiency indices are aimed at the consideration of issues such as material wastage, tool life, cycle time, extra operations, etc. The reported indices cover almost all major concerns in both machining and net shape manufacturing. However, they did not touch the feasibility of reasoning techniques to extract the required data and to computerize such indices.

Integrating design geometry and manufacturing knowledge in a systematic approach is the new perspective of future computer-based design tools. Many research prototypes try to incorporate an on-line manufacturability evaluator with the geometric modeler. Figure 2.1 lists several systems reported recently. The selections of these systems are based on either the specific strategy proposed in the manufacturability evaluator, or application domains focused on die/mold activities.

Researcher Reference	System Name	Part Modeling	Process Domain	Evaluation Capability : strategies and tasks
Shah, Hsiao, et al. Arizona State U.	ASU testbed	feature-based modeling	machining process planning	rule-based parameter checking least cost processing of alternatives
Poli, Rosen, et al. U. Massachusetts		design-by features	net shape process	feature parameters checking group technology part cost estimation
Luby, Dixon, et al. U. Massachusetts	Casper	design-by features	casting	feature parameters checking feature-based solidification modulus for feeder and hot spot detection
Chung, et al. SDRC		feature-based modeling	casting	rule-based geometry checking gating design parameters
You, et al. Purdue University	EXCAST	design-by features	casting	rule-based and task-oriented parameter checking feature-based solidification modulus for feeder and hot spot detection
Beiter, Ishii, et al. Ohio State Univ.	HyperDesign/ DAISIE	design-by features	injection molding	rule-based parameter checking quantitative pruning and qualitative ranking
Liou, Miller, et al. Ohio State Univ.	DIECAST	feature-based modeling	die casting	rule-based parameter checking rule-based and task-oriented geometry checking

Figure 2.1: Systems with manufacturability evaluator

In general, the capability of providing manufacturability evaluation comes from the part modeling (i.e. design-by features) which establishes a suitable representation and incorporates explicitly the data needed to check good practice rules. This allows checking of design parameters feature-by-feature only. These systems perform manufacturability evaluation through two steps: identifying the areas which may cause potential problems in manufacturing, and recommending modification suggestions based on those regions.

ASU Testbed - Application Shell for Machining Process Planning

Shah et al. explored a systematic methodology to perform manufacturability evaluation for a design described by a feature modeler and produced in machining operations (Shah, Hsiao et al, 1990, 1991). In their approach, manufacturability is measured from two aspects: manufacturing feasibility and economy. The reported manufacturability evaluator include four subsystems: a feature interpreter, good practice rule violation module, least cost processing module, and redesign suggestion module.

First design parameters associated with predefined features in a part are qualitatively checked by good practice rules to detect typical configurations which cause difficulties in machining. Then least cost processing strategy is used to explore the alternative machining sequences for individual features. Possible redesign opportunities from manufacturing point of view are listed in the order of machining cost of alternative sequences, feature by feature, and also suggestions for minimizing the required machining tools are provided.

Part Cost Estimation in Injection Molding and Die Casting

Research efforts at the University of Massachusetts have been resulted in the development of various manufacturability evaluation systems used in injection molding, die casting and stamping (Poli et al, 1992, 1991). The overall goal is typically aimed at the reduction in manufacturing cost of piece parts based on a series of group technology-based models whereby coding and classification systems are developed to identify part attributes which significantly increase manufacturing cost, and to provide a numerical rating of ease-of-manufacture. Manufacturing cost are estimated in terms of part material, die tooling (i.e., construction and material costs), and processing costs.

In order to support the estimation of processing cost, their tactic is to divide parts into two categories, entitled partitionable (i.e., those can be easily constructed by a series of elemental plates) and non-partitionable, and associating a solidification time with each elemental plate due to the features related to that plate. Processing cost is determined by the plate with the longest cooling time. For partitionable parts, a multi-digit classification coding scheme is then used to indicate the relative ease-of-manufacture for each process. In general, their approach restricts the recognizable geometric complexity as well as the possible parting proposals.

Processing Feasibility Evaluation

Three prototype systems listed in Figure 2.1 are proposed for evaluating the castability of design, which are: Casper developed at the University of Massachusetts (Luby et al, 1986), a prototype created by researchers at SDRC (Chung et al, 1990), and EXCAST from Purdue University (You et al, 1990 and 1989).

In Casper, a set of predefined features is provided to allow users to construct the design. Then the evaluator checks design parameters such as section thickness and overall dimensions from the aspect of process limits. The major characteristic of their approach is the detection of a default feeder and hot-spot regions by comparing the solidification modulus of each feature and its surrounding moduli. This method is also used in EXCAST for identifying similar tasks.

The prototype created by researchers at SDRC is aimed at the gating design for investment casting. Compared with other systems in Figure 2.1, it uses different strategies in geometric reasoning, i.e. "many rules are more purely geometric in nature for the determination of volume, distance, surface types (free or adjoining), and surface geometry (concave, convex, or planar)". Design characteristics, such as accessibility, gateability, gating parameters, and overall cost-effectiveness, are basically performed by these rules.

DIECAST is a system developed at the Ohio State University and proposed to make rapid and accurate detailed design for die casting process (Liou, 1990; Yueh et al, 1992). A commercial CAD system Pro/ENGINEER is incorporated for designing parts. DIECAST extracts the geometric data and constructs a separate part representation in a knowledge-based environment. In addition to checking feature parameters based on good practice rules, DIECAST also incorporates simple parting specification by splitting the part into two pieces. Detail evaluation is organized around problem-oriented tasks using B-rep data. Examples include which tolerance is intersected by the parting line, which face causes a undercut and which face needs draft. This system also supports interactive design aids to eliminate the "grunt" work in shape modification.

Since feature-based modeling has been reported by many researchers as a promising approach to support DFM as well as integrating other activities between design and manufacturing, the next sections of this chapter will focus on the feature-based technology, including the origin of feature concept, feature representation and classification, modeling/reasoning approaches, to some details of DFM methodologies. The review will investigate the validity studies and the foundation for developing DFM methodology which can be used in injection molding and die casting.

2.2 Traditional Computer-Aided Design Systems

Computer-Aided Design (CAD) systems, developed for a wide variety of users to construct designs on the basis of geometric constraints, are widely used in industry. These systems provide an easy way to facilitate design work including geometric construction, editing, realistic image generation, drawing generation, information storage and data transfer. Historically two major representation schemes have been used in CAD systems. One is based on defining an object in terms of its surfaces which enclose a volume, i.e., boundary representation (B-rep). The other is constructing an object based on a set of volumetric primitives, i.e., constructive solid geometry (CSG).

In CSG scheme, a variety of volume primitives (rectangular blocks, circular cylinders, cones, spheres, tori, etc.) and Boolean set operations (union, intersection and difference) are provided in part construction. This scheme also ensures the modeling validity easily on the basis of the syntactically correct primitives. However, users need to interpret and to decompose the design concept into the types of primitives available, and then apply suitable Boolean operations to form the part shape. For the same designed part, there

are several candidate construction trees in representing the geometric data. Moreover it is very difficult to model a part with sculptured surfaces.

On the other hand, a boundary modeler provides an explicit and unique representation (Rossignac, 1990). This representation also facilitates transfer of data, engineering drawing, FEA mesh creation, NC tooling path, and shaded image generation. The primary limitation of this approach is that users work with lower level entities such as vertex, edge and face types. Therefore an efficient user-interface design is required. Most CAD systems that use B-rep as the primary representation scheme still need CSG or sweep techniques as the input language (Requicha, 1980). Sweep modeling is a method to increase the dimensionality of elements by moving specified geometry along some path through space. It follows a bottom-up input procedure, such as moving a point to form a line or a curve, or moving a curve to form a surface, etc. Figure 2.2 gives an overview of the architecture of traditional CAD systems.

Figure 2.2: Traditional solid modelers

While creating mechanical parts, the designer usually organizes his ideas around functional requirements, quality and performance. Both CSG and B-rep schemes, however, only deal with geometric modeling issues rather than functional concerns. Functional characteristics must emerge from the details, either CSG primitives or low-level entities in B-reps, to communicate with CAD systems. Therefore the tools do not exactly meet the requirements of design. From the product life cycle point of view, various groups of designers and engineers must be involved in translating the design requirements from functions to shapes and in interpreting the shape for manufacturing via various processes. Problems in applying the data of geometry modelers to engineering applications have been identified by many reports (Chen and Miller, 1992; Gomes and Teixeira, 1991; Shah, 1991; and Shah and Rogers, 1988) and are summarized as the following:

- 1) **Incomplete database:** Traditional CAD systems use low-level geometric entities such as faces and edges as modeling elements and their databases generally do not incorporate non-geometric information such as tolerances, material properties, surface conditions, cosmetic requirements, manufacturing process, assembly relationships, etc.
- 2) **Mismatch in abstraction level:** Traditional CAD systems only support one level of abstraction, for example, an implicit representation of CSG trees, or an explicit expression of the B-rep in terms of topologic and geometric data. It is hard to extract the embedded engineering meaning or functional concerns, i.e. higher-level information, from the available geometric data.

- 3) **Loss of design source:** What current CAD databases support is only the geometric representation of design work. Two parts with the same performance but different shapes will be treated as two distinct objects without any relationships. It is hard to trace back the design intent and functionality since there is limited reasoning capability to address engineering activities in terms of design data and there is no way to explicitly relate the possible design alternatives. If any design objective is changed, users need to take full responsibility for necessary modifications.
- 4) **No design for manufacture:** Since current CAD modelers have the above limitations, manufacturability evaluation of design work is heavily dependent on designer's experience. If we focus on injection molding and die casting, design work usually involves different levels of expertise including part design, process design, tooling requirement and process concern. Current computer-based design tools do not really consider the life-cycle issues to facilitate the demand manufacturability in a concurrent manner.

2.3 Review of Features Technology

For these limitations, features have been proposed as a means of providing high-level semantic information for the integration of design and manufacturing concerns (Chen and Miller, 1992; Gomes and Teixeira, 1991; Shah 1988; Pratt, 1984). For example, functional features have been studied to facilitate the construction of design (Requicha and Vandenbrande, 1989; Wilson and Pratt, 1988). At the present time, more and more commercial CAD packages also provide features as the primary modeling interface.

2.3.1 The Concept of a Feature

The first definitions of features were process-planning-oriented. That is, the geometry could be associated with specific machining operations. The basic concept is that if a part has been constructed in terms of machinable elements then the part model can be used in process planning directly and manufacturability issues can be also checked at earlier design stages. Therefore the term "form features" was created and organized on the top of traditional CSG or B-rep modelers. Examples of features include holes, grooves, slots, bosses, pockets, etc.

As feature technology illustrates the potential integration capability between design and machining process planning, a lot of different kinds of features have been proposed for various engineering activities, such as functional features, abstract features and physical features, assembly features, mating features, analysis features, etc. The feature definitions tend to become more general; from a geometric form moving to a region of interest, a semantic grouping, or even a carrier of production information. An in-depth review is given by (Salomons et al, 1993).

Researchers at the University of Massachusetts defined a feature as "a model of the form and intent of some aspect of a design which is of direct interest in a CIM viewpoint. ... The set of features for a viewpoint is described as the set of semantics for reasoning in that viewpoint, and, therefore, a component designed by a set of features can be interpreted as an assignment of semantics to the geometry, dimensions, and tolerance" (Rosen et al, 1991).

In net shape manufacturing, a feature can be interpreted as a special region of interest in a part, which provides significant semantics by embedding the detailed information of typically related die/mold activities as inferable attributes. The embedded information provides a medium of communication between design and manufacturing, facilitates the reasoning for specific manufacturing questions, and provides smoother integration with engineering applications.

2.3.2 Feature Classification

Based on the details of the embedded information, features can be further categorized into types or classes. The categorization can be efficiently incorporated to retrieve a particular feature, to facilitate design modeling associated with other engineering activities, to simplify reasoning algorithms, and to exchange modeling data among various CAD systems.

PDES (Product Data Exchange Specification) classifies features as *Passages*, *Depressions*, *Protrusions*, *Transitions*, *Area features*, and *Deformations*. The categorization of these six types is focused on geometric modeling issues, including volumetric associations and operation information to support the standard definitions of data exchange.

Wilson and Pratt presented a shape based taxonomy of features for use in incorporating design-by features into solid modeling (Wilson and Pratt, 1988). The classification of features is split along the notion of explicit and implicit representations. In the former cases, all the geometric details of a feature are fully defined. Implicit features are those unevaluated, i.e., only sufficient information is supplied but the geometric details have to

be calculated when required. For example, a cylindrical hole is represented by its centerline, radius and depth. In their taxonomy, explicit features are classified into four types, *through hole*, *depression*, *protrusion*, and *area*, and implicit features fall into two classes; *generic* types in terms of general sweep operations, and *modifier* of low-level B-rep entities such as knurls, rounds, fillets, bevels, chamfers, etc. They also addresses some issues of *compound* features. *Compound* features are combinations of features, including *parent/dependent* features and *pattern* features (Pratt, 1988).

Rather than modeling issues, Shah and Rogers (1988) classified features into four classes from a engineering perspective. *Form features* are used to address nominal geometry. Allowable deviations from form features are defined by *Precision features*, and material composition and condition are described by *Material features*. *Technological features* include information related to part performance and operation. Later, *Assembly features* are introduced to address part relative orientation, interaction surfaces, fits and kinematics relationships (Shah, 1991).

Chen et al. proposed a feature class taxonomy to classify generic features in terms of three hierarchy levels: 1) form features and process features, 2) primitive features and secondary features, and 3) positive features and negative features (Chen et al, 1991). This hierarchy provides various levels of abstraction to support object creation and property inheritance.

Cunningham and Dixon (1988) emphasized that features used in design should consist of two types: static and kinetic. Static features are grouped around the functional intent of modeling primitives, and kinetic features are defined as entities that entail motion or energy transfer. Along this taxonomy, Rosen et al. refined the concept of static type as

four major types for conversions of feature-based representations (Rosen et al, 1991), including: *Primitives* for major shape or primary structural blocks, *Add-ons* (such as holes and bosses) for local function or modification, *Intersections* (such as rounds and fillets) the connection between primitive and add-on features, and *Macros* (such as U-channels and boxes) for pre-specified combinations of other primitives.

2.3.3 Feature-Based Modeling

The key to addressing the manufacturing questions is the ability to perform reasoning on the part model (Ishii and Miller, 1992). The term "features" has been proposed as the means to enable this to occur. To incorporate features explicitly in part modeling, research work can be generally categorized into three distinct approaches: design-by features, feature extraction, and interactive feature definition (Salomons et al, 1993; Shan, 1991).

Design-by Features

In this approach, designers are encouraged to construct parts explicitly in terms of pre-defined form features. The approach of design-by features needs a pre-defined feature set or feature library in geometric modeling. The pre-defined feature set basically provides a convenient vocabulary for accessing relevant groups of boundary information as well as an abstraction level for characterizing certain types of shapes (Gomes and Teixeira, 1991). Features are internally represented to group various kinds of application-dependent information associated with low-level geometric entities. Therefore the necessary reasoning or interpretation of geometric details can be focused

on the common base. Most DFM systems reported in Section 2.1 adopt this approach in building models. Figure 2.3 illustrates a hypothetical example constructed in this way.

Figure 2.3: An example of design-by features

However different engineering applications need different groups of information. As mentioned in Section 2.3, there is no agreement about a generic feature classification. Similarly it is very difficult to form an universal feature library which can generally support a variety of applications, especially for the possible complexity of geometry in injection molding and die casting. This nature makes the approach of design-by features is only useful for typical part families, such as in EXCAST (You et al, 1989).

Since features are highly application-dependent, practical feature-based modelers should provide users the capability of generating their own features (user-defined features) as well as the basic form features (system-supported features). Based on the capability of traditional CSG or B-rep modelers, a specific tag can be used, at the top level of the user

interface, to associate the related components or entities within an user-defined features. Then an application-dependent feature interpreter is incorporated to extract the required information. The benefit of this approach is reasoning is only performed for the limited entities rather than the whole part. The methodology reported by Hsiao is an example for process planning with modeling in ASU testbed (Hsiao, 1990).

For net shape processes, another major drawback of design-by features is that some important information required at the stage of process design, such as draw directions and parting-line locations, can not be explicitly addressed in terms of pre-defined features. That is also why most DFM systems reviewed in Section 2.1 do not incorporate fully parting issues in their discussion.

Feature Recognition/Extraction

The approach of feature extraction employs reasoning programs to recognize and retrieve the necessary data from the geometric entities used in a traditional CAD database. The fundamental approaches can be broadly grouped into three categories: volume decomposition (Waco and Kim, 1994; Woo, 1982), manipulation of CSG trees (Hsiao, 1990; Lee and Fu, 1987), and reasoning on boundary model. Currently the last one occupies the limelight (Woodwark, 1988; Pratt, 1988).

For this research, some of the concepts proposed in the approach using reasoning on boundary models are very attractive. The typical methodology involved in reasoning on boundary models is constructing a graph representation which includes classification of geometric entities and association of topological relationships, then recognizing the desired features by pattern matching.

In general, a B-rep model provides an explicit description of solid volume in terms of its boundary surfaces. Two adjacent surfaces are related to each other by a common edge. In the algorithm for recognizing the elements of die/mold members, the propagation traverses between two face entities through their common edge whose morphological characteristics describe the possible shape types of the neighborhood and thus provide the propagation criterion; stop or continue.

Three basic structural primitives have been reported by Kyprianou's feature grammar for the classification of morphological features; a convex edge, a concave edge and a smooth edge (Kyprianou, 1980). Sakurai and Gossard extend the concept to classify edges into five types, shown in Figure 2.4, depending on the solid angle between two adjacent surfaces (Sakurai and Gossard, 1990).

Figure 2.4: Classification of edge types (Sakurai and Gossard, 1990)

Researchers at the Purdue University extended Kyprianou's concept of edge classification into graph structures for feature interaction problems. Joshi and Chang

developed the attributed adjacency graph (AAG) (Joshi and Chang, 1988). In the representation of AAGs, a face is addressed by a node and the common edge of two faces is represented by an arc with an attribute value of 0 for concavity or 1 for convexity. Then AAG-based heuristics is used to recognize machined features by searching subgraphs of the complete AAG. Marefat and Kashyap addressed the depressions of a part by cavity graphs in which the relative orientation of a face is tagged in the node and the link, between nodes, is used to reflect the concavity of the intersection (Marefat and Kashyap, 1990). The reasoning mechanism first generates the decomposition of the cavity graph into maximal subgraphs constituents. Then the incorrect ones are eliminated by rule-based experts.

Using similar edge classification skill, Gadh and Prinz define features in terms of sets of concave and convex edges, called links and loops (Gadh and Prinz, 1992). The reasoning of depressions, in their approach, is established by the cyclic traversal of edges, i.e., in the loop level of B-rep data. Bruzzone and Floriani use the face-to-face relationships between components in a graph form, called the connection graph or symmetric boundary graph, to generate feature categories (Bruzzone and Floriani, 1991; Floriani and Bruzzone 1989).

Following the principles of feature recognition, several algorithms have been published for the extraction of possible draw directions (Chen et al, 1993; Hui and Tan, 1992) and for the identification of the suitable parting-line locations along the specified or extracted direction (Bhargava, et al, 1991). In general, the reported algorithms take "minimizing die/mold components" as the premise in searching for possible draw directions, but they do not address tolerance/cosmetic specifications, draft requirements, die complexity, or other design issues such as locating the minimum depth in die/mold construction. Also,

the parting-line locations can not be practically identified by reasoning programs since the mapping from draw to parting-line is not unique without design details such as drafts. In general drafts should be added based on a parting proposal.

The outstanding merit of the feature recognition approach is that it removes the restriction of the designers' freedom associated with the use of predefined features. The major drawback is the incompleteness and computational load especially when the model becomes complex.

Interactive Feature Definition

The concept of this approach is that features are defined interactively by human assistance. In general the user interface for feature specification can be included into the classification mechanism for the design-by features approach, thus allowing a generic component created by sweep operations or CSG set operations to be organized as a member of the feature library. Also it can be broadly extended to specify the target shape to be matched by the reasoning mechanism for feature extraction.

Sakurai and Gossard introduced a methodology to recognize shape features based on an example interactively indicated by the user (Sakurai and Gossard, 1990). A shape feature is a single face or a set of contiguous faces. The reasoning mechanism searches for the typical pattern by comparing the boundary data of the pattern with the B-rep entities of the whole part. The geometric type, number of loops and number of edges provide data for face-matching procedures. Then four steps - edge generation, face generation, block generation and block assembly - are used to create the volumetric information for the recognized shape features.

It is generally difficult to describe a desire shape with languages or equations. The user interface of this approach demonstrates a flexible way to communicate with computers so that we do not need to embed the information of each feature previously in the feature recognition program. This approach also provides a strategy to incorporate with additional information not definable as modeling elements. Parting-line location is an obvious example for this research.

2.4 Feature-Based Manufacturability Assessment

In feature-based design, manufacturing information is tagged as related attributes of the feature definition. Features themselves are the means to integrate a variety of concerns, explicitly or implicitly, from design and from manufacturing into the part modeling representation. Therefore the constructed part model makes the pertinent data available for down stream applications and ensures the reasoning by directly looking at the relevant regions. This section will explore some issues of feature-based manufacturability assessment.

2.4.1 By Checking Feature Parameter

The capability of manufacturability evaluation of systems mentioned in Section 2.1 comes from good design practice rules associated with the corresponding features. An example constructed this way was shown in Figure 2.3. Compared with traditional modelers, the representation of the created part contains several form features with groups of parameters at the high level as well as the geometric details which can be evaluated from the modeling parameters. From design experience, good practice rules can then be organized along the feature category and incorporated with the parameters,

such as the safety zone, the desirable value, etc. Therefore the proposed features also provide the required data for the checking of good practice patterns. DIECAST, for example, uses this paradigm to include some limitations of die casting process, and stores the rules in a knowledge environment. Figure 2.5 outlines typical rules for boss and hole features.

BOSS	Aluminum	Magnesium
Boss without cored hole	$0.04 \text{ in} \leq \text{Radius} \leq 0.5 \text{ in}$ $\text{Height} \leq 10 \times \text{Radius}$	$0.03 \text{ in} \leq \text{Radius} \leq 0.3 \text{ in}$ $\text{Height} \leq 10 \times \text{Radius}$
Boss with cored hole	$0.04 \text{ in} \leq \text{Wall thickness} \leq 0.5 \text{ in}$ $\text{Height} \leq 10 \times \text{Wall thickness}$	$0.03 \text{ in} \leq \text{Wall thickness} \leq 0.3 \text{ in}$ $\text{Height} \leq 10 \times \text{Wall thickness}$

(a) DFM table for a boss

HOLE: radius (R)	Aluminum	Magnesium
$R \leq 0.0625 \text{ in}$	cannot be cored	cannot be cored
$0.0625 \text{ in} < R \leq 0.25 \text{ in}$	$2^\circ \leq \text{Draft} \leq 6^\circ$ $0.31 \text{ in} \leq \text{Depth} \leq 2 \text{ in}$	$1.8^\circ \leq \text{Draft} \leq 5^\circ$ $0.31 \text{ in} \leq \text{Depth} \leq 2 \text{ in}$
$0.25 \text{ in} < R \leq 0.5 \text{ in}$	$1.5^\circ \leq \text{Draft} \leq 2^\circ$ $2 \text{ in} \leq \text{Depth} \leq 6 \text{ in}$	$1^\circ \leq \text{Draft} \leq 1.8^\circ$ $2 \text{ in} \leq \text{Depth} \leq 12 \times R \text{ in}$
$0.5 \text{ in} < R$	$1.5^\circ \leq \text{Draft} \leq 3^\circ$ $3 \text{ in} \leq \text{Depth} \leq 12 \times R \text{ in}$	$1^\circ \leq \text{Draft} \leq 3^\circ$ $2 \text{ in} \leq \text{Depth} \leq 12 \times R \text{ in}$

(b) DFM table for a hole

Figure 2.5: Manufacturability evaluation associated with feature parameters

In this approach, manufacturing evaluation is straightforward by checking the proposed parameters through some look-up tables. However, since features relate only to local geometric information, these systems can only evaluate design in very limited regions,

feature by feature, in which recognized feature names and tagged attributes are used. Usually the shapes of designed parts in injection molding or die casting are very complex. From exercises with design-by features, we find it is almost impossible to create a pre-defined feature library to cover all the possible details used even in a relatively simple but real diecasting.

2.4.2 By the Ratios of Features Parameters

The section modulus, defined by the ration of casting volume to its surface area, has been widely used for the estimation of solidification time for castings (Shih and Li, 1990; Neises et al, 1987; Lopeet al, 1986; Heine et al, 1984). It is also proposed for the estimation of feeder locations and hot-spot regions, e.g., in DFM systems Casper (Luby et al, 1986) and EXCAST (You et al, 1990), by calculating the value with each feature and then comparing it with the surrounding ones. In the practice of die casting, Herman also suggested to use thermal sections in determining thermal work (Herman, 1985).

The basic philosophy of the reported works is a decomposition procedure of the casting or diecasting part along the gating segments or directional solidification regions. Then the section moduli of the subdivisions are used for manufacturability assessment. To incorporate this method, design-by features should be organized based on the processing concerns (i.e., casting features) as well as functional requirements (i.e., design features). How to categorize casting features, addressing fill and solidification issues, together with design features in a feature library is still an open question.

Poli et al. reported an important ratio for the measure of voluminosity (Poli et al, 1992). Originally, this ratio is defined as the surface area of the part divided by its projected area

along the draw direction, named $S : P$. It is believed that large $S : P$ will increase shape complexity in the direction of mold closure. In their approach, this ratio is replaced by a weighted sum of the features, such as holes, ribs, and holes, in the draw direction. However draw information is not an explicit data available from the geometric database. To explore the shape complexity of dies or molds we need parting information.

2.4.3 Manufacturing Aspects

As pointed out by many researchers, design-by features is a promising approach for operations planning in conventional machining simply because in such a process a part is produced by operations step by step and a part, created feature by feature, fits the nature of machining operations. Both are concerned with relatively local regions rather than the whole part at one time. And a form feature is only related to a limited set of operations (Ishii and Miller, 1992; Pratt, 1984). For example, a cylindrical hole could be manufactured by drilling, boring or reaming depending on its tolerance. The distinction between primary and secondary features or between positive and negative features provides meaningful relations to address the practical machining sequence.

However, such a degree of correspondence does not exist in net shape manufacturing because the manufacturing operation, both filling and solidification, is essentially applied to the whole part. Therefore evaluations done at the feature level can not guarantee the manufacturability of the part design. Ishii and Miller mentioned two types of methods are important in manufacturability evaluation: macroscopic search of problems in the entire design and microscopic evaluation of a local form features (Ishii and Miller, 1992). To facilitate design in injection molding and die casting, what we need is methodology

which builds a representation, for data aggregation and geometric relationships from a global point of view, in which the required reasoning can be focused on the suitable data.

2.4.4 Some Design Examples

It is well known that current practice in die casting or injection molding involves a lot of trial and error. This trial-and-error step can be treated as a compensation procedure between design parameters and process parameters to meet the quality requirement. Several examples are used in this section to illustrate the concepts of critical dimension, geometric data interpretation and compensation strategy in more detail.

Critical Dimensions

In the first example, a part is constructed by three features: two bosses and a blind hole, as shown in Figure 2.6(a). If a boss is defined by boss height, boss radius and its center line and a hole is defined by depth, radius and also its centerline, the created part will contain at least six feature parameters and three center lines. For the simplest case, these three features are coaxial and all features pass the checking (i.e., their parameters all satisfy the rules in Figure 2.5). Can we ensure this part is manufacturable in die casting? Probably not because the summation of boss height A and boss height B, i.e., total height, may be too large for filling. However, total height is not available explicitly as feature parameters especially when the boss A is located by a datum plane rather than the top face of Boss B.

Figure 2.6: Critical Dimensions vs. feature parameters

In general, critical dimensions such as the total height are more important than feature parameters for evaluating problems globally but design-by features may never favor their feasibility unless we have very powerful reasoning algorithms to derive all the required data from feature interactions (Ishii and Miller, 1992).

Interpretation of Manufacturing Meaning

Even it is possible that we do have the algorithms, data is static but a process phenomenon such as filling or solidification is dynamic. How to really derive their relationships is still an open question. For example, the same boss is placed in different orientations like Figure 2.7 in which the geometric data of "height" in a boss may play different roles as we interpret the geometry from the manufacturing point of view. If we think that the rule "boss is too high" is concerned with filling issues, how to associate the physical meaning of "too high" with geometric data such that the rule can provide meaningful evaluation is very difficult.

Figure 2.7: Geometric data vs. manufacturing meaning

Compensation Strategy Among Trade-Offs

On the other hand, if we change the design from a blind hole to a through hole as in Figure 2.6(b), evaluation rules may say the hole is too deep. However, in die design it may be formed by two die components, i.e., we have an internal parting somewhere inside the hole. In this case, the problem of a too deep hole does not exist. This issue can be generally interpreted as the compensation strategy among trade-offs, which is very important for complex design such as injection molding and die casting, but it can not be supported unless we can associate process-related features with the geometric modeling data.

Figure 2.8 is an example of compensation of data entities. In Figure 2.8(a) the boss is too high due to removing extra material by adding a cored hole, however it is also a common practice to add ribs to enhance strength. From the filling aspect, a "too high" boss with ribs, in Figure 2.8(b), may not be too high because ribs provide extra channels

for material fill. The invalidity of one data entity checked by evaluation rules may be overcome by changing another data entity. Considering such relations among modeling elements is really a challenge.

Figure 2.8: Invalid feature compensated by other features

Such information results from long-time experience in the application domain and valuable strategies (or tricks). For example, too deep ribs may be qualified by changing or adding gate locations, or a too deep boss may be compensated by adding extra ribs to help filling and to improve strength. Unqualified features may also be compensated by other mechanisms, such as adding ejector pins to overcome faces with zero draft.

The reason for providing these examples is only to show that the manufacturability evaluation used in process planning for machining may not be helpful for solving problems in injection molding or die casting, although many researchers declare their DFM systems are very useful for casting or injection molding processes on the basis of design-by features approach. This research does not try to solve the puzzle directly because the author does not believe the design-by features approach is so promising. At least it is not necessary for designers to lose the freedom of choosing so many nice modeling tools, such as linear or rotational sweep operations based on the nature of the

desirable shape, or shell operations (provided by Pro/ENGINEER from Parametric Technology Corporation) to easily remove extra material for uniform wall thickness.

2.5 Summary

This chapter briefly reviews features technology and outlines several reported DFM systems in terms of their representations and the manufacturability assessment mechanisms. Some basic conclusions are listed as follows:

- 1) The reported DFM systems generally only provide manufacturability evaluation within the local range of individual features. It is demanded to have a methodology which can facilitate a global problem search.
- 2) It has been shown that feature-based design is not easily used to ensure design for manufacturability in injection molding and die casting due to the substantial part complexity and sophisticated process concerns.
- 3) Features recognized through the B-rep graph with a variety of attributes eliminate the requirement of a predefined feature set. Algorithms such as edge classification and face aggregation can be used to build models very efficiently in injection molding and die casting, since the interactions are not so sensitive to the levels of abstraction.
- 4) Process-related information such as draw direction and parting proposals should be explicitly incorporated with geometric data to support manufacturability assessment for detailed part design and for the related die/mold design.

Due to the substantial complexity of a design in injection molding and die casting, reasoning about the geometry of the part should include macroscopic search for problems in the entire design and microscopic evaluation of local shapes. The compatibility with the process should be checked over all portions of the design (Ishii and Miller, 1992). Therefore, it is necessary to develop a methodology which can utilize process-related information in model-building, allowing the reasoning guided for typical interaction problems between part design and die/mold design, and providing global information for manufacturability evaluations.

CHAPTER III

A FRAMEWORK TO SUPPORT DESIGN FOR MANUFACTURABILITY

Based on the discussion of the DFM methodologies currently reported by a variety of research work, it is not practical to apply the approach of design-by features alone in injection molding and die casting. Therefore, it is necessary to develop a methodology which can include macroscopic search for problems in the entire design as well as evaluation of local shapes. This chapter will introduce a systematic approach for this purpose. The proposed system facilitates incorporation of process-related information into model-building, guides the reasoning for typical interaction problems between part design and die/mold design, and provides globally structured information for manufacturability assessment.

3.1 Manufacturing Concerns and Manufacturability Assessment

Manufacturability assessment is the means to efficiently evaluate the manufacturability of part and die designs, and to detect and highlight problem areas where necessary. In addition to finding problem areas, suggestions for improvements should be provided where possible, and the design changes should be feasible with a minimum of tedious user input. "Rough cut" assessment using design rules might be used, but an assessment system must be flexible enough to incorporate problem specific analysis modules as these

modules become available and are validated. A system with the capability of manufacturability assessment will help designers to examine current design work and to facilitate the creation of a manufacturable part. In general, a DFM system in injection molding and die casting should have the capability to answer the following five questions (Yueh and Miller, 1993):

1. Will the part fill properly?
2. Will the part cool and solidify without defects?
3. Will the part eject without damage?
4. Will the part result in high die construction or maintenance costs?
5. Can the tolerance and precision requirements be met effectively?

To answer these five questions, we need different kinds of manufacturability assessment design tools which can be generally classified into two categories, numerical simulation and geometric reasoning and shown in Figure 3.1. Numerical simulation can provide quantitative solutions in terms of a variety of property distributions, such as stress, velocity, temperature, etc., by solving differential equations using various numerical schemes such as Finite Element Analysis (FEA), Finite Difference Method (FDM) and Boundary Element Method (BEM). Engineers must be involved to specify the required initial or boundary conditions to fit the physical phenomena, to interpret the calculated data with respect to the related design problems, and to figure out possible redesign strategies. To apply this approach, a geometric model must be created before executing the simulations. The simulation usually takes a long time to solve sophisticated equations. Therefore it is more practical to use this technology only for design verification.

Figure 4.1: Manufacturability assessment design tools

Compared with numerical simulation, reasoning approaches can link CSG or B-rep models with some empirical design knowledge and quickly provide qualitative solutions. The major research effort is to derive the suitable data representation which can guide the reasoning efficiently. The reasoning can be also associated with design knowledge and therefore provide some on-line redesign strategies.

The key to addressing the manufacturability questions is the ability to perform geometric reasoning on the part model. Due to the substantial design complexity in injection molding and die casting, design-by features alone is not able to provide sufficient details to guide the reasoning. Reasoning about the part geometry should include global search of problems in the entire design and evaluation of local shapes. That is, all portions of the design should be checked for the compatibility with the process (Ishii and Miller, 1992).

In addition to feature recognition, two types of geometric reasoning are required to support manufacturability evaluation and to facilitate the shape modification for die casting and injection molding. They are reasoning about volumetric information for the modification of wall thickness, and identification of specific B-rep entities for undercut, draft and round/fillet issues. Spatial reasoning on a voxel-based representation provides a robust way to identify heavy mass regions for the modification of wall thickness as well as fill and solidification concerns (Lu and Miller, 1993). This approach has also been used in performing medial axis transformations to represent a thin-wall part by its skeleton (Hjalmarsson, et al, 1994; Rosen, 1993; You et al, 1990).

Following a similar paradigm of feature recognition, die/mold reasoning is proposed to extract a suitable parting proposal from the geometric data of a part. Examples include

draw determination (Chen et al, 1993; Hui and Han, 1992), and parting extraction (Ren, 1994; Bhargava et al, 1991; Ganter and Tuss, 1990). This chapter will briefly organize their approaches into the development of an integrated system.

3.2 Parting Design Guidelines

One of the most important pieces of process related information associated with the part design is the choice of draw directions and parting-line locations. The determination involves "know-how" with respect to the selected manufacturing process. Ravi and Srinivasan developed a system to support the decision making about the desired parting location by evaluating nine parameters, which are projected area, flatness, draw, draft, undercuts, dimensional stability, flash, machined surfaces and directional solidification (Ravi and Srinivasan, 1990). The system first retrieves the part description from a file containing geometric, topological, and technological data. Parting information is interactively specified in terms of face patches. Then this system can generate numerical values of the nine decision criteria.

Basically, their approach is an evaluation-based reasoning about the parting design. The algorithm is used to provide an analysis of a particular specification rather than the suggestion of an optimized parting proposal. That is, they did not present algorithms for generating one or more parting proposals. Moreover, their approach is restricted to a planar parting along one of the three principal axes of the part coordinate system.

Ganter and Tuss reported a set of heuristic rules for cast pattern production from various sources of casting literature. These included (Ganter and Tuss, 1990):

1. Keep the greatest portion of cavity in the drag.
2. Avoid slender sections in the cope.
3. Avoid excessive depth in either drag or cope.
4. Minimize the weight of the cope.
5. Keep the thickest sections in parting surfaces.
6. Avoid mold erosion and turbulence.
7. Minimize the required number of cores.
8. Minimize the surface number which needs draft.
9. Avoid irregular part lines if possible.

According to their report, the development of parting lines is a search of plane style patterns using rules nine, five, three and eight only. First test planes are generated along either a specified direction, the object's center of gravity, or one of the object's three principle axes based on a sample set of 50 points and/or a specified interval number. Then each generated plane is used to cut the part into two sectioned halves. The search repeats the testing of sectioned parts against the rules and classifies potential parting lines. As a result only plane-type parting lines can be generated. By using sampling points, the approach may not be applicable for complex parts. That is, the generated test planes may not cover all the details or the nature of the required parting in a complex part.

In real practice, Herman suggested that parting design should be evaluated in terms of the following concerns (Herman, 1985):

1. Difficulty of building dies: including parting surface development, complexity of die construction, manufacturing and maintenance cost of dies,
2. Desired filling pattern: considering suitable gate locations and overflows,
3. Heat balance or desirable heat flow conditions,
4. Flash to be trimmed: secondary machining operation and cosmetic concern, and

5. Tolerance Requirements: dimensional tolerance and cosmetic surface.

Based on a review of previous work, the general design guidelines for parting proposals in casting/molding processes are listed as follows:

1. Select a draw direction which maximizes the projected area of the part and minimizes the required depth of the die/mold blocks.
2. Locate parting lines along the external contour of the projected area and avoid irregular parting lines if possible.
3. Minimize the required number of moving cores and slides.
4. Minimize the number of surfaces which need draft.
5. Consider the effect on the ability to hold tolerances.
6. Avoid locating the parting line on cosmetic surfaces.
7. Hold the part in the ejection die/mold half when die/mold opens.
8. Insure a smooth, unobstructed fill pattern.
9. Consider heat balance or desirable heat flow conditions.

3.3 Data Extraction for Process Design Features

Regarding the shape characteristics, parting information may be extractable by reasoning programs. This section will review several reported algorithms for draw determination and parting line locations. The discussion will focus on their advantages and limitations for the development of the proposed system.

3.3.1 Draw Determination

For selecting an optimized draw direction, Hui and Tan presented a heuristic search technique and then apply the detected direction to modeling of die/mold geometry

through sweep operations (Hui and Tan, 1992). The optimized selection of a draw direction is a heuristic search of the estimation of the following three factors:

1. Blocking Factor (BF): which is used to indicate the amount of undercuts by measuring of the relative amount of obstruction in a certain direction, i.e.,

$$BF = \frac{\text{number of obscured points}}{\text{total number of test points}} \quad BF \in [0, 1] \quad (3.1)$$

2. Preference Value (PV): which can measure the degree of preference in the selection of a direction as the parting direction, i.e.,

$$PV = \frac{\text{projected area in given direction}}{\text{maximum projected area}} \quad PV \in [0, 1] \quad (3.2)$$

3. Parameter PB: which is for the measurement of the degree of compromise, i.e.,

$$PB = PV * (1 - BF) \quad (3.3)$$

In their approach, a given part is meshed to generate sample points. Then visibility testing of mesh points is introduced to get the block factor, BF, which is the estimation of undercuts for a pre-selected draw direction. At the same time the part is projected based on this direction to calculate the preference value, PV. The optimized draw direction should be the one with the minimum BF and the largest PV. However, this may not be possible in practice. To measure the degree of compromise, PB is introduced as the multiple of PV and (1-BF). The higher the PB value is, the more preferred the pre-defined direction is as the main draw direction. Therefore, the choice of the major draw direction is identified by searching the highest value of all possible PBs (for all possible draw directions) in a part. The computation of their algorithm is very expensive due to the required sampling points and the result does not provide the suitable locations of parting lines.

Chen et al. developed an algorithm by using convex hulls in handling the problems of surface interference globally (Chen, Chou, and Woo, 1993). In their approach, the convex hulls of a given part is generated and then compared with all surfaces of the part. Those surfaces that belong to the part but not to the convex hull are collected as pocket surfaces. For the search of a pair of opposite directions $\mathbf{d}$ and $-\mathbf{d}$ which minimize the required number of cores, pocket surfaces can be classified as three subsets: completely visible from $\mathbf{d}$, completely visible from $-\mathbf{d}$, and partially visible (i.e. not completely visible) from either $\mathbf{d}$ or $-\mathbf{d}$. The partial visibility comes from either local inference (due to the surface itself) or global inference (other surfaces). Visibility maps and concave regions are used to solve the effect of inference. However, the reported algorithm is not complete for partial visibility as well as for the desired parting locations.

3.3.2 Parting-Line Locations

Researchers at the Carnegie Mellon University developed a procedure of locating parting-line position based on the maximum projected area of a given draw direction (Bhargava, Weiss, and Prinz, 1991). The basic idea comes from the fact "parting lines must occur along the line round the position of maximum dimension when viewed in the draw direction".

Figure 3.2 is an example to illustrate their approach. Ejectability analysis is used to classify face entities into three types of patches, named plus, minus and zero. Along the die opening direction (Z-axis), part shape is then projected onto a XY plane. The desired parting line locations are identified based on the boundary between plus and minus patches or the mapping of the external boundary of the projected area back into 3D space. The presence of zero paths will carry a range *[high : low]* of positions to

facilitate the reasoning about the non-unique parting line problem, as shown in Figure 3.2(a).

Figure 3.2: Parting lines identified by projected data (Bhargava et al, 1991)

One advantage of their work is the capability to detect undercuts resulting from face intersections. But the detection can not distinguish between internal undercuts and external ones. The non-unique mapping from the projected boundary into the part entities is only addressed by a range attribute $[high : low]$ without a mechanism provided for detailing the locations.

Reasoning algorithms can only identify the possible ranges of parting locations because the mapping from a silhouette edge to the part geometry is not unique. Bhargava, et al presented a range attribute $[high : low]$ in handling this situation (Bhargava, et al, 1990). And others split the part into sectioned components to generate the locations. Examples include parting-line development for cast pattern production (Ganter and Tuss, 1990), and MODCON (Chan and Knight, 1980). The earlier DIECAST also adopted this approach (Yueh and Miller, 1993).

One nice feature of this approach is generating explicit entities to address parting issues. However, the split operation can only proceed for simple parting cases. And, once the part has been split, it is very difficult to maintain the connectivity between the two halves. Figure 3.3 gives an example to illustrate the major limitations.

Figure 3.3: Part-sectioned approach for parting description

In this example, parting lines crossing someplace on the part, as shown in Figure 3.3(a), can not be defined by existing edge data. Users can use the desired parting locations as reference data to cut the part into two separate pieces, as Figure 3.3(c) shows, which are stored as two distinct elements in CAD databases. Two faces will be generated from the

splitting operation, which belong to the two portions individually, and they provide explicit entities for the definition of the desired parting line locations.

However, the proposed parting line in Figure 3.3(a) is only associated with the external face, but the split operation will separate the internal face too. Two problems will arise under this condition. For the external faces, the difficulty is how to maintain the connectivity between two separated regions after adding drafts. For the internal one, the splitting approach loses the reference data for drafting the top portion, i.e. the bottom contour of the internal faces. Therefore it is impossible to apply the draft function such that the sectioned parts can be associated with each other like Figure 3.3(d). Moreover, it is hard to cut parts along irregular parting lines. Therefore this approach is not practicable for general parting specification.

3.4 System Design Strategy

Based on the review of related work, we find two kinds of limitations with respect to the parting determination. First the reported algorithms for reasoning draw directions are performed by emphasizing one particular heuristic rule as the premise, i.e., "minimizing die/mold components", but not covering other important design issues. Second, parting-line locations can only be addressed with the existing edges or by the splitting approach.

Process-related information is used to establish the foundation for the activities of part design and die/mold design so that upstream and downstream activities can be related together to support design for manufacturability. Therefore there is a need to develop a

systematic approach which can facilitate the establishment of a parting proposal and also formalize the suitable data to support the manufacturability assessment.

The strategy of the proposed system is first to provide an user interface which allows users to select the major design principle. For example, "locating the maximum projection area" or "minimizing the required die/mold members" is specified for the selection of the major draw direction. A set of reasoning algorithms can be implemented under the items of the proposed "draw-selection" interface. Figure 3.4 shows the different draw selections for a given example: one is based on "locating the maximum projection area" and another for "minimizing required die/mold members".

Figure 3.4: Draw selection in competing factors

Then the specified draw direction is used for the reasoning of parting-line locations. In general, reasoning algorithms can only identify the possible regions but not the exact location for parts without drafts at the conceptual design stage. Therefore the proposed system needs to provide an user interface to assist in the desired specification. This specification is then associated with the part geometry internally in order to create sufficient data for modeling the embedded die/mold configuration.

Finally, reasoning procedures are developed to generate die/mold information embedded in the parting specification. The generation is basically a data refinement procedure which rebuilds pieces of the part in order to define the related die/mold information. The generated data enhances the part model with sufficient, global and structured information to support manufacturability assessment.

3.5 An Infrastructure to Support Design for Manufacturability

Based on the discussion, three modules are included in the proposed system. They are parting design, linkage generation, and manufacturability assessment as shown in Figure 3.5.

Figure 3.5: Three major modules to support DFM

For two way of communication in terms of the evaluation and modification purposes, the implementation is fully integrated with a commercial CAD system, Pro/Engineer from Parametric Technology Corp. To the user the system looks like Pro/Engineer with additional functions. Note however that implementation does not require Pro/Engineer, only a system using a B-Rep part representation and an appropriate application interface.

3.5.1 Parting Design Module

Parting design module is used to relate a parting proposal for the two major die/mold halves with geometric data of the initial part. The required input includes parting-line location and draw direction which can be specified with or without reasoning algorithms, as illustrated in Figure 3.6.

Figure 3.6: Parting design module

The desired information may not be always extractable from initial part design due to designers' habits and non-unique solutions. The reasoning algorithms for draw directions

and parting locations can be viewed as filters to eliminate the unnecessary geometric data and to simplify the establishment. An user interface is demanded to allow users to specify the definition based on the geometric data or the reasoning result. Without the help of reasoning algorithms, designers can still communicate with the system through user interfaces to establish the wanted parting proposal. In general it is difficult to describe a shape with languages or equations. The interface design provides users a simple and straightforward way to handle complex parting requirement with less effort in communicating with the system.

3.5.2 Linkage Generation Module

Since the solid region of a product in injection molding and die casting is formed by filling and solidification procedures rather than machining raw material directly, it is important to rebuild pieces of the part to address die-related issues based on a parting proposal. A Linkage generation module is used to recognize the embedded face group features from a CAD database. The required part description for this system is a boundary representation (B-rep) which is unique, unambiguous, and widely supported by current CAD systems. The topology of a boundary model contains at least three levels of geometric data: face, edge and vertex. Parting definition may cross geometric entities which need be split into different sections for addressing the issue of different dies or molds.

Figure 3.7 demonstrates the required functional procedures and the related data elements.

Figure 3.7: Linkage generation module

The first function of this module is to associate the parting definition with the extracted B-rep data and to request split operations if necessary. That is, the system should have the capability of knowing whether there is any geometric entity covered by different die/mold components. The split operation is conceptually used to generate extra B-rep entities with consistent topology for modeling die/mold components.

Second, the candidate geometric entities need to be tagged as the corresponding die/mold identification by an algorithm. Many factors could affect the final classification, such as through holes and tolerance requirements. At present, the proposed reasoning is a traversal procedure based on morphological characteristics such as convexity and concavity. For those regions which can be covered by either side from a geometric perspective, an user assistance interface is designed to acquire the design intent.

The linkage information is represented by face groups. A face group is a set of face elements with the parting definition as the boundary and with a draw direction to

describe the movement direction of the corresponding die/mold. In this approach, manufacturing information can be strongly coupled with geometric data to form a complete part model, to support manufacturability evaluation, and to facilitate the necessary shape transformation.

3.5.3 Manufacturability Assessment Module

The reasoning about the linkage relationships incorporates the downstream manufacturing information explicitly into the part design stage. It helps designers to consider die/mold issues during part design. Design concerns such as die complexity, tolerance/cosmetic, ejectability, draft and round/fillet requirements, etc., can be fully integrated into the proposed representation and associated with manufacturability assessment to ensure design for manufacturability.

The proposed manufacturability assessment is organized as shown in Figure 3.8, including the available data representation and two levels of assessment: evaluation and modification.

For the lower-level geometric data such as faces and edges, the system can evaluate whether a face causes an undercut or needs a draft to enhance ejectability and whether an edge needs round/fillet modification to improve the manufacturability. If a face causes an undercut problem, the system will reason whether it can be removed if the face is covered by another die/mold member such as a moving core/slide or another die half through the operation of face-group refinement. For faces that need draft or edges that

need round/fillet, empirical design guidelines are incorporated to establish the correct draft angle or round radius for shape modifications.

Figure 3.8: Manufacturability assessment module

Face groups generated from the linkage module provide the representation for reasoning about some problems globally. For example, to ensure the design rule "tight tolerances should be kept in the same die member", we can check the definition of each tolerance to see whether its reference elements are within the same face group, i.e., covering by one die/mold member. Moreover, the profile of a face group describes the insert shape and the envelop of a face group defines the minimum size of the insert block, which provide useful information about dies/molds. Global reasoning also provides the means to

evaluate parting proposals and therefore a desirable parting definition can be selected to eliminate most difficulty and to control cost.

CHAPTER IV

COMPUTER-BASED PARTING SPECIFICATION

4.1 Overview

Several reported algorithms were reviewed in Chapter III for the extraction of parting information. Those algorithms attempt to recognize the optimum draw direction based on the principle of the minimum number of required cores (Chen et al, 1993; Hui and Tan, 1992), and to identify the suitable parting-line locations along the specified or extracted direction (Bhargava, et al, 1991). In general, reasoning algorithms cannot easily incorporate other design principles and/or exactly locate the parting lines on a conceptual design.

To make a system practical, automatic reasoning algorithms should be organized around a custom user interface which contains several options related to the various design principles. This provides a designer the freedom to express his design intent with or without the help of reasoning mechanisms. This chapter will focus on the issue of computer-aided parting description, including the usage of the user interface and several design examples.

4.2 User-Interface Design for Parting Information

A parting proposal associated with a part design contains two fundamental items, i.e., draw directions and parting locations. The required draw directions used for a part design depend on many factors including the number of die/mold components. Also, parting location can be classified into three types. The place where the cover die and the ejector die meet are called either an external parting line or an internal parting line, depending on the location of the associated part face. The adjacent area of moving cores or slides, if used, is called a parting interface. In most cases, draw directions and parting locations should be determined simultaneously by considering both geometry and manufacturing issues at the same time. This section will outline some useful strategies for the specification of a parting proposal in an integrated system.

4.2.1 Draw Direction Selection

It is difficult to cover both geometry and process concerns in a single algorithm which can compromise among competing rules and provide useful data. For example the design principles, "locating the maximum projection area" and "minimizing the required number of cores", result in different draw selections such as in Figure 4.1.

To incorporate different heuristic rules or empirical knowledge, a custom user interface is proposed in Figure 4.2 which integrates the reasoning with design principles and allows designers to work with different design issues. This organization provides three levels by which designers can describe an intuitive parting proposal if the information is not extractable from reasoning algorithms.

Figure 4.1: Draw selection in competing factors

Figure 4.2: User interface for the determination of draw direction

In the first level, a draw direction can be extracted by reasoning principles, such as minimizing die/mold members and minimizing the draw depth. It can also be specified by the user based on geometric entities on the part or vector input. The second level shows the reference information. For example, the minimum depth can be defined in terms of the principle axes or the convex hull information of a part. The geometric entities used to describe a draw direction can be the normal vector of a selected face or the direction

formed by two specified vertices. This direction can also be specified by vector input if the user knows the desired (x, y, z) values. The third level provides viewing functions to examine the part in the selected draw direction. The implementation at this time only supports the selection based on either envelop box along three principle axes, geometric entity or vector input.

4.2.2 Parting Line/Interface Location

As was done with draw selection, three modes are proposed to associate parting locations with existing geometric data describing the part. These modes are organized in the first level of the menu for the parting-line locations, which are:

1) Automatic recognition mode: One feature of parting lines is that the location is usually at the extreme external regions (silhouette edges). This means the identification of the external parting lines can be done based on two types of data: part convex hull and projection of part entities along some particular direction (i.e., draw direction). The first one is based on the maximum projection of a part. This also means the major draw direction is dependent on the envelop information. The second one provides more flexibility in choosing draw direction first, then determining if the parting line is feasible for the selected direction. Neither approach can actually locate the position of the parting lines because the mapping from the external contour to the part is generally one to many, i.e., only the surfaces on which the parting lines must fall can be identified.

2) User-specified mode: Since the parting line locations can not be uniquely identified by available reasoning procedures, a more practical way to associate the

parting line with the geometric data is to ask for user input to help guide the construction. The parting line could be related to edges already existing in the database or crossing certain faces. A custom interface is proposed to allow users to specify the parting line information related to various kinds of geometric entities.

3) System-aided mode: For complex parts, users may find it is quite difficult to specify every detail about the parting line in user-specified mode. A hybrid approach will be more feasible in practice. Since the information generated by reasoning procedures in the first mode basically describes the "best" regions for parting lines, we can use it as a check or help for users' input. In this approach, users still have the freedom to define what they want but with extra system-aided information.

For the automatic reasoning approach, a feasible way to extract parting-line locations is using the concept of silhouette contour defined by a particular view direction (Crow, 1977; Bhargava, et al, 1991). The algorithm developed by (Ren, 1994) can be used to extract silhouette contours of planar and simple quadratic surfaces for parting locations in the implementation. The procedure contains the following steps:

1. Select draw direction (as specified using functions shown in Figure 4.2),
2. Compute surface visible portions and create virtual edges,
3. Extract contour edges between visible and hidden regions,
4. Project extracted contour edges into a 2D plane,
5. Derive silhouette edges from projected contour edges,
6. Identify 3D geometric entities from silhouette edges, and
7. Use interface to specify parting-line locations if the mapped 3D entity is a surface.

As mentioned, the mapping from the projection to parting location, in general, is not unique, i.e., step 5 to step 6. This is illustrated by an example in Figure 4.3. Therefore the parting lines may not be identified as exact locations. However the mapped geometric entities provide useful information from which at least we know the most exterior and interior regions and the possible range for parting locations. Based on this data, the system can ask users to specify more details about parting-line locations or the system can use it to verify users' definition. If some specification falls in the regions between an interior contour and an exterior one, this section can be identified as invalid.

Figure 4.3: The mapping from the projected silhouette contours to the part geometry

It may not be practical to ask users to specify all segments of the parting line especially for very complex parts. To simplify the input procedure, the system is designed to request only the external parting lines, i.e., the locations between the cover die and the

ejector die. Then reasoning algorithm will identify the related internal parting lines as well as other parting interfaces.

Figure 4.4 shows the menu structure for the input of parting locations, which is generally applied to these three types of parting data. It can be used for the external parting when entering the system. Also it can be used to specify the internal parting lines, if requested later during the reasoning.

Figure 4.4: User interface for parting-line specification

4.3 Parting-Line Specification

This section will introduce a general description tool which can be used as an input device to specify the wanted parting locations. The input interface for specifying external parting lines is designed as two interactive options, named *By Reference* and *By Location*.

4.3.1 By Reference Entities

A practical parting proposal should be as simple as possible to reduce die/mold complexity and tooling cost. If possible, plane types of parting surfaces are always the best choice. Bhargava et al. reported various types of simple parting proposals, commonly used, shown in Figure 4.5 (Bhargava et al, 1991). From a parting surface point of view, Figures 4.5(a) and 4.5(d) are actually the same.

Figure 4.5: Various kinds of parting surfaces (Bhargava et al, 1991)

The "*By Reference*" option is proposed for this purpose. Two types of reference entities, face and datum, are organized in this option. Figure 4.6 illustrates several examples of using them in the parting description. In Figure 4.6(a), a datum plane is used as a reference entity on which the exterior intersection with the part is defined as the parting input. The selected datum entity embeds the definition of one or more parting surfaces which will be used later for the construction of die/mold blocks. The

concept can be extended to a set of datum entities for angled or stepped parting planes in Figure 4.5.

Figure 4.6: Parting-line locations specified by reference entities

Figure 4.6(b) uses the external contour of a selected face as the parting specification. Examples of multiple selections are shown in Figures 4.6(c) and 4.6(d). In these cases, the system will merge the selected entities as contours and then choose the external one as the description. This can be done by removing the common edges shared among the selections and by collecting what left starting from an exterior one. The internal contour could be the candidate parting depending whether it is part of a through feature which will be recognized in the linkage generation module.

4.3.2 By Locations

Geometric data resulting from part modeling in general is not sufficient to describe all possible partings of a part. For example, if the parting line is crossing a surface as in Figure 4.7, the position of parting lines can not be explicitly defined in terms of existing edge entities. The "*By Location*" option provides users tools to describe the location directly based on a combination of entities including an edge, a point along an edge, a point on a surface, and a vertex. Each is shown in Figure 4.7.

Figure 4.7: An example of parting lines specified by location entities

4.3.3 A Combination Input

Beside the two options mentioned above, the system also provides a combination operation. Whenever the entities selected in the "By Reference" option form two or more external loops, the system will enter this option and ask users to select two edges each of which belong to different loops. The selected edges are removed from the list, making the two selected loops open. Then users enter the "By Location" option and add new entities to close the two open loops. This demonstrates the flexibility provided by the interface design such that particular case can be easily specified. Figure 4.8 is an example of combined operations.

(a) Design example

(b) Interactive operation and the related menus

Figure 4.8: Parting-line locations specified by combination operations

4.4 Parting-Line Segment Representation

The selections possible from the user interface mentioned above range from face types to point locations. Therefore, the elements of an user-input list are not homogeneous. Figure 4.9 outlines the data storage of possible users' input based on the user interface of the system. The data of the user input list, no matter which options have been chosen, are transferred into a uniform parting-line segment structure which will be discussed later.

Figure 4.9: User-input data list for parting definition

To simplify the procedures of deriving the parting definition, as well as to facilitate the checking of parting validity, the specification is converted into a homogeneous list and represented as a segment structure which fits within the B-rep hierarchy and includes three types of data: segment, line and point, as shown in Figure 4.10.

Closed: the last point is the same as the first point.

Seg_j a PL segment defined by a set of lines on the same face

Lin_j a PL element defined by two points

Pt_k a PL point defined by (x, y, z) on the part shape

Figure 4.10: Parting-line segment structure

A segment is a collection of line elements on the same B-rep face entity and serves three functions. First, it provides the base for checking parting validity. Second, the segment data facilitates the determination of the parting locations especially on sculptured surfaces. Third, it supports the "split" function to generate the elements for die/mold modeling.

4.4.1 The Validity of Parting Specification

A valid parting specification input should be located on the external part surfaces because parting line is the place where a part and its die members meet together when the die closes. When users specify the input through the user interface, the definition could be invalid for three kinds of reasons. First, the definition does not entirely fall on those exterior surfaces. Second, the specification is not complete or not closed. Third, it may not be entirely located on the part shape, i.e., some portion is inside or outside the part.

For the first case, the system can check the input based on regions from the silhouette contours. And the detection about whether the input is closed or not can check the connectivity of the input list to see whether the first point of a parting line is the same as the last point of the previous one. If not, the system can either ask users for more input data. For verification of the third case, Figure 4.11 gives two examples in which parting specification jumps between edges or between surfaces.

The segment structure can facilitate the reasoning of parting validity because line elements within each segment should start and end at the boundary of the corresponding face. Whenever the definition from one segment to another one does not contain data on the common edge of two adjacent faces, we know the input is not specified along the shape and therefore is invalid.

Figure 4.11: Invalid parting-line specification

4.4.2 The Interpretation of Parting Location

The proposed face-based segment structure also supports the interpretation of parting locations. Since the input data may not satisfy the needed points to exactly fit the curvature of a sculptured surface, extra points may be required, depending on the surface type. For example, two points are used to define a line exactly on a plane, three points are required for a curve on a quadratic surface, etc.

The PL segment structure represents the parting data in a face order. Each segment only stores the data for one face. Therefore the system can easily verify the definition of the segment list, face by face, by checking how many points are required based on the face type and how many points have been specified. An example is shown in Figure 4.12.

Figure 4.12: Segment structure for the parting details

Exactly locating the parting position mathematically is wonderful but it may not be desirable in all cases. Because a parting definition with high curvature will increase the difficulty in tooling parting surfaces, and therefore increase the die/mold cost as well as maintenance difficulty. The die/mold components in die casting and injection molding should be as simple as possible once they meet the manufacturing requirements.

A practical way to interpret parting location is based on plane types of parting surfaces. In this approach, each line element in the PL segment is first associated with the selected draw direction to create a datum plane. This datum is a parting plane between die/mold members. Then this datum is used as a reference entity to calculate the intersection of the corresponding face to define the location of a parting line. The intersection uses two points of the line element as the boundary. The drawback of this approach is that the parting line is only maintained in C^0 continuity but loses higher orders (i.e. only a common point between two adjacent parting lines but not a common tangent line or equal curvature at that common point).

4.4.3 The Linkage Between Part Design and Die/Mold Design

The segment structure mentioned above supports flexibility of parting description and its hierarchy is naturally related to the B-rep topology structure. Through the user interface for parting design, users can easily specify the major draw direction and the external parting-line locations. The specification is then aggregated with the extracted CAD geometric data for "split" operations which generate the required geometry entities to address the die/mold issues.

In other words, this scheme provides us the paradigm for a complete part definition, including a part model, the required manufacturing information and the related die/mold linkage, and therefore it is suitable for the integration of design activities in various phases. By using this scheme, manufacturing information such as parting issues can be tightly coupled with the geometric data of a designed part. The usage of PL segments in "splitting" geometric entities to derive the linkage between part design and die/mold design for manufacturability assessment will be discussed in the next chapter.

CHAPTER V

GEOMETRIC REASONING FOR DIE/MOLD LINKAGE GENERATION

Chapter IV describes a prototype system with parting design functionality. The system provides a custom user interface to allow users easily to incorporate parting proposals with geometric data. In general, a complete parting description includes external parting lines, internal parting lines and parting interfaces. The strategy used for a parting definition starts from users' specification of the external parting lines. Then the system recognizes other parting details including internal parting lines and parting interfaces during the generation of the data linkage between part design and die/mold design. This chapter will introduce the data linkage generation module, including the association and aggregation operations for reasoning the linkage, and the face-group data representation.

5.1 Data Refinement Procedure for the Linkage Information

The linkage generation module is used to rebuild pieces of the part to address die-related issues based on a parting proposal. To generate the embedded data linkage for the detailed coverage of die/mold components, two types of data refinement operations are required, namely association and aggregation. Association creates all the necessary entities for modeling dies/molds, and aggregation reasoning, then, groups these entities into the corresponding sets. Figure 5.1 outlines the whole picture of this module.

Figure 5.1: Data refinement from part design to die/mold characterization

5.2 Association Reasoning

There are two purposes behind the association reasoning discussed here. First it associates the external parting lines specified by users with the extracted B-rep part description from the CAD database. Second it prepares the geometric elements required for modeling the die/mold configuration which is implicitly embedded in the parting definition.

For the first purpose, the system needs to refine the particular B-rep schema of the CAD database. A typical example is that two separated face regions of a part solid model may have the same identification, but they may be covered by different die/mold components

when the part is produced. Also any entity intersected by the parting specification should be identified and split into various sections for the modeling the die/mold.

5.2.1 Separated Face Regions

In a B-rep structure, geometric data is represented by three or four levels of topological entities, i.e., face, (loop), edge and vertex. In general, the B-rep schema of face and loop levels could be different from system to system. One face entity could have only one external loop with or without internal contours. It is also possible that more than one external loop shares the same face identification to emphasize that these external loops are created by the same operation during modeling. That is, the construction history may be reflected in the converted B-rep data. Therefore using different modeling operations to construct the same part may result in different geometric data instances.

For example, adding a slot on the top face of a block as in Figure 5.2(a) will separate the top face into two regions (two external loops). They both are originally on the same plane, the B-rep converted from feature-based modeling may still share the original face identification to index them as shown in Figure 5.2(b). In this case, the two separated regions have the same identification. Maintaining the construction history along with the detailed geometric data simplifies the reversal of the operation, e.g., deleting the slot. However entities with the same identification derived from modeling operations may not have the same characteristics from the manufacturing point of view, e.g., covered by the same die/mold member.

Figure 5.2: Separated regions with the same identification

To ensure the modeling concern do not affect the manufacturing issue in the wrong way, it is better to represent the B-rep model based on the shape nature. Therefore any extracted face with multiple external loops is stored as a set of separated regions in this research. Each separated region is named a face area which has only one external loop to indicate the standing-alone characteristic.

In the representation, the term "*Face Area*" is added between the levels "*Face*" and "*Loop*" of the traditional B-rep hierarchy as shown in Figure 5.3. Figure 5.3 also shows the data classes used in this research, such as *FG_Area* for a separated face region, *FG_LpEg* for a list of data elements, and *FG_Data* for a generalized data element. Edges are the fundamental entities for this application and represented by *FG_Data*, which contains pointers and identifications to communicate with a CAD database, and flags to distinguish their application attributes such as concavity or convexity.

Figure 5.3: B-rep data structure for the data linkage generation

Based on the proposed representation, two types of operations are required. First, the internal loops of the same face with several separated regions are stored in the corresponding "Face Area". Second, for each edge, the identifications of two adjacent faces needs to be indexed in terms of the face-area structure. That is, the winged-edge structure used in two-manifold modelers (Baumgart, 1972) is maintained in this structure for the topologic consistence. To facilitate the reasoning algorithm, each separated region has attributes to indicate its range in the UV domain and its ejectability (0, 1, 2, or 3) with respect to the selected draw direction, and each edge has a convexity attribute based on the solid angle between its two adjacent faces.

5.2.2 Split Operations

If the parting specification is not entirely defined in terms of edge entities, the algorithm needs to identify which geometric entities have been intersected by the parting specification, i.e., it will be covered by two or more die/mold components. The detected entity should be split into sections. The separated sections are extra B-rep entities for die/mold modeling. Meanwhile the topology relationships, e.g. winged-edge structure (Baumgart, 1974), is maintained between the split edge sections and the split face regions. Figure 5.4 gives a special case of the proposed split operations by using the PL segment structure.

Figure 5.4: Geometric entities split by parting-line segments

As shown in Figure 5.4(a), the parting specification is defined by four lines and five points on a part face, F_j . The corresponding PL segment representation is shown in Figure 5.4(b), associated with the related geometric information. For example, in this case, the segment Seg_i is related to the face F_j , points Pt_2 and Pt_3 are associated with E_j , and point Pt_5 is associated with E_j .

The segment structure facilitates the proposed splitting operations in a bottom-up manner. Based on the parting points along an edge, an edge-split flag is associated with that edge, e.g., PL_2_EG for the edge E_j and PL_3_EG for the edge E_i in Figure 5.4(c), and split it into various sections. If the entire edge or split section is defined as a parting line, it will be tagged as PL_1_EG and associated with the parting line, such as the split section E_{j2} and the parting line Lin_{j2} .

For any face crossed by the parting definition, the untagged line elements in the PL segment are then used to split the face. In this example, the parting-line element, Lin_{j2} , has been tagged with E_{j2} . The untagged line elements in Figure 5.4(b) will be separated as two sets, one for Lin_{j1} and the other for Lin_{j3} and Lin_{j4} , which will cut the face, F_j , into three pieces as shown in Figure 5.4(d).

Compared with the approach of splitting parts, the proposed operations separate the B-rep entities into the required details and manipulate the extracted B-rep data representation in a non-manifold way (Weiler, 1988), which is a very simple way to create the required entities for modeling dies/molds based on the traditional B-rep model.

5.3 Aggregation Reasoning

Aggregation reasoning is used to further classify the geometric entities (with and without split sections) into a higher abstraction form, i.e. a face group. This reasoning is basically a traversal procedure by taking a particular die/mold flag and starting from the geometric entities directly adjacent to the external parting lines. Several important concepts to facilitate the aggregation reasoning will be introduced here.

Considering the silhouette algorithm has been used to identify the extreme boundary elements, the external parting lines specified by users can be checked for the validity as described in Section 5.4.1. For any valid external parting input, a part without through depressions can be easily separated into two groups by removing parting lines from the B-rep topology graph. Figure 5.5(a) - (c) gives an example. In this case, the traverse propagation will remain within one die/mold member once it is not crossing the parting definition.

On the other hand, if a part has through depressions, the separation can not be done simply by removing parting entities. As shown in Figure 5.5(e), even once the entities associated with the parting definition have been removed, the B-rep graph is still connected via the entities of the through hole. For parts with through entities, the grouping function for generating the data linkage can not be done by a simple traversal procedure without reasoning about those regions. Because depressions or through features which contain face entities connecting to different die/mold members could make the propagation fail, i.e., passing from an entity of one die/mold member to another.

Figure 5.5: Entity propagation for die/mold tags based on parting definition

Most designs in either injection molding or die casting have depression features in order to remove extra volume or material to achieve weight reduction, uniform wall thickness or material saving. To identify those regions, two types of reasoning are used in this research, local characteristics and global attributes. From the literature review, two types of data, edge type and face adjacency, have been widely used to describe the local geometry shape and to classify the extracted data into depressions. A similar approach is adopted. The difference is that we will test each classified depression along its boundary and against the selected draw direction to provide us the global attributes for the linkage

generation. From the testing, we will also identify the possible internal parting lines and parting interfaces.

5.3.1 Edge Type and Face Adjacency

Edge type and face adjacency are used to locally characterize geometric shape based on the B-rep entities and to classify the extracted data into depression regions. In a two-manifold modeler, two surfaces are adjacent to each other along a common edge. Based on the solid angle between them, edge entities can be classified into five types: convex, concave, smooth convex, smooth concave and smooth mixed (Sakurai and Gossard, 1990). Using the morphological characteristics of edge types, several algorithms have been reported to facilitate feature categorization (Kyprianou, 1980; Gadh and Prinz, 1992; Bruzzone and Floriani, 1991; Floriani and Bruzzone 1989). Figure 5.6 provides two examples using concave edges to aggregate the adjacent faces into different sets for potential regions of depression features.

Figure 5.6: Aggregation based on concave edges

5.3.2 Ejectability and Boundary Tagging Classification

The aggregated depressions provide us two kinds of global attributes for reasoning about the data linkage of die/mold information. First, a depression feature bounded by its surfaces restricts the possible draw directions to a limited range. For example, a blind hole can be covered only by the die/mold moving along single direction of its center line but if it has drafts then the die/mold can open within the core range. Several examples are shown in Figure 5.7.

Figure 5.7: Draw directions of depression features

By testing the ejectability of an aggregated unit against the selected draw directions of the major die/mold halves, **d** and **-d**, the unit can be categorized into one of the three classes: covered by only one direction (**d** or **-d**), covered by both directions, or against

both directions. This characteristic is called the ejectability attribute of an aggregated depression.

Second, each depression is adjacent to other entities of the part model by its boundaries or the placement information as shown in Figure 5.6. The adjacent surfaces of its boundaries are called the placement surfaces of this region. Using their tagged die/mold flags in reasoning is called boundary tagging classification.

During traversal, if the ejectability attribute of an aggregated unit shows that it can be covered by only one direction, we check whether this direction is the same as the direction(s) used for the placement surface(s). For consistent aggregated sets, the reasoning will automatically classify them into the face group of the placement surface(s). If an aggregated set is against both draw directions (**d** and **-d** specified by users), it will be organized as an individual face group which indicates a moving core/slide (extra die/mold members) is required in the die/mold construction to cover the entities of this set.

5.3.3 Internal Parting and Slide Interface Locations

It is still possible that some entities are unrecognized from global attributes after the traversal, e.g., a through hole without draft. For those entities or regions, the system will ask the user to specify the desired classification: one of the two major die/mold halves or an additional moving member. To facilitate the specification, the internal parting edges associated with the design will show on the screen. Internal parting edges are those edges whose two adjacent surfaces have been aggregated into different face groups derived from the aggregation reasoning and/or users' specification.

Figure 5.8 contains two examples; one is the automatic aggregation and one is classified by the users' specification. In Figure 5.8(a), the taper on the hole requires ejection upward so the hole is associated with the top face and the hole contour on the bottom face is classified as an internal parting line. In Figure 5.8(b), both directions, d and $-d$, can be potentially used for the die/mold forming this hole. In this case, the system will highlight the hole and ask users to specify their intent. Once one is selected by the users, the hole will be associated with the appropriated face and the hole contour on the opposite face will be identified as an internal parting line.

Figure 5.8: Internal parting locations generated through face groups

If the hole is too deep, it may not be practical to use only one die/mold member to cover the whole surfaces. To facilitate the parting design of the configuration of two die/mold members for one depression, the user interface mentioned in Chapter IV can be used for the specification of the internal parting lines. The required function is performed by the

"*System-aided*" mode, shown in Figure 4.3, in which the surfaces of the depression are used as the constraints for the input.

From the die/mold perspective, two adjacent depressions may be constructed in the some die/mold member. The system has the capability of identifying the adjacent depressions through their shared boundary contours. During data linkage generation, the system will verify adjacent depressions and ask users whether they should belong one die/mold set. Figure 5.9 give an example.

Figure 5.9: Slide refinement based on adjacent depressions

5.4 Data Refinement Procedure and Face-Group Representation

5.4.1 Data Refinement Procedure

The data refinement procedure for the data linkage generation can be organized in the following steps, with a flow chart shown in Figure 5.10 :

1. Check whether the parting specification is totally associated with edge entities. If not, request split operations to generate the explicit elements for face-group classification.
2. Tag the face and edge entities of both sides of the parting definition as either *Die_1* (based on the selected draw direction, **d**) or *Die_2* (based on the opposite one, **-d**).
3. Traverse through the edge loops of the tagged surfaces, recursively from one face to an adjacent one and individually within each face group. If the edge is concave, the propagation will aggregate the adjacent surface. If the edge is convex, the classification will enter the adjacent surface only if it can be covered by the same draw direction of the current one but not by the inverse direction.
4. For those untagged elements, use concave edges to aggregate the adjacent surfaces as different unrecognized sets. For each set, derive its ejectability attribute and the die/mold tag(s) of its placement surface(s). If consistent, automatically aggregate it into either face group *Die_1* or *Die_2*. If not, ask user to classify it into either face group *Die_1*, *Die_2*, or additional ones *Die_X* ($X > 2$).
5. For those sets tagged as *Die_X* where $X > 2$, the connecting relationships among them will be recognized. Then ask users to identify whether the connecting ones are

constructed by one die/mold member. Also ask user to specify the desired draw directions for extra moving components.

Figure 5.10: Data refinement procedure for linkage generation

5.4.2 Face-Group Representation

The generated unit recognized by the above procedure is called a face group. A face group is a higher abstraction element which can be treated as a surface feature derived from lower-level B-rep data for addressing die-based indexing issue. The representation of face groups associated with a parting proposal in a part is shown in Figure 5.11.

Figure 5.11: Face group representation for the data linkage

In general one part is formed by at least two die/mold members, i.e., cover die and ejector die. In face group representation, they are addressed by *Die_1* and *Die_2*,

followed by the selected draw direction $\mathbf{d}$ and the opposite one $-\mathbf{d}$. The reasoning result will be stored as a list of face groups represented by data structures named *FG_Die*. During reasoning, *FG_Die* is also used to store the geometric entities of the depressions, which are classified by the concave edges.

A face group is a set of face elements with the parting definition as the boundary and with draw information as the moving direction. The parting definition, both the user-specified external parting lines and the system-recognized internal parting lines or slide interfaces, of each face group is stored in the data record *lps*. And the information about adjacent face groups which have at least one common edge with the proposed face group is stored in the data record *fgs*. Data records *lps* and *fgs* are used for the boundary data of a face list in the structure *FG_Die*. Therefore depressions can be checked for the adjacency relationships. Also the internal parting lines between the major die/mold halves and parting interfaces caused by the moving cores/slides can be easily identified based on these records.

Each element of a face group is a complete or partial face, defined in the CAD database or split by the association operation based on the parting definition, which is represented by the data structure named *FG_DieND*. A node *FG_DieND* is an element of the face-area level under which a set of low level entities such as loops, edges and vertices are grouped.

CHAPTER VI

GEOMETRIC-DRIVEN MANUFACTURABILITY ASSESSMENT

6.1 An Overview of Geometric-Driven Manufacturability Assessment

The generation of the data linkage between part design and die/mold design is a data refinement procedure which rebuilds pieces of the part to address die-related issues based on a parting proposal. The representation of face groups is basically constructed by two types of data: manufacturing information and geometric data. In this approach, manufacturing information can be strongly coupled with geometric data to form a complete part model which supports manufacturability assessment and facilitates the necessary shape transformations to achieve a manufacturable part in a straightforward manner.

The proposed system incorporates the face group representation as the refined part model to support the geometric-driven manufacturability assessment. In general, two levels of capability are required. One provides evaluation capability, pointing out problems as early as possible. The other helps designers with functions to eliminate the detected problems. In this research, evaluation reports are created by evaluating the design in terms of tolerance and ejectability issues. Then users can go to the details about the detected problems to modify or redesign the part. Figure 6.1 shows the

overview of the user-interface design. Since the underlying implementation is modularized, the proposed user interface can be changed flexibly in terms of specific custom requirements.

Figure 6.1: User interface design for manufacturability assessment

At present most of the functions in each of the system features described have been implemented. The implementation is fully integrated with the Pro/Engineer CAD system from Parametric Technology Corp. This chapter will give a general view of manufacturability assessment, starting from a real design example for face group generation.

6.2 A Design Example for Face Group Generation

To demonstrate the implementation of the data linkage generation mechanism mentioned above, a real part is analyzed step by step, starting from users' input to the final result. In Figure 6.2, the user first specifies the wanted parting proposal by using the interface mentioned in Chapter IV. In this example, user can define the draw direction of the two major die/mold halves by using the shortest edge of the envelop of the part. The external parting lines are defined by selecting the bottom face in the "*By Reference*" option.

Figure 6.2: Specifying a parting proposal

Based on the input, the system will retrieve the external edges of the selected face and define them as the external parting lines as shown in Figure 6.3. Then the reasoning will check whether there is any entity intersected by the parting definition. In this example, all the parting locations are defined by edge entities and therefore a split operation is not required.

Figure 6.3: Recursive propagation starting from the parting definition

The data linkage reasoning will traverse from the two adjacent faces of each specified parting line. The traversal propagation will carry one die/mold flag for each side of the parting definition recursively from one face to an adjacent one through the common edge. At this moment the recognized geometric data will be classified into two face groups for the two major die/mold member. During the traversal procedure, the convexity of the common edge and the ejectability testing of the adjacent face are used to decide whether the propagation should stop.

In general a convex edge in an internal loop is the boundary of a depression region, which will stop the propagation. As a result the traversal of the design will recognize several external entities as shown in Figure 6.3. Unrecognized face elements are highlighted in Figure 6.4.

Figure 6.4: A list of unrecognized entities

For the unrecognized face elements, the system collects them into a list which contains the unrecognized B-rep entities including loops and edges. Then the concave edges are used to further classify those faces into a set of depression units. The classification is also a recursive procedure which aggregates the entities of the list into one depression unit at one time.

The procedure is as follows. Starting from one concave edge in the list, first get the two adjacent faces and test whether they are in the list. If positive then aggregate them into one unit which is represented by the structure *FG_Die*. Then, try to find another concave edge from the edges of the aggregated faces in this unit, get its two adjacent faces and check their status; if the face is in the unrecognized list, then remove it from the list and place it in this unit.

The procedure repeats the above steps until no face can be aggregated from the concave edges into this unit. If there is still element in the unrecognized list, the algorithm will find another starting concave edge in the list, create a new depression unit, and then proceed with the mentioned steps. For those elements which can not be recognized by

the traversal procedure and also can not be aggregated from depression classification, we leave them in the list until the final step; either using their boundary tagging information or asking users to classify them. The result of the depression classification for the design example includes 13 units as shown in Figure 6.5.

Figure 6.5: Unrecognized entities aggregated by concave edges

The aggregated depression units are tested against the selected draw direction to classify them into four types. The testing generates sampling points on each face of the depression unit and derives a normal vector for each sampling point based on the curvature of the point's position on the surface. Ejectability can be evaluated by the angle between the normal vector and the draw direction.

If the angle at a point is less than 90 degree, we define the point covered by the draw direction and it passes the test. One unit is classified into the face group of *Die_1* only when all the sampling points have passed the test of the draw direction, $\mathbf{d}$. The same test is proposed for the face group of *Die_2* by using the opposite draw direction, $-\mathbf{d}$. If the

angles of all sampling points are 90 degree, we define the unit can be covered by both directions. Otherwise, the unit will be classified into the face group of a moving core or slide. Figure 6.6 shows the result of the ejectability testing for those depression units recognized and shown in Figure 6.5.

Type A: Only Covered By *Die_1* : None

Type B: Only Covered By *Die_2* : 3 Depression Units

Type C: Covered By Both Sides : 7 Depression Units (Ask Users)

Type D: Neither Side Can Cover : 3 Depression Units (Moving Cores/Slides)

- Checking Adjacency Relationships

Figure 6.6: Classification of the aggregated depression units

Based on the ejectability classification, the system will ask the user to specify the grouping of depression units which can be covered by both directions. And for those classified as face groups of moving cores/slides, the system will further check their

adjacency relationships and ask the user whether the connected ones should be covered by one die/mold component.

If the user specifies that all of the depression units classified as Type C in Figure 6.6 are covered by *Die_1*, and the two adjacent depression in Type D in Figure 6.6 are covered by the same die/mold component, the final result, shown in Figure 6.7, is that four face groups are used to address the data linkage between part design and die/mold design based on the input in Figure 6.2.

Figure 6.7: Final reasoning result after users' verification

In addition to generating the explicit representation between part design and die/mold design, users will also find that the proposed aggregation procedures will help them, especially for the beginners, better understand details about the die coverage information,

including the depression details and all the necessary parting locations and interfaces between different die/mold members.

6.3 Manufacturability Evaluation

As shown in the above example, the B-rep entities of a part description are organized into a list of face groups which provide the detailed coverage of the corresponding die/mold components. From a global point of view, the part has been rebuilt to define die/mold members and the part model has been reorganized in terms of the data linkage between part design and die/mold design. Therefore typical concerns can be evaluated. Currently the system can provide two kinds of evaluation reports: ejectability and tolerance.

6.3.1 Tolerance and Cosmetic Issue

It is hard to meet tight tolerance specifications or dimensions formed between moving die/mold members because they can be separated slightly by the loading associated with the injection of molten material. Dimensions with critical tolerances should relate to only one die member. Similarly, cosmetic surfaces or surfaces with a strict surface finish requirement cannot be crossed by the parting line. Minute imperfections in the manufacture of the dies or molds, which are impossible to eliminate, will result in blemishes on the surface along the parting line.

The work on tolerance evaluation depends on having the parting definition, and an identification of the faces which are formed by specific components of the die. In essence, the specification of the parting definition results in a new part geometry in

which certain faces are split as they will appear in the finished part. It is this process of defining, as automatically as possible, the true cast geometry which this work is about.

Geometric tolerancing provides the information of a detailed drawing used to control the size and shape of the part and the position of its features. Based on American National Standard ANSI Y 14.5, geometric tolerances are classified as three groups and five classes. The three groups are used for individual features, for individual or related features and for related features. And the five classes are form, profile, orientation, location and runout (ANSI, 1982).

To detect which geometric tolerance is affected by the parting line, the system will retrieve the specified tolerances with their reference or datum information from the CAD database. The evaluation will check any tolerance associated with geometric entities which are covered by different die/mold components or defined as the parting line. The current evaluation only provides qualitative information without argument of the tolerance value used. The evaluation result will be stored in a file and displayed on the screen to provide on-line help. Figure 6.8 is the format used in the current report.

The first two columns are the sequential number of tolerancing and the tolerance type. Tolerance value and material condition are shown in the third and fourth columns. Different types of tolerances will need different sets of references. In general, at least one reference entity is required for the specification. The B-rep entity which has been specified with the tolerance definition is shown in the fifth column, and the associated reference(s) or datum(s) will display in the sixth and seventh columns.

ID	Tolerance Type	Value	MCS	B-rep ID	Reference DTM_1	Reference DTM_2	Check
0	Straightness			152_F_1			
1	Circular			111_F_1			
2	Flatness			22_F_2			
3	Perpendicular			73_F_1	15_F_1		
4	Parallel			83_F_1	62_F_1		
5	(deleted)						
6	Parallel			15_F_1	10_F_2		CUT_.
7	Position			111_F_1	18_E_1	17_E_1	PL.
8	Surface			10_F_2	10_F_2		
9	Line			82_E_0	17_E_1	16_E_1	_PL.
10	Cir. Runout			152_F_1	11_E_0		

Figure 6.8: Tolerance evaluation report

The format used in these three columns is a triple of data which contains Id-type-data, including the B-rep identification in the CAD database; the entity type; and manufacturing information (die coverage for faces or parting association for edges). For example, 152_F_1 in the first row and the fifth column means the B-rep entity 152 has been specified "straightness" tolerancing, which is a face and which is recognized and stored in the *Die_1* face group. In the triple 11_E_0, manufacturing data "0" indicates that parting definition is not associated with or defined by this edge.

The last column is the evaluation result which contains two important pieces of information: CUT and PL. CUT means this tolerance is affected or intersected by the parting line. For example, tolerance no. 6 is intersected by the parting line because the face entity 15 refers another face entity 10 as the parallel definition. Face 15 and face 10 are covered by different die/mold members and therefore the parallel requirement may not be achieved. PL means this tolerance refers to the parting line as its reference(s) which could potentially cause some problems. Tolerances no. 7 and 9 both refer some edges which are defined as the parting locations.

The proposed qualitative evaluation is only detecting the tolerances in terms of the relationships of the die/mold information and the parting definition based on the specified entities and their references. However, quantitative evaluation of the specified values in terms of process capability is also important. This work is in progress. The quantitative evaluation will check the specification in terms of NADCA product standards to advise designers of the generally acceptability based on empirical rules which address tolerance at the lowest cost. The reported face group representation can be used to support this future work.

6.3.2 Ejectability Evaluation

Creating a part to be produced in die casting or injection molding, designers need to know whether or not the part can be properly removed from the die or mold without damage. This requires orientation the part correctly with respect to the die or mold and ensuring there are no undercuts. Also faces parallel to the draw direction must be identified and properly drafted.

If the draft interferes with functional requirements, the design is unacceptable and a more complicated manufacturing process including secondary machining may be required, or a more complicated die/mold with moving components may be required. The designers should have this information at the time the part features are constructed.

With the enhanced part model, face entities of the part are organized into sets, based on the parting proposal, corresponding to the dies or molds and associated with the draw direction used. Therefore the detection of ejectability requirements can be supported in a consistent way. Based on the face group representation, the ejectability evaluation is performed by the order of faces in each face group and tested against the draw direction used for the face group.

For each face, the testing first generates the sampling points which have normal vectors with the angle of two adjacent sampling points less than a predefined value. Currently the implementation of generating sampling points is based on a "25 degree" difference. That is, if the angle of the normal vectors at two sampling points is larger than 25 degree, the system will sample another point between them. However the desired value can be easily modified, if necessary. Then the testing will calculate the angle between the normal vector at each sampling point and the draw direction of the face group which the face belongs to.

The current implementation also uses certain critical values, 88 degree and 90 degree, to check the calculated angle. If the angle is larger than 90 degree, the sampling point will cause an undercut problem. If the angle is larger than 88 degree and less than or equal to 90 degree, the sampling point will request a draft. Otherwise, the sampling point passes the test.

A face is named as an "undercut" if it has one or more sampling points which causes the undercut problem. A face is named as "draft required" if it has one or more sampling points which require draft. If all the sampling points pass the test, the face is classified as a normal one. It is also possible that a face has both the "undercut" and "draft" problems. Organized in this way, the system can flexibly point out the problem associated with a face and the detailed locations.

6.4 Adding Geometric Details for Shape Transformation

In addition to finding problem areas, suggestions for improvements are also provided where possible. The design changes should be feasible with a minimum of tedious user input. Current system provides the capability of "Rough cut" assessment using design rules incorporated with some predefined features in the shape transformations such as adding drafts and rounds/fillets. The modification procedure can be performed either automatically by system-supported functionality or interactively by user input of simple parameters. In general the detailed shape modification should consider functional requirements and modeling limitations of CAD tools. Some issues will be discussed here but more research is still required to reach the final goal.

6.4.1 Undercut Removal

Undercuts are those regions in a casting which block die closure or opening and can not be removed without the use of moving cores or slides. From a manufacturing point of view, undercuts will increase die complexity and maintenance cost. The extra die members also introduce more flash, which needs secondary operations to be trimmed.

Shin and Lee detected the interference faces in terms of die/mold components (Shin and Lee, 1993). Based on their approach; parting line associated edges are first used to generate the die/mold components by Euler operations. Then the interference faces are detected for each die/mold base. In general their approach has the same drawbacks of specifying parting locations by splitting the part into sectioned components. Also it may not be practical to generate the detailed die/mold components for a conceptual design.

Rosen presented algorithms to classify undercuts into internal and external types depending on the accessibility of moving die members (Rosen, 1994). Figure 6.9 shows the general undercut types.

Figure 6.9: Undercut classification for undercut removal

It is usually hard to remove internal undercuts which should be avoided in the design. Also he distinguished the external undercuts as extensive or not extensive (Rosen, Dixon, Poli, and Dong, 1992). Extensive undercuts, which are not caused by circular holes or depression features, sometimes can be eliminated by changing the parting line location if there is no intersection region between them.

Compared to their approach, a different strategy to remove possible undercuts has been shown in this research. Here we incorporate ejectability attributes during reasoning and explicitly group them into the corresponding face groups to address the moving components. The reasoning algorithm for face group generation has considered the non-extensive type undercuts and therefore they will be aggregated into different face groups.

However it is still possible that faces represented in face groups cause undercuts because users' specification has been involved. But the detection will show them the inconsistent design intent. It is also possible to classify them into internal and external types by using Rosen's algorithms. A robust algorithm to remove the detected undercuts is still an open issue due to the possible geometry complexity and the design intent. In general undercut removal relies on redesigning shapes as well as the die/mold coverage issue.

6.4.2 Face Draft for Ejectability Improvement

Draft is highly recommended on surfaces parallel to the die opening direction because it facilitates ejection of castings from dies (NADCA, 1988). Empirical knowledge indicates that the required draft angle is a function of the length of the dimension parallel to the draw direction, the face type (inside or outside), and the material. Twice as much draft is recommended for the inside surfaces as for the outside ones.

The current system uses predefined features to draft the detected face. Draft features help users modify the initial part shape by two types of operations: automatically by using default values, or semi-automatically by interactively specifying some parameters as shown in Figure 6.1. In the earlier system, there was no solution for two kinds of problems shown in Figure 6.10 (Yueh et al, 1992). First, adding draft to the internal

surface first may cause the intersection between geometric entities. Second, draft should be added properly such that the product can stay on the ejector side when dies open. The proposed face group representation provides some possible solutions.

Figure 6.10: Adding drafts

With the representation of face groups, face entities have been organized based on the die/mold configuration. Since the faces adjacent to convex edges are detected during the reasoning traversal and aggregated into depression units, e.g. Figures 6.3 and 6.4. From the reasoning performed, the inside surfaces have been identified such that the order of adding drafts is basically supported by the system, i.e., performing the outside faces first, then the inside ones.

The full answer of the second problem relies on some physical model which can estimate the shrinkage effects such that the effects of both sides can be compared. However the *Die_1* and *Die_2* face groups will facilitate the required comparison. Without the physical model, we can only use different rules for different die/mold members to determine the draft angles such that the design can be insured staying on the ejector side when dies open.

6.4.3 Edge Rounds/Fillets

Rounds and fillets are two types of features commonly found between in die castings and injection moldings. Adding fillets along concave edges and rounds along convex edges with proper radii will enhance structural integrity by reducing stress concentration, and promote good material flow with reduced erosion in the die (NADCA, 1988). Empirical rules for selecting proper radii can be found in design books. Figure 6.11 shows some typical rules from (NADCA, 1988).

Empirical rules are organized in terms of the typical shape patterns such as "L", "T", "Y", and "X" shapes. Also empirical rules show that the desired radius along an edge primarily depends on the wall thickness of the neighborhood around the edge and the angle between the surfaces incident to the edge.

The key to build the mechanism to adding rounds/fillets in the system for the removal of sharp corners is the ability to reason about the shape pattern and the related wall thickness associated with the edge. As mentioned in Chapter III, volumetric and wall thickness types of information are better addressed and recognized by the voxel representation. In addition to the voxel representation, Lu and Miller also reported the algorithm to extract the shape pattern (Lu and Miller, 1993). The reported algorithm has been integrated with the system to perform the round/fillet shape modification.

Figure 6.11: Empirical design rules for rounds/fillets in die casting (NADCA, 1988)

In our approach, each edge of the design is identified whether or not it is part of the parting definition including the external parting lines, internal parting lines and parting interfaces. If not, the edge will be categorized as convex or concave types. Then the algorithm is used to extract the shape pattern and other related information with respect to the specific empirical rule applied to the edge.

The extracted information is associated with predefined round/fillet features to apply the local shape modification. The user interface includes several options shown in Figure 6.1. For special cases, users only need to pick one button and then the system can add the required rounds/fillets into all edges automatically by a default radius or by the values from an empirical rule.

6.4.4 Modeling Constraints

From the exercise of using features in local shape modification, some CAD modeling constraints are found and listed here as a reference (Yueh and Miller, 1993; Lu and Miller, 1993). For example, adding draft automatically by draft features, sometimes draft features may create some undesired shapes from the designers' point of view. Figure 6.12 gives two examples. In Figure 6.12(a), the face requiring a draft is related to some critical dimension in the design. After adding the draft, since the intersection position between faces has changed (new P.L.), the critical dimension is no longer held the same as the original specification. Also, draft may create some undesired area like Figure 6.12(b). From the modeling point of view, these undesired shapes are valid and reasonable results after modeling mathematics. In the cases shown, automatic drafting is not preferred if the shape has rigid tolerances.

Figure 6.12: Adding draft II: modeling constraints

Figure 6.13: Modeling constraints for round/fillet operations

Similarly, Figure 6.13 is a case where a coincident edge is separated after adding rounds. In this example, the coincident edge ac originally connecting Face A, Face B and Face C is stored as two sections ab and bc in a two-manifold modeler. Round 1 is applied to the section ab which connects Face A and Face B, and Round 2 is for the section bc between Face A and Face C. Since round operation will create a new arc surface tangent to the connected faces, the center position of Round 1 will differ with the center of Round 2

even the radii are the same. Thus it may make some undesired shapes compared with the original one.

Also current geometric modelers restrict the order of adding drafts and rounds. That is, drafts should be added before round/fillet operations. To facilitate the shape transformation with less effort, automatically performing shape modification is excellent but, in some cases, it will introduce some unwanted shapes. More research is still required, from both geometric modelers and manufacturing applications, to reach the final goal.

CHAPTER VII

CONCLUSIONS AND FUTURE DIRECTIONS

7.1 Research Contributions

In designing a part to be produced by injection molding or die casting, designers need to consider manufacturing characteristics of the part such as filling and ejectability from the dies as well as functional issues. The typical design cycle is iterative, laborious and time-consuming. Current CAD/CAM systems are not able to support the application tasks requiring reasoning due to (1) insufficient database, (2) mismatch in abstraction level, (3) loss of design intent, and (4) insufficient information to support design for manufacture.

Feature-based design is widely accepted as a means of providing high-level semantic information for the integration of design and manufacturing concerns. This research reviewed features technology and several reported DFM systems in terms of their representations and the evaluation methodologies. In general it is not practical to apply design-by features alone into applications such as die casting and injection molding, due to:

- 1) a large number of features needed to be defined for the realistic part complexity and sophisticated process concerns, and

- 2) the manufacturability evaluation reported is only practical for limited features domains and with very restricted capability to handling parting information.

A systematic approach has been introduced to support design for manufacturability in injection molding and die casting. In this approach, process-related information such as draw direction and parting location is strongly coupled with geometric data by the reported three modules, i.e., parting design interface, data linkage generation, and geometric-driven manufacturability assessment. Using the user interface developed in this research, part designers can easily describe the desired external parting lines. Then the system will use reasoning algorithms to build the geometric model which addresses the related die/mold configuration in terms of the face group representation. The major advantages of this approach are that it eliminates the drawback of a non-unique mapping for the parting-line determination, and the reported face group representation systematically enhance the part model with sufficient structures.

The most significant contribution of this research is the approach and the methodologies developed for modeling parts in design for injection molding and die casting. The approach can be also applied to other net shape manufacturing applications. The reasoning method of generating the linkage between part design and die/mold design is an example. The results are implemented in a prototype system with:

- 1) an integrated design environment which provides functions to specify desired manufacturing information and to communicate with a commercial CAD system,

- 2) a set of well-defined interface routines which can extract data/information, perform cavity reasoning and ejectability classification, construct a hybrid part model, modify the initial part geometry, and generate required face groups for die inserts.
- 3) manufacturability assessment for evaluation and shape modification, and
- 4) the capability of generating the data linkage information which can be used to support a variety of downstream applications as well as other net shape processes.

The prototype system has been tested on numerous real industrial parts and has been incorporated into Ford Motor Co's design for die casting design environment.

7.2 Future Directions

This research focuses on the development of the data linkage generation from the users' specification, and the application of the created part model to perform manufacturability assessment. It is also practical to include the recognition algorithms reported in previous work into the system to simplify the domain of possible regions for parting-line locations. The implementation of such integration is now under development.

The face-group representation generated in this research contains both geometric data and manufacturing information as attributes. It is a more complete part model which provides information required for manufacturing assessment as well as other die/mold applications. Cost estimation, for example, will be integrated with the system in the near future.

Some possible future work is outlined, with respect to the part design and the die/mold design, as follows, which can be integrated with current system in the architecture of Figure 7.1:

A. Applications in the Part Level

- 1) Integrate parting-line reasoning algorithms with the user-specification approach,
- 2) Enhance the interaction functions of parting-line specification,
- 3) Enhance the capability of current manufacturability assessment,
- 4) Incorporate empirical rules with tolerance/cosmetic evaluation,
- 5) Link with third party cost models to perform cost estimation,
- 6) Think about the reasoning algorithm for the selection of draw directions, and
- 7) Integrate the parting design module with visual reasoning tools.

B. Applications in the Die/Mold Level

- 1) Use generated data to facilitate die construction in a CAD system,
- 2) Incorporate with die design tools currently developed at OSU/ERC,
- 3) Transfer face-group geometric data into surface-based CAD systems,
- 4) Establish cooling system design tools using the generated data, and
- 5) Integrate design tools for die manufacture and construction with current system.

Figure 7.1: An integrated design for manufacturability environment

LIST OF REFERENCES

- Adler, R.E. and Ishii, K. (1989) "DAISIE: Designer's Aid for Simultaneous Engineering," ASME Computers In Engineering Conference, 1989, pp. 19-24.
- Alander, J.T. (1986) "Algorithms for Automatic Mould Division Design," Proceedings of Computer Graphics, Tokyo, pp. 60-70.
- ANSI Standard Y14.5M-1982, "Dimensioning and Tolerancing," United States of American Standards Institute, 1982.
- Baumgart, B. (1974) "Geometric Modeling for Computer Vision," Ph.D. Dissertation, Stanford University, August, 1974.
- Beiter, K., Krizan, S., Ishii, K. and Hornberger, L. (1991) "HYPERQ/PLASTICS: An Expert System for Plastic Material and Process Selection," ASME Computers In Engineering Conference, 1991, pp. 71-76.
- Bhargava, R., Weiss, L.E. and Prinz, F.B. (1991) "Automated Ejectability Analysis and Parting Surface Generation for Mold Tool Design," Technical Report EDRC 24-58-91, Engineering Design Research Center, Carnegie Mellon University, May, 1991.
- Bruzzone, E. and Floriani, L. De (1991) "Extracting Adjacency Relationships from a Modular Boundary Model," CAD, Vol.23, No.5, pp. 344-356, June, 1991.
- Chan, Y.K. and Knight, W.A. (1980) "MODCON: A System for The Cam of Dies and Moulds," CAD 80 4th International Conference and Exhibition on Computers in Design Engineering, Brighton, England, pp. 370-381.

- Chen, L.L., Chou, S.Y. and Woo, T.C. (1993) "Parting Directions for Mould and Die Design," CAD, Vol.25, No.12, pp. 762-768, December, 1993.
- Chen, Y.M., and Miller, R.A. (1992) "Extraction of Geometry Characteristics for Integrated Design for Process," Technical Report, Engineering Research Center for Net Shape Manufacturing, The Ohio State University, 1992.
- Chen, Y.M. (1991) "An Approach To Part Modeling For Geometric Reasoning," Ph.D. Dissertation, The Ohio State University, August, 1991.
- Chen, Y.M., Miller, R.A. and Vemuri, K.T. (1991) "On Implementing an Integrated Design-Manufacturability Assessment Environment," ASME Computers in Engineering Conference, 1991, pp. 407-413.
- Chen, Y.M., and Miller, R.A. (1991) "Feature-Based Design for Manufacturability Assessment," Technical Report ERC/NSM-D-91-60, Engineering Research Center for Net Shape Manufacturing, The Ohio State University, September, 1991.
- Chung, J.C.H., Patel, D.R., Cook, R.L. and Simmons, M.K. (1990) "Feature-Based Modeling for Mechanical Design," Computer and Graphics, Vol.14, No.2, pp. 189-199, 1990.
- Crow, F.C. (1977) "Shadow Algorithms for Computer Graphics," Computer Graphics, Vol. 11, No. 2, pp. 442-448, 1977.
- Cunningham, J.J. and Dixon, J.R. (1988) "Designing With Features: The Origin of Features," ASME Computers in Engineering Conference, 1988, pp. 237-243.
- Dewhurst, P. and Boothroyd, G. (1988) "Early Cost Estimating in Product Design," Journal of Manufacturing Systems, Vol.7, No.3, pp. 183-191.
- Dutta, D. and Hoffmann, C.M. (1990) "A Geometric Investigation of the Skeleton of CSG Objects," 16th ASME Design Automation Conference, September 16-19, 1990, pp. 67-75.

- Fathailall, A.K. and Dixon, J.R. (1994) "A Method for Early Manufacturability Evaluation of Proposed Tolerance Plans for Thin-Walled Parts," ASME Conference on Design Theory and Methodology, DE-Vol. 68, 1994, pp. 9-17.
- Floriani, L. De and Bruzzone, E. (1989) "Building a Feature-Based Object Description from a Boundary Model," CAD, Vol.21, No.10, pp. 602-610, December, 1989.
- Gadh R. and Prinz, F.B. (1992) "manuFeature: A Framework for Recognizing CAD Interactions in Design-For-Manufacturing Analysis," The 1992 ASME Design Technical Conferences-18th Design Automation Conference, DE-Vol. 44-2, pp. 91-103, September, 1992.
- Ganter, M.A. and Tuss, L.L. (1990) "Computer-Assisted Parting Line Development for Cast Pattern Production," AFS transactions, 1990, pp. 795-800.
- Gomes, A.J.P., and Teixeira, J.C.G. (1991) "Form Feature Modelling In A Hybrid CSG/BRep Scheme," Computer and Graphics, Vol.15, No.2, pp. 217-229, 1991.
- Heine, R.W., Uicker, J.J. and Gantenbein, D. (1984) "Geometric Modeling of Mold Aggregate, Superheat, Edge Effects, Feeding Distance, Chills, and Solidification Macrostructure," AFS transactions, 1984, pp. 135-150.
- Herman, E.A. (1985) "Die Casting Dies: Designing", Society of Die Casting Engineers, River Grove, ILL., 1985.
- Hjalmarsson, H., Sudhalkar, A., Gursoz, L. and Prinz, F. (1994) "Automated Model Building for Moldability Analysis," ASME International Mechanical Engineering Congress and Exposition, Chigo, Illinois, November 6-11, 1994, pp. 71-85.
- Hsiao, W.C. (1990) "Feature Mapping and Manufacturability Evaluation with an Open Set Feature Modeler," Ph.D. Dissertation, Arizona State University, December, 1990.
- Hui, K.C., and Tan, S.T. (1992) "Mould Design with Sweep Operations - a Heuristic Search Approach," CAD, Vol.24, No.2, pp. 81-91, 1992.

- Ishii, K., and Miller, R.A. (1992) "Design Representation for Manufacturability Evaluation in CAD: Beyond Feature-based Design," ASME Computers in Engineering Conference, 1992, pp. 37-44.
- Jansson, D.G., Shankar, S.R. and Polisetty, F.S.K. (1990) "Generalized Measures of Manufacturability," ASME Conference on Design Theory and Methodology, DE-Vol. 27, 1990, pp. 85-96.
- Joshi, S. and Chang, T.C. (1988) "Graph-Based Heuristics for Recognition of Machined Features from a 3D Solid Model," CAD, Vol.20, No.2, pp. 58-66, March 1988.
- Kyprianou, L.K. (1980) "Shape Classification in Computer-Aided Design," Ph.D. Dissertation, University of Cambridge, Cambridge, England, July, 1980.
- Kimura, F. (1993) "Product and Process Modeling as a Kernel for Virtual Manufacturing Environment," Annals of the CIRP, Vol. 42/1, pp. 147-150.
- Lee, Y.C. and Fu, K.S. (1987) "Machine Understanding of CSG: Extraction and Unification of Manufacturing Features," IEEE Computer Graphics & Applications, Vol.7, No.1, pp. 20-32.
- Liou, S.Y. (1990) "DIECAST: A Knowledge-Based Approach to Die Casting Design," Ph.D. Dissertation, The Ohio State University, December, 1990.
- Loper, C.R., Copur, M. and Kotschi, R.M. (1986) "Analysis of the Solidification Order in Selected Casting Sections," AFS transactions, 1986, pp. 529-536.
- Lu, S.C. and Miller, R.A. (1993) "Physically-Based Geometric Reasoning for Diecastability Evaluation," Technical Report ERC/NSM-C-94-01, Engineering Research Center for Net Shape Manufacturing, The Ohio State University, 1993.
- Luby, S.C., Dixon, J.R., and Simmons, M.K. (1986) "Designing With Features: Creating and Using a Features Data Base for Evaluation of Manufacturability of Castings," ASME Computers in Engineering Conference, 1986, pp. 285-292.

- Marefat, M. and Kashyap, R.L. (1990) "Geometric Reasoning for Recognition of Three-Dimensional Object Features," IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol.12, No.10, pp. 949-965, October 1990.
- Miller, R.A. and Waldron, M.B. (1988), "Research Issues in Process Planning for Net Shape Manufacturing," AAI88 Workshop on AI Production Planning and Scheduling, St. Paul, Minnesota, August 25, 1988.
- NADCA (1988) "Product Design for Die Casting", North American Die Casting Association, 1988.
- Neises, S.J., Uicker, J.J. and Heine, R.W. (1987) "Geometric Modeling of Directional Solidification Based on Section Modulus," AFS transactions, 1987, pp. 25-30.
- Nielsen, E.H. (1990) "Designing Mechanical Components with Features," Ph.D. Dissertation, University of Massachusetts, Amherst.
- Peckham, J., and Maryanski, F. (1988) "Semantic Data Models," ACM Computing Surveys, Vol. 20, No. 3, pp. 153-189, September 1988.
- Poli, C., Dastidar, P. and Graves, R. (1992) "Design Knowledge Acquisition for DFM Methodologies," Research in Engineering Design, Vol.4, No.3, pp. 131-146, 1992.
- Poli, C. and Shanmugasundaram, S. (1991) "Design for Die Casting: A Group Technology Based Approach," ASME Conference on Design Theory and Methodology, DE-Vol. 31, 1991, pp. 135-141.
- Poli, C. and Rajagopalan, S. (1991) "Design for Injection Molding and Die Casting: A Knowledge-Based Approach," ASME Computers in Engineering Conference, pp. 53-59, 1991.
- Pratt, M.J. (1984) "Solid Modeling and the Interface Between Design and Manufacture," IEEE Computer Graphics & Applications, Vol. 4, No.7, pp. 52-59, July, 1984.

- Pratt, M.J. (1988) "Synthesis of An Optimal Approach to Form Feature Modeling," ASME Computers in Engineering Conference, pp. 263-274.
- Ravi, B., and Srinivasan, M.N. (1990) "Decision Criteria for Computer-Aided Parting Surface Design," CAD, Vol.22, No.1, pp. 11-18, 1990.
- Ren, F. (1994) "A Silhouette Algorithm for the Parting Line Location Identification for Parts with Planar and Simple Quadratic Faces," M.S. Thesis, The Ohio State University, 1994.
- Requicha, A.A.G. (1980) "Representations for Rigid Solids: Theory, Methods and Systems," ACM Computing Surveys, Vol.12, No.4, pp. 437-464, December, 1980.
- Requicha, A.A.G., and Vandenbrande, J.H. (1989) "Form Features for Mechanical Design and Manufacturing," ASME Computers in Engineering Conference, 1989, pp. 47-52.
- Rosen, D.W. (1994) "Towards Automated Construction of Molds and Dies," ASME Computers in Engineering Conference, 1994, pp. 317-326.
- Rosen, D.W., Dixon, J.R., Poli, C., and Dong, X. (1992) "Features and Algorithms for Tooling Cost Evaluation in Injection Molding and Die Casting," ASME Computers in Engineering Conference, 1992, pp. 45-52.
- Rosen, D.W., Dixon, J.R. and Dong, X. (1991) "A Methodology for Conversions of Feature-Based Representations," ASME Conference on Design Theory and Methodology, DE-Vol. 31, 1991, pp. 45-51.
- Rossignac, J.R. (1990) "Issues on Feature-Based Editing and Interrogation of Solid Models," Computer and Graphics, Vol.14, No.2, pp. 149-172.
- Samet, H. (1990) "Applications of Spatial Data Structures," Addison-Wesley Publishing Company, 1990.

- Sakurai, H. and Gossard, D.C. (1990) "Recognizing Shape Features in Solid Models," IEEE Computer Graphics & Applications, Vol.10, September 1990, pp. 22-32.
- Salomons, O.W., van Houten, F.J.A.M. and Kals, H.J.J. (1993) "Review of Research in Feature-Based Design," Journal of Manufacturing Systems, Vol.12, No.2, pp. 113-132.
- Shah, J.J. (1991) "Assessment of Feature Technology," CAD, Vol.23, No.5, pp. 331-343, June 1991.
- Shah, J.J. and Hsiao, D.W.(1991) "A Meta Knowledge Base for Machining Process Selection," ASME Computers in Engineering Conference, 1991, pp. 77-84.
- Shah, J.J., Hsiao, D.W. and Robinson, R. (1990) "A Framework for Manufacturability Evaluation in the Machine Domain," Proceedings of NSF Design and Manufacturing Systems Conference, January 1990, pp. 61-66.
- Shah, J.J., Rogers, M.T., Sreevalsan, P.C. and Hsiao, D.W. (1990) "The A.S.U. Features Testbed: An Overview," ASME Computers in Engineering Conference, 1990, pp. 233-241.
- Shah, J.J. and Rogers, M.T. (1988) "Functional Requirements and Conceptual Design of the Feature-Based Modeling System," Computer-Aided Engineering Journal, February 1988, pp. 9-15.
- Shih, T.S. and Li, M.Y. (1990) "Geometric Modeling of Casting Solidification," Journal of the Chinese Society of Mechanical Engineers, Vol.11, No.1, 1990, pp. 75-84.
- Shin, K.H. and Lee, K. (1993) "Design of Side Cores of Injection Moulds from Automatic Detection of Interference Faces," Journal of Design and Manufacturing, Vol.3, pp. 225-236.
- Suh, N.P. (1988) "Basic Concepts in Design for Producibility," Annals of the CIRP, Vol. 37/2, pp. 559-567.

- Voelcker, H.B., Requicha, A.A.G. and Conway, R.W. (1988) "Computer Applications in Manufacturing," Annual Review of Computer Science, Vol.3, pp.349-387, 1988.
- Waco, D.L and Kim, Y.S. (1994) "Geometric Reasoning for Machining Features Using Convex Decomposition," CAD, Vol.26, No.6, June 1994, pp. 477-489
- Webster, Lt. Col. (1991) "The DoD Initiative in Concurrent Engineer," U. S. Army/NSF Joint Symposium for the Technology Transfer of Concurrent Engineering Tools and Methodologies, Huntsville, Alabama, June 4-5, 1991.
- Weiler, K. (1988) "The Radial Edge Structure: A Topological Representation for Non-Manifold Geometric Boundary Modeling," in M.J. Wozny, H.W. McLaughlin and J.L. Encarnacao (eds.) Geometric Modeling for CAD Applications, IFIP WG5.2 Working Conference, Rensselaerville, NY, May 1986, North-Holland Publishing Co.
- Wilson, P.R. and Pratt, M.J. (1988) "A Taxonomy of Features for Solid Modeling," in M.J. Wozny, H.W. McLaughlin and J.L. Encarnacao (eds.) Geometric Modeling for CAD Applications, IFIP WG5.2 Working Conference, Rensselaerville, NY, May 1986, North-Holland Publishing Co.
- Woo, T.C. (1982) "Feature Extraction by Volume Decomposition," Proc. Conf. CAD/CAM Technology in Mechanical Engineering, Cambridge, MA, March 1982, pp. 76-94.
- Yoshikawa, H. (1982) "General Design Theory: Theory and Application," Conference on CAD/CAM Technology in Mechanical Engineering, Cambridge, MA, March 1982, pp. 370-376.
- You, I.C., Chu, C.N. and Kashyap, R.L. (1990) "Three-Dimensional Net Shape Analysis for Manufacturability Evaluation," 1990 IEEE International Conference on Systems, Man, and Cybernetics, November 4-7, 1990, LA, pp. 715-720.
- You, I.C., Chu, C.N. and Kashyap, R.L. (1989) "Expert System for Castability Evaluation: Using A Fixed-Features Based Design Approach," Robotics and Computer-Integrated Manufacturing, Vol.6, No.3, pp181-189, 1989.

- Yueh, Y.S. and Miller, R.A. (1995) "An Infrastructure to Support Design for Manufacturability in Injection Molding and Die Casting," Technical Report ERC/NSM-D-95-10, Engineering Research Center for Net Shape Manufacturing, The Ohio State University, January 1995.
- Yueh, Y.S. and Miller, R.A. (1993) "DIECAST: Current Status and Research Directions," Technical Report ERC/NSM-D-93-63, Engineering Research Center for Net Shape Manufacturing, The Ohio State University, 1993.
- Yueh, Y.S., Rebello, A. and Miller, R.A. (1992) "DIECAST: Design for Die Casting," Technical Report ERC/NSM-D-C-92-65, Engineering Research Center for Net Shape Manufacturing, The Ohio State University, 1992.