Computer-aided Tooling Design for Manufacturing Processes

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Abstract—**Tooling design for manufacturing processes refers to direct tooling for making a part such as molds and dies for injection molded parts and metal stampings, or for supporting machining operations such as jigs and fixtures. This paper summarizes some of the R&D activities in those areas over a period of 20 years in the Department of Mechanical Engineering, National University of Singapore. It is notable that increasing use of computer tools has turned what is used to be known as a "black art" into a discipline embracing both heuristic and scientific analyses.**

Index Terms—**Computer-aided Tool Design, Plastic Injection Molds, Jigs and Fixtures.**

I. Introduction

Manufacturing engineering constitutes an important branch of engineering study as any direct improvement of existing manufacturing processes or an introduction of novel processes could significantly improve production efficiency, product quality and reduce design and processing time. This would enhance the competitiveness of a manufacturing company and maintain its leading edge over its competitors. Tooling design is as important a topic as the manufacturing process itself. Without suitable tooling, manufacturing processes are often crippled or rendered totally inefficient. The trade of a tooling designer, however, has been traditionally linked to long years of apprenticeship and skilled craftsmanship. There appears to be more heuristic know-how and knowledge acquired through trial and error than deep scientific analysis and understanding. With the increasing use of computer tools and technology, this scenario has changed rapidly since the introduction of CAE tools in the early 1980s.

This paper addresses several topics in tooling design and the use of computer tools in achieving better and faster design, and the use of simulation techniques in depicting the actual working condition. One area is in the design of tooling for molds and dies, and another area is tooling for supporting machining operations, i.e. jigs and fixtures for orienting, locating and supporting parts in a machining centre. All these areas used to rely heavily on skilled tool designers, and unfortunately, there is a worldwide shortage of such people due to long years of acquiring the necessary skill and the reluctance of the younger generation to enter into this trade.

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II. Fixtures in Supporting Manufacturing Operations

A. Introduction

Fixtures are generally mechanical devices used in assisting machining, assembly, inspection, and other manufacturing operations. The function of such devices is to establish and secure the desired position(s) and orientation(s) of workpieces in relation to one another and according to the design specifications in a predictable and repeatable manner. With the advent of CNC technology and the capability of multi-axis machines to perform several operations and reduce the number of set-ups, the fixture design task has been somewhat simplified in terms of the number of fixtures which would need to be designed. However, there is a need to address the faster response and shorter lead-time required in designing and constructing new fixtures. The rapid development and application of Flexible Manufacturing System (FMS) has added to the requirement for more flexible and cost-effective fixtures. Traditional fixtures (dedicated fixtures) which have been used for many years are not able to meet the requirements of modern manufacturing due to the lack of flexibility and low reusability. The replacement of dedicated fixtures by modular and flexible fixtures is eminent in automated manufacturing systems, due to much smaller batch sizes and shortened time-to-market.

Modular fixtures are constructed from standard fixturing elements such as base-plates, locators, supports and clamps. These elements can be assembled together without the need of additional machining operations and are designed for reuse after disassembly [1]. The main advantages of using modular fixtures are their flexibility and the reduction of time and cost required for the intended manufacturing operations. Automation in fixture design is largely based on the concept of modular fixtures, especially the hole-based systems, due to the following characteristics: (a) predictable and finite number of locating and supporting positions which allow heuristic or mathematical search for the optimum positions, (b) ease in assembly and disassembly and the potential of automated assembly using robotic devices, (c) relative ease of applying design rules due to the finite number of element combinations.

In this paper, most of the reported research activities are based on modular fixtures.

B. Computer-aided Fixture Research in the last two Decades

Fixture research employing computer aids started in the late 70s and early 80s. In the initial years, interactive and semi-interactive fixture design techniques were built on top of commercial CAD systems and expert system tools. These approaches were mainly concerned with fixture configuration and there was little analysis on the other aspects such as workpiece-fixture-cutting tool interactions.

A comprehensive fixture research plan should involve the analysis at different computational levels, *viz.,* geometric, kinematic, force and deformation analyses. The following sections will present brief overviews of the research activities in each of the above-mentioned areas, followed by the need to design an intelligent fixture which can be integrated with the machine tool.

1) Geometric Analysis

Geometric analysis is closely associated with fixture planning and spatial reasoning. It determines the selection of the type and number of fixturing elements, support and locating elements, the order of datum planes, etc. The analysis also includes the checking of interference between workpiece and fixturing elements, as well as cutting tools.

Most of the early fixture research involved geometric analysis and synthesis of fixture construction with relatively little attention to kinematic and deformation analysis.

2) Kinematic Analysis

Kinematic analysis is used to determine whether a fixture configuration is able to correctly locate and provide complete constraint to a workpiece.

Previous work on fixture design automation offers relatively little consideration in providing a comprehensive fixture-element database and effective assembly strategies for the generation and construction of modular fixtures. The assembly of modular fixtures is to configure the fixture elements such as locators, clamps and supports (in most cases, accessory elements are needed to generate fixture towers to fulfill the fixturing functions) on the base-plate according to a fixturing principle (e.g. 3-2-1 principle). The determination of the locating, supporting and clamping points for the assembly of modular fixtures is a key issue in fixture design automation.

3) Force Analysis

In a machining fixture, different forces are experienced, *viz*., inertial, gravitational, machining and clamping forces. While the first three categories of forces are usually more predictable, clamping force can be rather subjective in terms of magnitude, point of application as well as sequence of application.

It has been widely accepted that a thorough analysis of all the forces involved in a fixture is a formidable task since it is an indeterminate problem with a large number of fixturing elements. When friction is taken into account, the problem becomes even more complex because both the magnitude and the direction of the static friction forces are unknown.

4) Deformation Analysis

Due to the complexity of force interaction, workpiece deformation can be attributed to a combination of factors. Firstly, a workpiece would deform under high cutting and clamping forces. Secondly, a workpiece could also deform if the support and locating elements are not rigid enough to resist the above-mentioned forces. In the present analysis, it is assumed that workpiece deformation is largely due to the first cause mentioned above.

The most commonly used method in analysing workpiece deformation and fixturing forces is the finite-element method.

C. Work-holding Analysis

A good fixture design is critical to the quality of the finished workpiece in terms of dimensional accuracy, form precision and surface finish. One of the essential considerations in designing a good workable fixture is the generation of clamping configuration that includes the clamp placement, clamping sequence, and clamping intensities. Placing the clamps in wrong positions may disturb the equilibrium of the workpiece on the locators, resulting in the lost position of the part. Likewise, using an inadequate clamping intensity may give rise to slippage and/or lift-off of the workpiece during the machining process. On the other hand, an application of excessive clamping forces would result in excessive deflection and high contact deformation of the workpiece. In short, a poor clamping layout could cause the final accuracy of the workpiece to be out of the specified tolerances and bring about unnecessary rejects.

A less addressed research area is the performance of a fixture during machining in terms of its dynamic response and deformation. The issue is to guarantee machining accuracy through the proper control of workholding operation during machining. Therefore, a best approach to the fixturing problem is to integrate optimal fixture design with optimum fixturing execution in a unified procedure.

An intelligent fixturing system [2] has been built. This system provides sensory feedback and on-line fixturing control strategy to perform an optimal workholding operation. Being an important part of the "live" fixture, a novel dynamic clamping actuator capable of providing time-varying clamping intensities has been implemented. Comparative experiments are carried out to investigate the effects of the dynamic fixturing nature of the system on workpiece quality. Measured geometric errors are compared with and without using the dynamic clamping forces.

1) An Intelligent Fixturing System

An intelligent fixturing system incorporating three interdependent sub-functions has been built. The sub-functions are: analysis and synthesis, fixture hardware generation and workholding execution (Figure 1). Each sub-function contributes to the final quality of the finished workpiece and should be treated with equally attention. A discerning implementation of workholding operation starts with an analytical fixturing planning procedure which would generate a fixture design that can accurately locate and hold the workpiece with respect to the machine tool, and a set of optimised fixturing parameters.

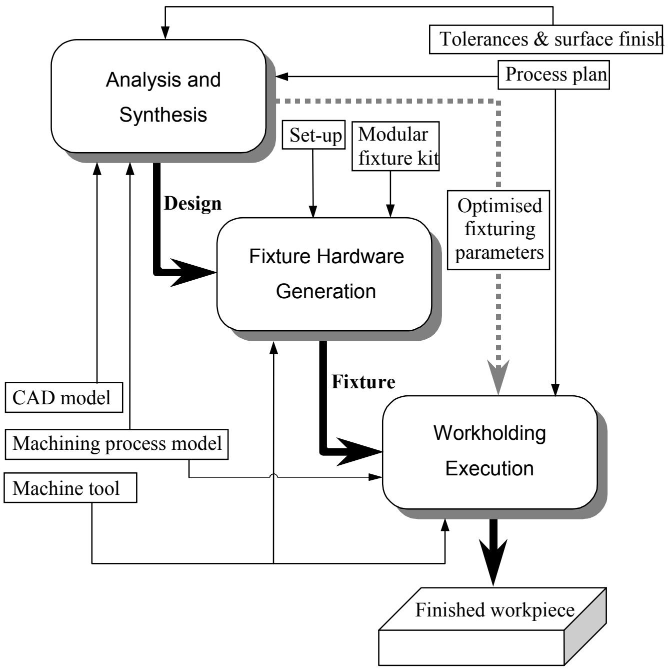


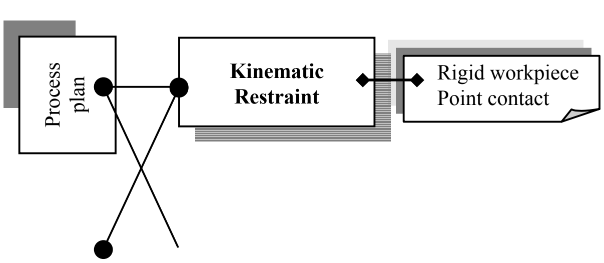
Fig.1 Model of an intelligent fixture system

The next sub-function is the hardware assembly of the fixture using modular fixture kit as well as sensing and control devices, clamping driver, electronics and interfacing circuitry, and a PC. This fixture, equipped with sensors and actuators, is capable of on-line control of fixturing actions, as opposed to a conventional "dummy" fixture with hard-wired clamping devices.

The final sub-function is the execution of the adaptive workholding operation. It is critical to ensure perpendicularity and parallelism of the part within the fixture after clamping actuation. Therefore a probing procedure is performed to detect the genuine position and orientation of the workpiece within the fixture and correspondingly the tool path is compensated through NC code manipulation according to the evaluated workpiece displacement. The fixture should minimise workpiece distortion during machining. This is achieved through both providing appropriate supports and applying dynamic clamping forces. Supports should be used to uphold flexible features on the workpiece whenever possible to avoid large deflection or permanent damage to the part. Dynamic clamping forces are applied just enough to sustain the impact of the cutting force load.

2) Fixture Design Consideration

During the fixture design stage, a series of analyses are performed in order to generate an optimal design. As depicted in Figure 2, the complete procedure consists of such modules as kinematic restraint analysis, total restraint analysis, clamping intensity analysis and FEM analysis.



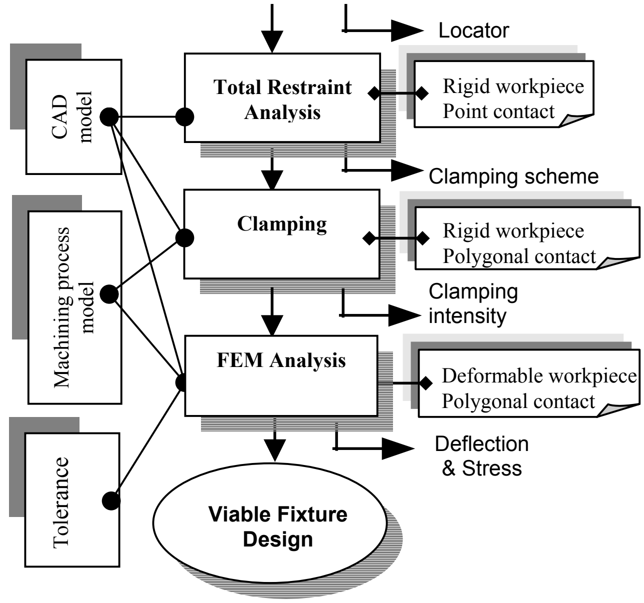


Fig.2 Analysis and synthesis procedures

The integrated design programme and its functions are summarised as follows:

(a) Kinematic restraint analysis

Assuming rigid body and point contact, kinematic restraint analysis is to determine a locating scheme that is sufficient to provide uniquely accurate position for the part. It can be accomplished either by an expert system based on heuristic knowledge and the experience of tool designers, or by an analytical module relying on twist and wrench vectors from the Screw Theory. Once the locating points and placements are determined, the type of locators and their geometry can be designed according to the availability of modular fixtures and the type of the machine tool. In this study, the locating layout is decided by heuristics rules such as the 3-2-1 principle to ensure proper locating specification.

(b) Total Restraint Analysis

Based on computational geometry theory and geometric reasoning technique, this module is to automatically generate a clamping scheme and clamping sequence that is sufficient to totally constraint the part. This module would also provide feedback concerning whether the kinematic restraint by the locating layout is adequate. At this time, the clamps are still assumed to make point contact with a rigid workpiece. Once the contact geometry of the clamps is designed, the resultant contact would be either point, linear or polygonal depending on the workpiece geometry.

(c) Clamping Intensity Analysis

Generation of clamping intensity is based on the assumption of rigid body and polygonal contacts. Quasi-static equilibrium conditions are used in calculation so that the impact of cutting force dynamics is well accounted for. Processing forces are derived from proven tool force model [3]. Both minimum and maximum clamping intensities are generated using non-linear programming techniques.

(d) FEM Analysis

Workpiece displacement and distortion is due to a number of physical phenomena such as workpiece elasticity, fixture flexure, and deformation/lift-off at the workpiece-fixture element contact regions. It is can be quite severe during the machining of thin-walled features on otherwise structurally rigid workpieces. Assuming flexible workpiece and polygonal contact, FEM analysis is performed to predict workpiece deflection and/or lift-off that would introduce form error into the finished workpiece in the pattern of lost flatness or cylindricity.

3) Function of an Intelligent Fixture

The core elements of an intelligent fixturing system should provide proactive reactions to the workholding process and correct workpiece displacement and restrain distortion as much as possible to guarantee the specified accuracy. As illustrated in Figure 3, its two essential functions are tool path compensation and dynamic clamping actuation.

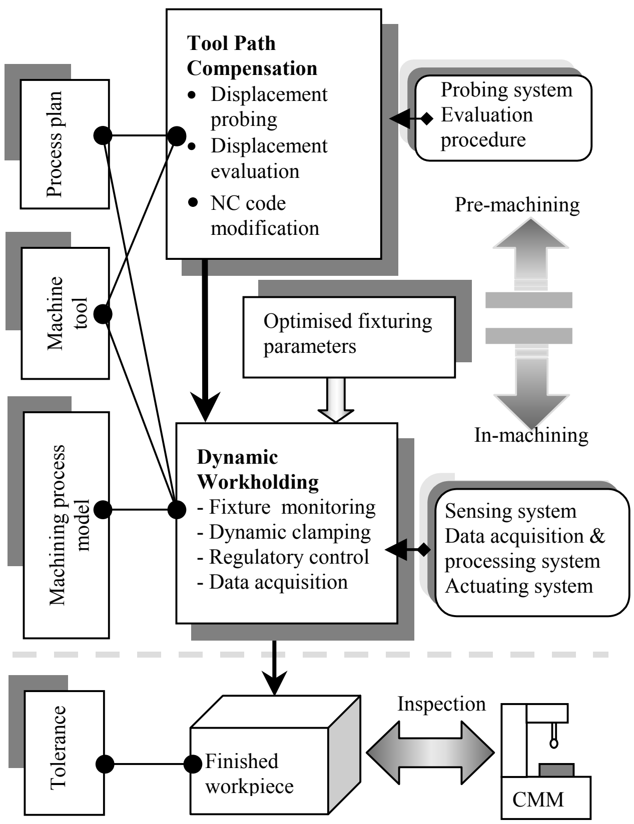


Fig.3 Functions of an intelligent fixture

As all the ambient forces would cause the workpiece to be displaced within a fixture, it is best to perform tool path compensation both before and during the machining process. A variety of techniques such as inductive displacement sensing can be employed to perform on-line measurements of the workpiece displacement. However, it would require an open-architecture NC controller for this purpose. At this stage, tool path compensation is only used to correct the displacement caused by clamping actuation before machining. During machining, the intelligent fixture would perform functions such as monitoring, dynamic clamping, regulatory control, and data acquisition to ensure successful performance of machining operation and minimise workpiece deflection.

Its schematic configuration is shown in Figure 4.

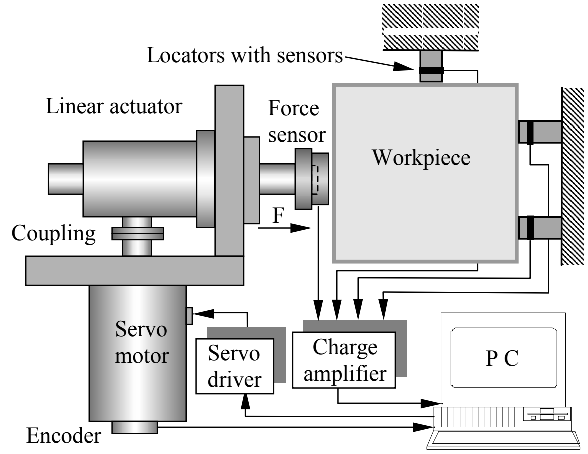


Fig. 4 Intelligent fixture with dynamic clamping

The characteristic features of the intelligent fixture include the following:

(a) Automated monitoring

Automated monitoring refers to the identification of the characteristic changes of a workpiece-fixture system based on the evaluation of system signatures. It mainly consists of three tasks: sensing, signal processing and monitoring decision-making. Appropriate sensor signal sources include reaction forces on the fixturing elements, clamping forces, workpiece deflection, chatter and vibration. At this time, only reaction forces are used to monitor the stability of the workpiece-fixture system and as input to the decision-making strategy for the self-configuration of the fixture system to provide the highest workpiece accuracy. The hardware required for performing this task includes force sensors and data acquisition board.

(b) Applying dynamic clamping forces

Applying dynamic clamping forces refers to the action of adapting the clamping intensities according to the optimised fixturing parameters generated at the fixture planning stage as well as the sensed information of workholding stability. The execution involves the co-ordination of the clamping action with the machining operation. Electromechanical or hydraulic actuators may be employed to apply the real-time optimal forces to the part. In this study, an electromechanical clamping actuator was developed.

(c) Regulatory control of workholding stability

While automated monitoring tracks the execution of workholding process and detects the departures from normal condition, regulatory control applies preventive/corrective action with respect to clamping intensities in response to sudden undesirable changes in the workholding conditions due to external disturbances.

(d) Data acquisition

Data acquisition refers to the collection and recording of the fixture processing information and associated data validation, conditioning, smoothing, and corrective measures. After machining, a workholding history could be produced from the collected data, and significant workholding events (e.g., “lift-off”, “sliding”, “vibration”, “chatter”, etc) and the time of their occurrence can be identified through the evaluation of the sensed information. Consequently, corrections to the fixturing process and the fixture design specification can be made as necessary so as to fine-tune the workholding operations in subsequent executions.

D. Dynamic Workholding

The set-up consists of several steps. First the fixture is placed on the machine table and the machine tool axes, cutter and fixture reference frames are aligned. A dial indicator could be attached to the machine spindle so that the indicator could run across the datum surface on the fixture to align the axes. Here it is assumed that the locating datum has already been precisely aligned with respect to the fixture datum surface. The position of the cutting tool relative to the fixture reference frame is then established using an edge finder. Subsequently the NC code is updated so that the reference dimensions in the part and programme reference frames are aligned.

The host computer downloads the optimised fixturing parameters for a part to be machined. The clamp controller then retrieves the dynamic clamping intensity model from the host. After that, the workpiece is loaded into the fixture. Six dial indicators are placed over and brought into contact with the part and their readings are zeroed. Now the host flags the controller to actuate the clamps until individual force set-points are reached. After the workpiece is clamped, the part displacement is determined through the evaluation of the taken measurements. Tool path compensation is then performed and the transformed NC code is subsequently downloaded to the machine controller. At this time the cutter path is aligned with the actual workpiece location rather than the axes of the machine tool. The clamping controller is simultaneously adapting the clamping intensity with respect to the position of the cutter. At the same time, the acquisition system collects and saves all the force values on the locators and clamps. These actions are continuously carried out until the completion of the machining process.

E. Experimental Study of a thin-walled Workpiece

The main problem associated with machining of thin-walled parts is elastic deformation, which can be due to many factors such as cutting and clamping forces, workpiece rigidity, cutting temperature and internal stresses. The defection of the workpiece would result in dimensional and form errors. It is possible to reduce the elastic deformation through holding the part with an optimised fixture and applying minimal clamping forces.

In order to investigate the impact of the dynamic clamping scheme on the workpiece quality and machining process, a pocketing operation is performed on a box-shaped thin-walled workpiece to compare the finished accuracy under fixed and dynamic clamping schemes. As shown in Figure 5, the workpiece has an overall size of 80(H) x 130(W) x 220(L) mm with a cubic cavity. The wall thickness of the part is reduced from 5 mm to 3 mm through finish pocketing by a 20 mm flat-end mill. The depth of cavity is 35mm so that the pocket walls are milled at 5mm increments until the bottom of the pocket is reached. Therefore, the axial and radial depths of cut are 5mm and 2mm respectively.

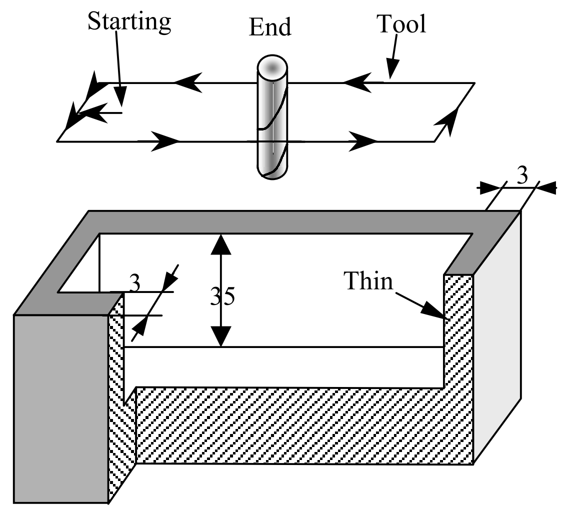


Fig.5 Pocket milling operation on a thin-walled part

The spindle speed was set at 500 rev/min and the feed rate at 100 mm/min. Two identical parts are machined with the same cutting parameters following the same machining procedure, but under fixed and dynamic clamping schemes respectively. All the end milling operations are conducted in downward cutting (climb cut) due to various reasons such as service life of tool, machining accuracy, and vibration. The part is located by six flat tipped locating pins according to the 3-2-1 principle and held by two dynamic clamps from the sides.

It should be noted that the magnitude and direction of the cutting force vary drastically in a pocketing operation. As the cutter reaches a corner of cavity, the engagement width increases dramatically from 2mm to 16mm in this case, resulting in sharply higher cutting forces with increment of resultant force from 264.2N to 482.8N. Once the cutter passes the corner, the cutting forces return to the normal, but changes its direction. The change of the cutting forces is taken into consideration in the generation of dynamic claming force spectrum.

F. Workpiece accuracy comparison

In machining operations on flexible workpieces, both cutter and workpiece deflection would cause errors of the machined surface. Workpiece deflections could be induced by both cutting and clamping forces. While the cutting forces produce deflections both on the cutter and on the workpiece such as the case of pocketing with thin walls, clamping forces only bring about deformation on the part. For climb milling, the cutter always deflects away from the workpiece so the final dimension of the part is always larger than desired. The opposite is true for the clamping action as they usually constrict the part. In this study, it is assumed that the surface errors induced by the cutting forces are the same for both fixed and dynamic clamping cases as the cutting parameters and conditions are identical. The attention is hence concentrated on the surface errors caused by the clamping force induced deflections.

The profiles of the finished thin walls were measured using a CMM for determining the surface errors. For each experiment, the machined surface is inspected several times so as to provide statistically sound measurements. Cross-sections of the thin-walled part under fixed and dynamic clamping schemes are shown in Figures 6 and 7. The fixed clamping scheme has to maintain larger clamping forces throughout the machining pass, more material is thus removed around the area opposite to the clamping points as the clamping forces cause inward deformation. In the figure, a dip in the middle can be observed, this is caused by the applied clamping force. It is clear that the dominating component of the surface accuracy is from the clamping induced deflection.

It is possible to predict the magnitudes of the errors of the machined profiles using FEM computations. Workpiece deformation analysis can be performed in discrete time instants for the machining operation using the FEM model. They are useful for establishing the basic knowledge of the characteristics of the errors produced with different clamping situations. An FEM simulation of the workpiece under the fixed clamping scheme is shown in Figure 8.

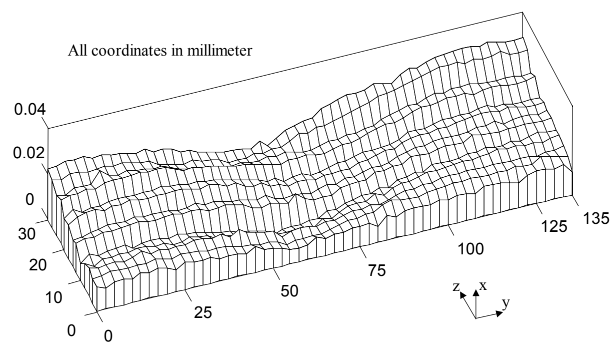


Fig.6 Measured profile under fixed clamping scheme

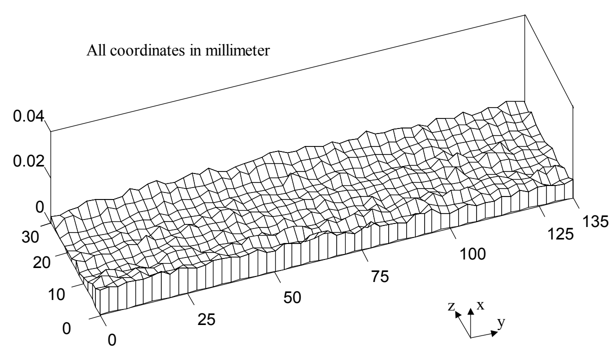


Fig. 7 Measured profile under dynamic clamping scheme

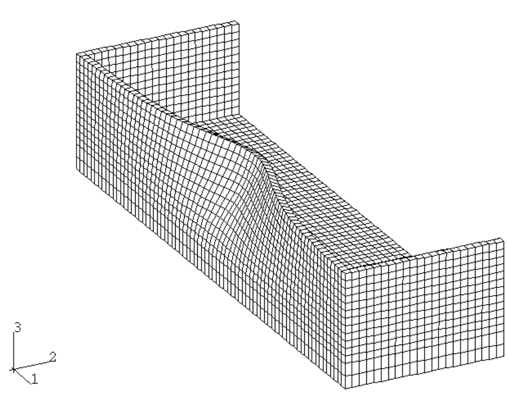


Fig.8 FEM simulation of workpiece deformation

The dynamic and flexible clamping scheme of an intelligent fixture has proven to be more superior than a fixed clamping scheme of traditional fixtures in terms of the capability to reduce workpiece deformation. This prototype intelligent fixturing system would eventually lead to a new generation of workholding devices that can regulate themselves based on sensory feedback.

III. PLASTIC INJECTION MOLD DESIGN AND ANALYSIS

A. Introduction

Molding-making used to be largely experience-based and relies heavily on skilled craftsmen, typically trained under an apprenticeship scheme, and have acquired their expertise through years of practice. The supply of trained manpower, however, is rapidly diminishing as the younger generation is reluctant to go through the long training periods and would prefer other types of jobs. This situation was arrested to some extent with the introduction of CAD/CAM technologies in the late 70s. The mold-making scene has largely been transformed from the tacit knowledge acquired by the individuals to knowledge-based intelligent computer systems. Compared to the application of computer tools in the other manufacturing areas, however, mold design has been relatively slow in progress. Until only quite recently, commercial software systems have begun to appear and are adopted in the tool-making and molding industry.

According to CIMdata [4] in a recent study of the mold-making industry revealed that mold design accounts for some 20% of the total work effort in mold shops and CAM programming accounts for about 8%. Approximately half of the 20% design work is associated with core and cavity design, with the remaining activities associated with mold base design/selection and the preparation of a design model for manufacturing. From this analysis, it can be seen that mold design is a major function in the mold shops. This high concentration of design activities has led to many software systems focusing their effort on providing solutions to the mold design aspects. These software systems are able to assist the mold designer in the various aspects of design such as automated parting line and surface determination, core and cavity design, runner and gate selection, analysis of temperature distribution and flow of plastic material in the mold, and the effective interfacing with different mold bases. A typical injection mold generated from the IMOLD® system is shown in Figure 9.

full dimensional and annotation capabilities from a final 3-D design is available

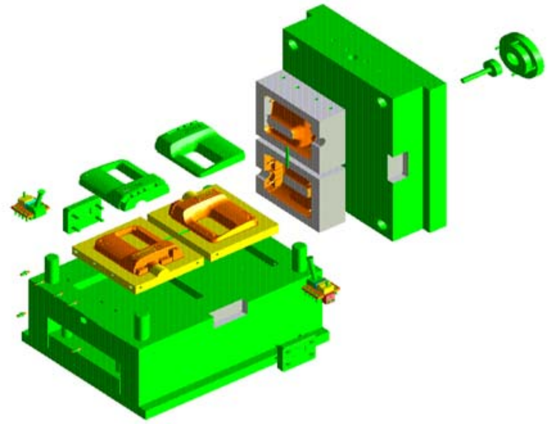


Fig. 9. An injection mold generated from the IMOLD® system (Courtesy of Manusoft Technologies Pte. Ltd.)

B. Computer-aided Design of Plastic Injection Molds

CAD, CAE and CAM tools have been developed in the last two decades to assist mold designers in mold design configuration, analysis and machining. More specifically, they can be divided into the following categories.

1) More plastic part designs are presented to the mold shops in electronic formats and this is expected to increase from the present 53% to 90% in the next two years [4]. Mold designers would need to use compatible CAD software to retrieve the part design information, edit the design and make necessary alterations to prepare a final design model that meets all the manufacturing specifications.

(1) Computer-aided engineering (CAE) software such as temperature and flow analysis programs is used to simulate the plastic injection process to check for possible defects in the molded parts, and for the suitable design of runners and gates. Such feedbacks will be used for modification of the molded part and/or the mold so optimum cooling and material flow can be achieved.

(2) CAM software for the direct generation of NC tool-paths and programs for machining complex 3D surfaces based on the number of axes and configuration of an NC machine is available from several vendors. With the advent of high speed machining technology and the rapid adoption by the mold-makers, a new breed of CAM software has now been designed to cater for the high machining speeds and feed rates.

(3) Although high speed machining of hardened die blocks has reduced the amount of EDM work, it is still necessary for EDM to handle the finer details of a mold. CAD/CAM software is able to extract features from cavities and design electrodes for EDM machining of complex 3D surfaces.

(4) Many mold-shops would still prefer to document their designs and assembly details with 2-D drawings. CAD software for the automatic generation of 2-D drawings with full dimensional and annotation capabilities from a final 3-D design is available.

(5) Many mold-shops would still prefer to document their designs and assembly details with 2-D drawings. CAD software for the automatic generation of 2-D drawings with

C. Research on Plastic Injection Mold Design and Analysis

1) Undercut features, parting direction and parting line determination

The recognition and extraction of undercut features and parting line determination are the first steps in injection mold design. Many researchers have attempted to provide solutions to these problems.

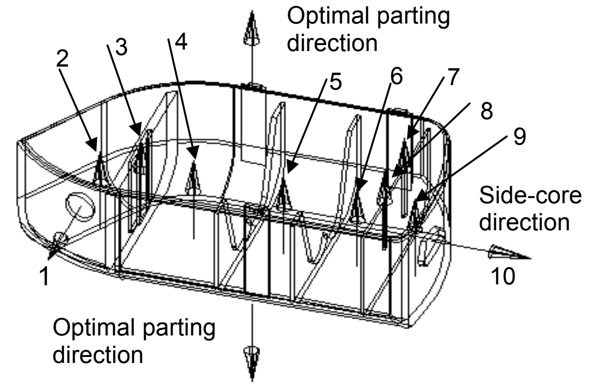


Figure 10. A sample part to illustrate the identi-fication of the optimal parting direction [5]

Figure 10 illustrates a sample part where the optimal parting direction has been identified. Automatic determination of parting lines and surfaces were reported by Nee *et al* [6] using a novel molding surface classification scheme and generation of edge-loops in different surface groups. Li *et al* [7] presented a novel approach for 3-D parting line search using all the surfaces in an initial solid model and divided them into union parting surfaces and multiple parting surfaces. The multiple parting surfaces are then decomposed into several union parting surfaces using the discrete model method before parting line search, creating the new edges as potential parting lines. Parting line search is completed based on the pure union parting surface model.

2) EDM electrode design

In plastic injection mold manufacturing, NC milling and EDM have been the main processes traditionally until the advent of high speed machining. However, the two processes are still complementary as EDM is able to produce finer features and the required type of surface finish. Currently, the design of EDM electrodes is time-consuming and is done interactively using a CAD system. Over 100 sets of electrodes may be needed to manufacture the mold of a relatively simple hand phone cover. For more complex parts, it may run into several hundreds. Electrode design and manufacturing is a bottleneck in the entire mold manufacturing process [8]. Unfortunately, until today, there are very few software systems which are able to meet the needs of the mold-maker. Figure 11 shows a set of electrodes for the mold of a handphone cover.

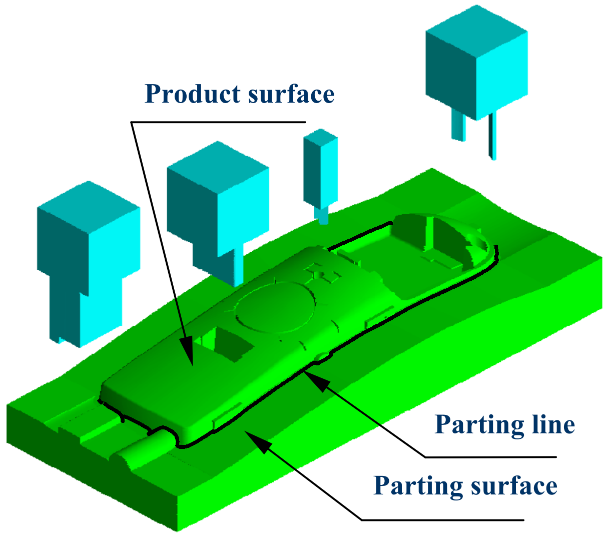


Fig. 11 Electrode design for a handphone cover [8]

3) Mold cooling analysis

Injection mold cooling design is a critical consideration as efficient and uniform cooling effect could improve both the productivity and part quality. As the mold cooling process is highly complex, a rigorous cooling analysis is essential to accurately predict the required cooling time and simulate the cooling process of a given design. In the last two decades, many research studies applied the 2-D Boundary Element Method (BEM) based techniques on the simulations and optimizations to reduce cost and computation time [9-13]. Most of the commercially available CAE software, either in 2-D or 2½-D, utilizes the BEM- or FEM-based shell elements and the Hele-Shaw approximation. For a 2½-D software, the mesh used in the analysis comprises shells with reference surfaces located at the mid-plane of the component, which is generally not a simple matter to derive from a solid model. Another technique, the so called Dual Domain Finite Element Method (DD/FEM), uses a surface mesh on the exterior of the part for flow analysis [14]. Sun *et al.* [15] studied a mold with a hot runner system using a 3-D, transient, FEM cooling analysis.

Simulation results in Figure 12 indicated that for a mouse cover, the temperature distributions of core and cavity with 'U'-shape milled grooves are more uniform. Besides, the 'U'-shape milled grooves is able to remove heat more efficiently; the temperatures of the molds are lower than the ones with straight cooling channels. As a result, the molding cycle time with the 'U'-shape milled grooves can be shorter, hence a shorter molding time per loading, leading to a higher production rate and increased efficiency.

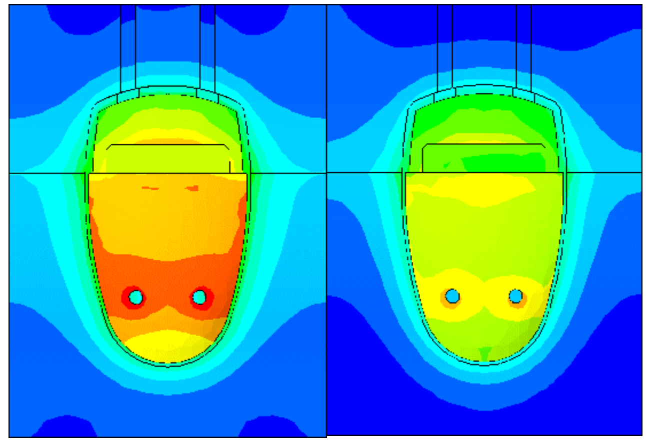


Fig. 12 Temperature distribution of a straight drilled and a 'U'-shape milled groove mold of a mouse cover [15]

4) Tool path regeneration techniques

To reduce the time required for regenerating tool paths, a novel tool path regeneration approach that can make use of the generated cutter location (CL) points for die and mold design modification has been reported [16] With this approach, the affected CL points which cannot be reused are identified and removed first, new CL points are then calculated and added to replace the removed ones, and those unaffected CL points are maintained in the new CL data. Hence, only the affected tool path points need to be re-calculated, the new tool paths for the modified work-piece can be regenerated efficiently. An algorithm of tool path modification has been developed and tested with several industrial parts. Figure 13 illustrates the tool paths of the work-piece before and after modification.

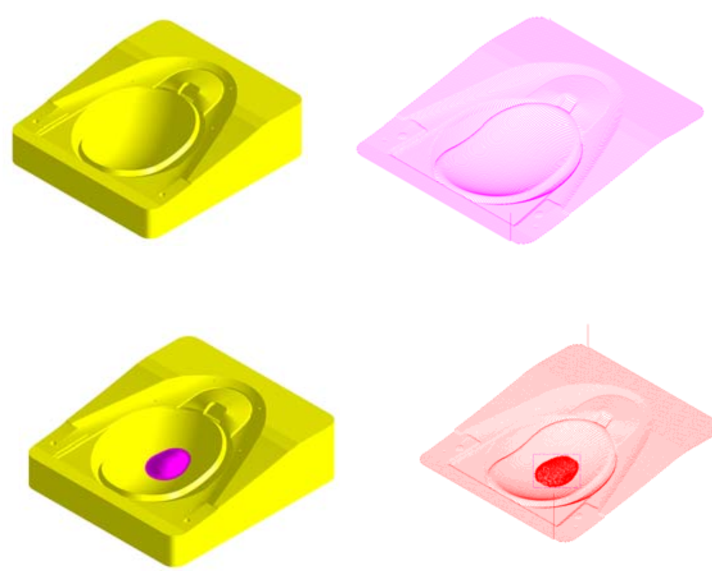


Fig. 13 Tool paths of workpiece before and after modification [16]

IV. CONCLUSION

This paper summaries some of the developments in computer-aided fixture and plastic injection mould research in the last one and half decades at the National University of Singapore.

Although fixture design and planning has traditionally been regarded as a science as much as an art, it is now possible to successfully design and plan fixtures using computer applications. Optimal clamping force control remains an essential issue to be addressed. With the development of intelligent fixtures incorporating dynamic clamping force control, workpiece accuracy can be controlled on-line and this will further enhance the smooth operation of automated manufacturing systems.

Similarly, mold design and machining has taken a great step ahead as advanced software algorithms, machining and computer technologies are now available to the mold makers. A trade that was used to be craft-based has now become totally revolutionized and largely IT-based. Customers can now expect to see faster delivery times as well as better quality products. An increasing trend is the use of Internet technologies and this is expected to play a much bigger role in the next few years, in terms of distributed design as well as e-business activities.

Tooling design for manufacturing processes has been transformed from the "black art" into a science-based and IT savvy discipline. The notable increasing trend is towards the greater use of computer tools and Internet technology. It is foreseeable that tooling design activities will now be drawn from various geographical locations and there will be reduced reliance on the diminishing expertise in tool design.

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