SRC TR 86-88

Implementation of a Flexible Manufacturing Protocol

by

J. A. Kirk, D. K. Anand,
M. Anjanappa, and R. Uppal

Implementation of a Flexible Manufacturing Protocol

J.A. Kirk, Professor
D.K. Anand, Professor
M. Anjanappa, Assistant Professor
R. Uppal, Research Assistant

Department of Mechanical Engineering and The Systems Research Center
University of Maryland, College Park, MD 20742

Keywords: IGES, Manufacturing Automation Protocol, FMS, FMC

ABSTRACT

This paper is concerned with the development and implementation of a flexible manufacturing protocol for automated machining. Of specific interest is the machining of prismatic parts in a flexible manufacturing cell.

The flexible manufacturing protocol involves providing design input via a computer aided design (CAD) environment, an expert system for establishing manufacturability of the design, an intelligent process planning module for optimal component machining, design data base in an IGES format, automatic generation of machining codes, and finally, the downloading of machine data to the computer numerical control (CNC) machine, where the manufacture of the designed part occurs.

The flexibility of work reported in this paper is enhanced by the use of standardization of design data base and the standardization of machine control codes. By using standardization it will also be shown that commercial CAD software can be interfaced directly with the flexible manufacturing protocol discussed in this paper.

This paper also addresses the hardware interfacing issues inherent in the flexible manufacturing cell. An example of the flexible manufacturing protocol is presented and a machine-generated part is discussed.

INTRODUCTION

Automation was first introduced for mass production due to its positive cost performance effect on investment. After most shops were automated by the mid 1960's, it was realized that mass production accounted for only 25% of the total production in the United States [7]. The other 75% of production is batch type which imposed difficulties for automation because of lack of flexibility of the automation practice. The need to automate batch production, however, was essential to improving productivity and flexible manufacturing was the logical approach.

Numerical Controlled (NC) machines were installed at various factories in the early 1960's to achieve flexibility in automation. These NC machines accepted programmed tool paths in the form of punched paper tapes prepared on computers, and hence a different part only needed a new punched tape. Later versions of these machines, called Direct Numerical Controlled (DNC) machines and Computer Numerically Controlled (CNC) machines, allowed direct part programming on the machine controller as well as downloading of a part program through serial interface. Coupled with automatic tool changing mechanisms, Automated Guided Vehicles (AGV), and Robots, these machines for the first time allowed complete unmanned, but limited, machining. In the early 1980's several such systems were installed to machine parts such as engine blocks, jet engine parts, etc. [3]. Many of these manufacturing systems were specially developed by industrial giants, in an effort to introduce automation.

To adequately meet the wide range of system applications, manufacturing systems have been divided into three types as shown in Fig. 1. The three types are Special Systems, Flexible Manufacturing Systems (FMS), and the Flexible Manufacturing Cells (FMC). The degree of production flexibility is the major difference between the system types.

SPECIAL SYSTEMS - Of the three systems, special systems are the most 'process dedicated' but the least flexible. Typically, they produce only a few part numbers at a relatively high production rate. Special systems incorporate many advantages of transfer line techniques with a well balanced degree of flexibility. A special system obtains it's flexibility by the use of numerically controlled special machine tools. Their mechanical design promotes process specialization while numerical control allows random automatic tool changing, variable spindle speeds, and feed rates, and multiple axis movements without manual intervention. This system is capable of machining any one of the several parts simultaneously. However, each of the workpieces is machined in a sequential order as it moves from station to station along a fixed path on the material handling system.

FLEXIBLE MANUFACTURING SYSTEM - Flexible manufacturing systems are designed for mid-volume manufacturing of a small number of different parts. Being at the midpoint of production techniques, this system type possesses advantages from both high and low production concepts. In an FMS, various types of workpieces are randomly and simultaneously transported between and processed at various machine tools and other workstations, according to individual processing and production requirements. The unique characteristic of FMS relates to its bringing together the following elements: material handling and computer control to function as integrated automated manufacturing systems and in the system's random processing capability with each workpiece, having it's own unique set of processing steps which are being carried out in parallel with the processing of other parts.

FLEXIBLE MANUFACTURING CELLS - Flexible manufacturing cells are the most flexible of the three types and viewed as being effective when applied to the production of many different workpieces, each being produced at a comparatively low production rate. The three types of manufacturing systems do overlap one another in their applications.

It is helpful to draw a distinction between FMS and FMC. An FMS can be defined [1,4] as a computer controlled configuration of semi-independent work stations and a material handling system designed to efficiently manufacture more than one part number at a low to medium volume". An FMC [2,4] on the other hand is a group of machines and associated material handling equipment that is managed by a supervisory computer or the cell host. These cells may be independent units or may be tied together to a central computer to form an FMS. Fig. 2 shows the conceptual arrangement of FMS and Fig. 3 shows an FMC. FMC is gaining popularity among small to medium size manufacturers due to its comparatively small initial investment and yet be able to upgrade to a full scale FMS at a later time.

This paper is concerned with a particular type of FMC currently under research and development at the University of Maryland. The FMC, shown in Fig. 3, is a flexible milling cell which is primarily intended for the production of prismatic parts. A similar cell for producing parts on a turning center is also under development but is not discussed in this paper.

THE FLEXIBLE MANUFACTURING PROTOCOL

A protocol for automated machining in a cell is concerned with a standardized methodology used for automated production within a cell. This includes all processes from design to part production including AGV and robot control. In this paper, our concern is primarily with automated machining. To simplify the process we have restricted the development, reported in this paper, to prismatic parts in which machining takes place without reorienting the part on the machine tool. Efforts are underway to implement a more general protocol (including axi-symmetric parts) and these results will be reported in the future.

Shown in Fig. 4 is a schematic diagram of the suggested protocol for implementing user-to-part automation. It is assumed that the user in Fig. 4 is a designer who will interact with a CAD system in order to obtain a suitable design for their requirements. In our current work we have taken the approach that the designer can design a part by using either a commercial CAD system or one that is specifically developed for enhanced graphics capability.

Typically the designer will sketch a part on a computer terminal in $2^1/_2$D with the aid of entities such as line, arc, rectangular pocket, circular pocket etc. Once the design is acceptable a design data base which is specific to each CAD system is generated. The design data base is then converted to Initial Graphics Exchange Specification (IGES) format through an IGES processor. At this point, as shown in figure 4, the user can instead bring in a design data base created by any commercial CAD system provided it is IGES compatible.

After the design data base is converted to standard IGES format a feature extracter is used to decompose the part into a library of standard solid primitives. These primitives include cylinders, pockets and slots, etc. The part features are then presented to the user and the user must input part material and tolerance information for each of the features. The information, along with the IGES geometrical representation of the part, is sufficient to completely represent the part for subsequent processing.

The next step is to evaluate the part and tolerance data in order to determine if production is compatible with the cells available to the user. Once the part has been evaluated as being compatible with an existing cell the part is then checked for manufacturability. This includes a check for tolerances, geometrical machinability and fixture constraints.

Next the design data base is converted to M & G cutting codes (as per EIA RS 274 D) which are the U.S. standard for cutting codes for NC/CNC machines. These codes are then downloaded to the CNC machine through a serial RS 232 port and the manufacturing of the part takes place as per the specification of the designer. For automation, parallel data for cell control is also downloaded. This includes specific instructions for fixture placement.

It is clear that for the Flexible Manufacturing Protocol to operate efficiently a high degree of standardization must exist throughout the system. specifically this includes the use of IGES for geometric part representation, the generation of standard machine tool control codes [i.e. M & G codes], and the use of the Feature Extractor and Expert Systems in a fully automated system.

The implementation of the protocol requires the development of software packages for purposes of establishing manufacturability, intelligent process planning, cell control and interfacing. In addition, it is necessary to establish database standardization using NBS procedures. These issues are discussed first and followed by an example using the new protocol.

DATABASE STANDARDIZATION

The usefulness of a protocol depends on how general it is. If it is used for a very specific purpose under very specific conditions then it is of very limited use. In the present work major emphasis was placed on making the protocol as general as possible. Towards achieving this goal, the data base standardization is introduced at two positions in this proposed protocol. At the design stage, the IGES format is introduced to store part design information so that this protocol will not be limited to its own CAD capabilities, but also be able to accept part design data file created by any commercial IGES compatible CAD system. The second stage at which the standardization is introduced is at the CAM data generation. the output of process planning is compatible with the US standard M & G cutting codes as per EIA RS-274D. This standardization allows that the proposed protocol is machine independent.

IGES is a standard being developed at the National Bureau of Standards for the exchange of graphics data. It establishes information structures to be used for the digital representation and communication of product definition data. It allows the compatible exchange of product definition data used by various CAD/CAM systems. The IGES version 2.0 specifies a file structure format, a language format and the representation of geometric, topological and non-geometric product definition data. The methodology for representing the product definition data is independent of the geometric modeling method being used. In IGES, the product is described in terms of geometric information and non-geometric information with the non-geometric information being divided into annotations, definitions and organizations. The geometric category consists of elements such as points, lines, arcs, cubic splines and parametric surfaces that model the product. The annotation category consists of those elements which are used to clarify or enhance the geometry, including dimensions, drafting notations and text. The definition category provides the ability to define specific properties or characteristics of individual or collections of data entities. The structure category identifies the grouping of elements from geometric, annotations or property data which are to be evaluated and manipulated as single items.

M & G Codes are the standard for cutting codes for all numerically controlled machines and are specified in EIA RS-274D. The G codes are known as the preparatory functions and they define the actual machining moves and cutter tool movement such as point to point positioning, linear interpolation, (CW/CCW), axis selection, thread cutting, cutter compensation etc. The M codes are known as miscellaneous function control codes such as the program stop, spindle ON/OFF, coolant ON/OFF, clamp/unclamp, tool change etc. In both the standard M codes and the G codes there are some codes which are unassigned and left for the user to assign them for any special function not listed in the standard M & G codes.

In addition to the standard M & G codes, F function which defines the feed rate in the x, y, z axes, T function which defines the tool and S function which defines the surface speed of cutter have been used in this software.

MANUFACTURABILITY

The manufacturability module consists of a 3-D feature extractor and a knowledge base on manufacturability. The feature extractor is discussed in depth under the section of process planning. The manufacturability tests will be conducted by applying knowledge base on each feature of the output of feature extractor. This includes testing for manufacturability of sharp corners, tolerance, surface finish, interference between tool holders and workpiece, and materials encountered while drilling a hole, etc. If any of the above tests fail to qualify, then the manufacturability module will generate a message outlining the reason for failure. The user will have to change the design of the part iteratively until the design passes the manufacturability tests.

PROCESS PLANNING

Process planning can be defined as the process of determining the methods and the sequence of machining a workpiece to produce a finished part or component to design specifications. Process planning typically consists of the following activities -

- Selection of processes and tools
- Sequencing the processes
- Identification of all non machining elements and estimating the non machining times.
- Selection of workpiece holding devices
- Determination of proper cutting conditions and cutting times to machine the workpiece to specified dimensions

A good process planner must have a detailed understanding of the different manufacturing processes and select the order of processing based upon a given performance index. In the current protocol there are two parallel paths which can be followed in producing the process plan. On the left side of figure 4 the user must supply specific information, in the form of machinery data, as to how the part will be produced. The path on the right side of figure 4 is an intelligent process planner using expert system techniques.

The ordered process planning uses a well established approach and is not discussed. The unique feature of the present protocol is the intelligent process planner based upon an "expert system approach".

An expert system is defined as a computer system that "emulates human expertise by applying the techniques of inference to a knowledge base" [5]. Most importantly the system must be designed such that it can be easily updated or enhanced periodically. Although most expert systems are constructed for use in a particular domain, there are domain independent expert systems called "shells" [6]. They have empty data bases and knowledge bases and so may be used for a variety of applications. Such an approach is used here.

The intelligent process planning consists of a 3-D feature extractor which uses the given data on part geometry to decompose the workpiece into a set of primitive geometric features. The output from the feature extractor becomes the input to an expert system which outlines the required machining processes. The knowledge base for this expert system will include manufacturability information regarding each machinable primitive geometric feature and it will generate a set of processes for machining these primitive features on an automated machining center.

To carry out the above steps, one would start with a part drawing file (prepared by the designer by using a CAD package) represented in the standard IGES format. The feature extractor would read this file and create a linked list of faces, edges and vortices which will represent the complete topology of the part. The 3-D features will then be recognized by applying rules that test for predefined patterns which may exist within this linked list. The faces corresponding to the recognized feature will then be removed from the data base and set aside. Proceeding on a surface by surface basis, the above steps will be recursively applied until there are no more surfaces left. Before finalizing the feature extractor, an iterative procedure will be carried out to ensure that the selected primitive features are the optimum ones.

Once all the features have been identified, the expert system for process planning will outline a sequence of processes that need to be carried out to manufacture the part. A translator can then be used to generate the necessary NC tool path which can be downloaded to the automated machining center.

When the process plan has been completed the IGES database is reduced to a single CAM database, as indicated in Fig. 4. In essence the CAM database consists of a reordering of the part geometry information, with tool size requirements and tool change pause information included in the CAM file.

At this stage the CAM file is processed to prepare standard machine tool driver codes, known as M and G codes. Then M and G codes are then further post-processed to prepare a data file of machine specific M and G codes.

PART MACHINING

In the post-processed form the part data is now ready to be loaded directly to the machine tool. Prior to doing this step it is advantageous to perform a software graphics simulation of the cell action. The emulation will check for fixture interrupts, code accuracy, and provide an estimate of the actual machining time. If any errors are observed in the cell behavior then the user can make corrections as may be required.

Finally the data is downloaded to the cell and the part is processed as follows:

1. The AGV delivers the raw material to the cell
2. The robot loads the raw material to the machine tool.
3. The cutters are loaded in the correct magazine slots on the machine tool
4. The machining codes are downloaded to the machine tool and machining occurs
5. The robot moves the completed part from the machine tool to the AGV.
6. The AGV leaves the cell boundary

CELL CONTROL

The software package dealing with cell control has the following objectives:

- Transport the raw material into the cell via the AGV.
- Transfer the material from the AGV to the intelligent fixture on the machining center.
- Use the robot and unload the finished part from the machining center to the AGV.
- Transfer the finished part out of the cell via the AGV.

To accomplish these goals the software package produces interwoven control codes which mesh with the M and G coded CAM database. The cell command codes are single entity instruction codes which are used to initiate an activity. Once the activity is completed a cell signal is sent to the cell host computer and cell operation continues. Typically the CAM database is loaded to the machining center in the cell and then activity on the machining center is placed on hold until the raw material is in proper position. At this time machining starts and will continue uninterrupted until the intelligent part fixture must relocate to avoid a cutter intercept condition. When this condition is predicted the machining center pauses and the intelligent part fixture relocates the manner in which it holds the part. Machining then reinitiates and continues until a new fixture intercept is predicted, at which point the fixture movement occurs again. When machining is complete the part is removed from the fixture, placed on the AGV and the AGV is commanded to exit the cell. Once the cell boundary has been crossed, the cell is then free to initiate its next task.

AN EXAMPLE

The part shown in Fig. 5 was generated using the PC-based UOM CAD software. The output of the CAD system which is IGES compatible, becomes the input to the ordered process planner which generates the standard M and G codes as shown in Fig. 5. It is further postprocessed to obtain machine specific code. The part was manufactured by downloading the code from the PC to a machine controller on the CNC machine.

As an alternate approach the above part was also manufactured by downloading an ICES compatible design data file to PC, created from ANVIL-4000 residing on VAX 11/750 Computer.

CONCLUSIONS

A flexible manufacturing protocol has been suggested for user-to-part automation. The protocol has been enhanced by data and machine control code standardization and AI techniques in the process planner. An example illustrating the use of the protocol establishes its viability as a flexible test bed.

ACKNOWLEDGMENT

This work was partly supported by NSF Grant CDR-85-00108 through The System Research Center.

REFERENCES

1. Anand, D.K., Kirk, J.A., Anjanappa, M., Pecht, M.G., "Supercomputers and Hierarchial Control: A Systems Viewpoint", Proceedings, NSF Conference on Supercomputers in Mechanical Systems Research, Lawrence Livermore National Laboratory, California, 1984.

2. Anand, D.K., Kirk, J.A., Anjanappa, M., "Research in the Flexible Manufacturing Laboratory", The Systems Research Center, University of Maryland, College Park, 1986, SRC-TR-86-61.

3. "Computers in Manufacturing", By the Editors of American Machinist, McGraw-Hill Publications, New York, April 1983.

4. Cutkowsky, M., Fussel, P., "Precision Flexible Machining Cells within Flexible Manufacturing Systems", Carnegie Mellon University, Technical Report, CMU-RI-TR-83-2, 1983.

5. "Expert Systems 1986-Volume 1:USA & Canada", OVUM Limited, London, 1986.

6. Rychener, M.D., "Expert Systems for Engineering Design", Expert Systems, Volume 2, No. 1, pp. 30-44, 1985.

7. Sata, T., "Technology of the Unmanned Operations of FMS", Computers in Industry, Volume 4, No. 2, pp. 127-137, 1983.

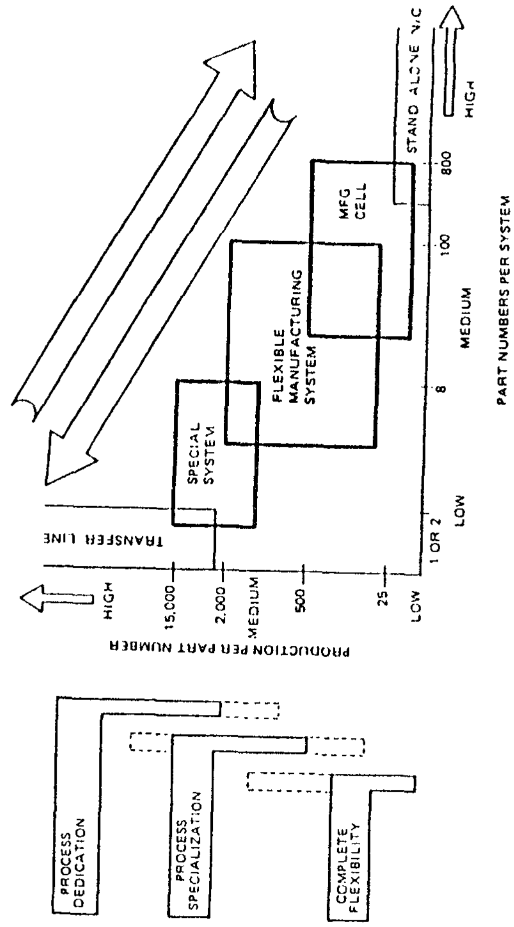

FIG 1 MANUFACTURING SYSTEMS (Courtesy of Kearney & Trecker Corp.)

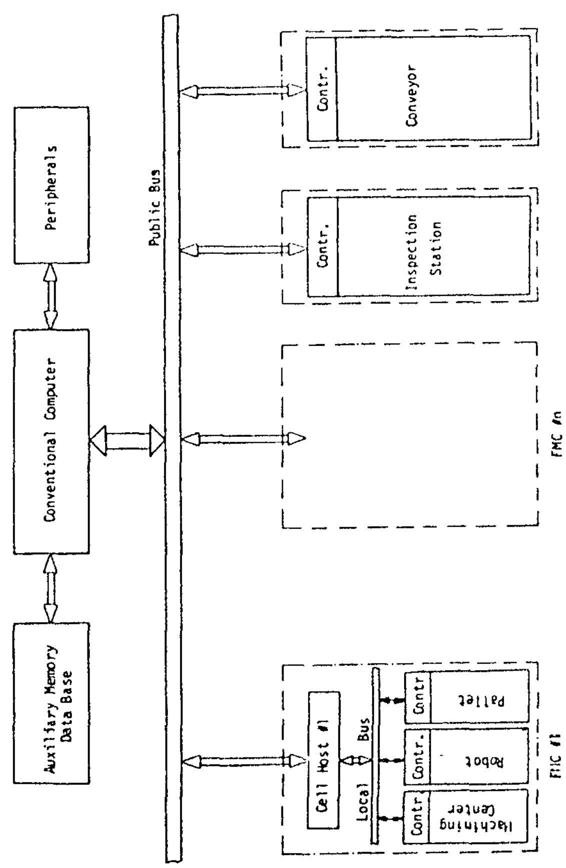

FIG. 2 FLEXIBLE MANUFACTURING SYSTEM

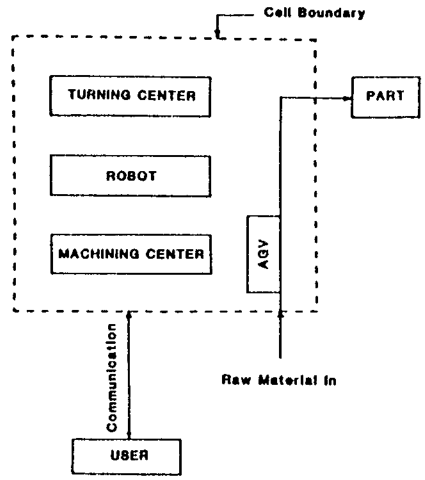

FIG. 3 FLEXIBLE MANUFACTURING CELL

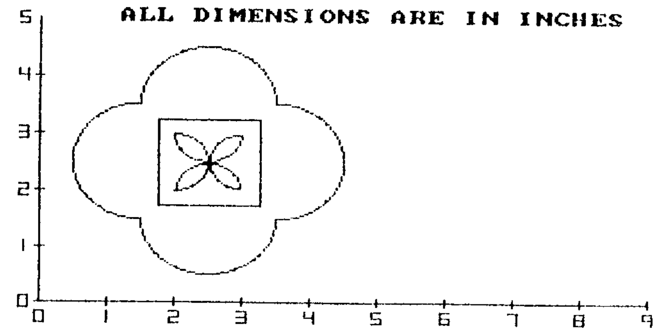

FIG. 5 TYPICAL PART

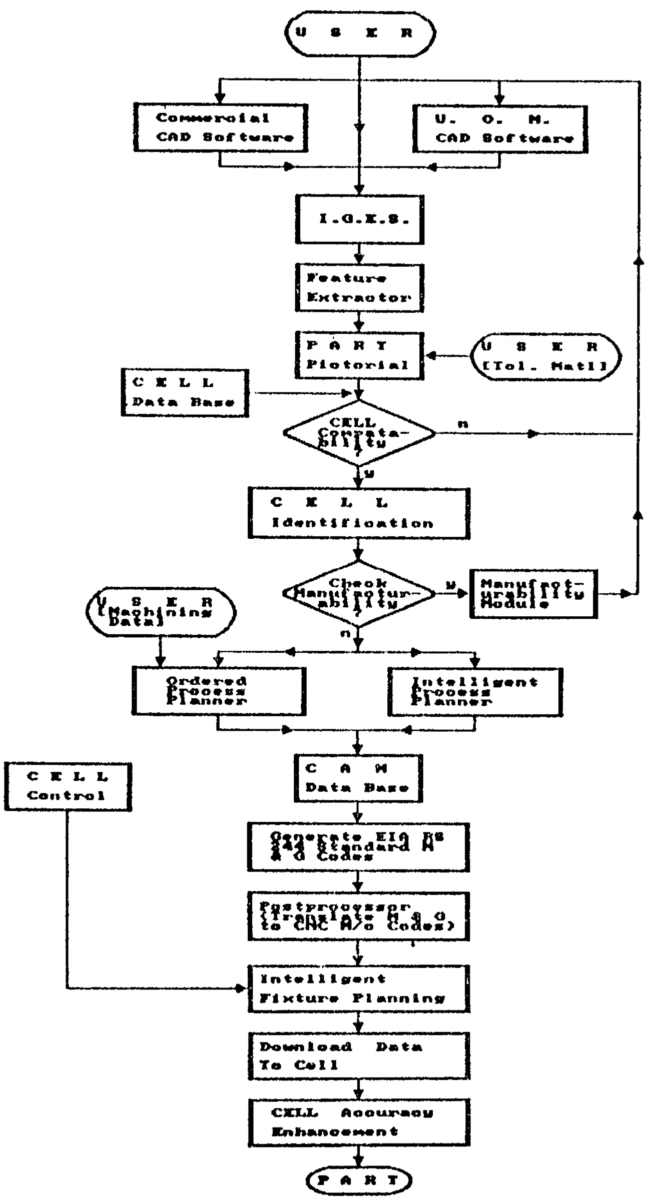

FIG. 4 FLEXIBLE MANUFACTURING PROTOCOL

```
                      M & G CODES

N001  T01 D .125 M06                 ;DEFINES TOOL DIA
N002  S 100 FX 8 FY 8 FZ 8           ;SURFACE SPEED AND FEED
N003  G00 X 1.5 Y 1.5                ;RAPID MOVE FROM ORIGN TO LOC 1
N004  G01 Z - .01                    ;LOWER TOOL .01 INCH INTO THE W/P
N005  G02 X 2.5 Y 1.5 I-1 J 0        ;MOVE FROM LOC 1 TO LOC 2
N006  G02 X 3.5 Y 2.5 I 0 J 1        ;MOVE FROM LOC- 2 TO LOC 3
N007  G02 X 2.5 Y 3.5 I 1 J 0        ;MOVE FROM LOC- 3 TO LOC- 4
N008  G02 X 1.5 Y 2.5 I 0 J 1        ;MOVE FROM LOC- 4 TO LOC 5
N009  G01 Z 0.5                      ;RAISE TOOL .5 INCH ABOVE W/P
N010  G00 X 2 Y 2                    ;RAPID MOVE W/O CUTTING
N011  G01 - .01                      ;LOWER THE TOOL .01 INCH INTO THE W/P
N012  G02 X 2 Y 2.5 I 0 J-.5         ;MOVE FROM LOC 6 TO LOC- 7
N013  G02 X 2.5 Y 3 I-.5 J 0         ;MOVE FROM LOC- 7 TO LOC- 8
N014  G02 X 3 Y 2.5 I 0 J .5         ;MOVE FROM LOC- 8 TO LOC- 9
N015  G02 X 2.5 Y 2 I .5 J 0         ;MOVE FROM LOC- 9 TO LOC- 10
N016  G01 Z 0.5                      ;RAISE TOOL .5 INCH ABOVE W/P
N017  G00 X 1.75 Y 1.75              ;RAPID MOVE W/O CUTTING
N018  G01 - .01                      ;LOWER THE TOOL .01 INCH INTO THE W/P
N019  G01 X 1.75 Y 3.25              ;MOVE FROM LOC- 11 TO LOC- 12
N020  G01 X 3.25 Y 3.25              ;MOVE FROM LOC- 12 TO LOC- 13
N021  G01 X 3.25 Y 1.75              ;MOVE FROM LOC- 13 TO LOC- 14
N022  G01 X 1.75 Y 1.75              ;MOVE FROM LOC- 14 TO LOC- 15
N023  G01 Z 0.5                      ;RAISE TOOL .5 INCH ABOVE THE W/P
N024  G00 Z 1.0                      ;RAPID RAISE THE TOOL
N025  M09                            ;COOLANT OFF
N026  G00 X 0 Y 0 M05                ;MOVE TO ORIGIN AND SPINDLE OFF
N027  M02                            ;STOP THE MACHINE
```

FIG. 6 CUTTING CODES