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Managing Product Performance through Design Engineering: Condition Monitoring in Automated Organisations

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Abstract: Despite impressive advances in automated production technology, manufacturing industry is still heavily reliant on conventional processes, particularly in processes designed for materials removal in which controlled shearing of the work-piece occurs. Such processes typically involve the use of automated computer controlled machining centers, which, in principle, are capable of sustained periods of unattended operation. However, the quality of the finished product, in terms of its conformance to dimensional and surface finish requirements as specified in the design, is strongly dependent upon the condition of the cutting tools used. A number of tool life management systems have been designed and engineered and are employed in production environments today, but these are usually based on expired life criteria and are of limited applicability. Crucially, in the context of increasing product life cycles, the disguarding of tools earlier than may be necessary is wasteful, expensive and inconsiderate to the environment. More sophisticated designs do exist, typically based on advanced technologies, such as acoustic emission or spindle torque sensors, for dynamically sensing tool condition during operation. Such systems are potentially more useful but still only indicate that some aspect of the cutting process has changed and usually require human intervention. This paper thus addresses the need for better control of production processes with the objective of increased operating efficiency based on reducing waste and improving the product life cycle. The work reported here is primarily concerned with the design and application of prototype intelligent systems for automated tool management.

Keywords: Automation, Production, Life Cycle, Quality, Tool Management, Environment

Introduction

DESPITE IMPRESSIVE ADVANCES in forming and joining technology, manufacturing industry is still heavily reliant on conventional material removal processes, in which controlled shearing of the work-piece occurs. Such processes involve the use of cutting tools which are significantly harder than the work-piece itself and are usually carried out on CNC machining centres, either as stand alone devices or as integral parts of machining cells and systems. Such systems typically include automated tool and work-piece transport/handling and swarf management and, in principle, are capable of sustained periods of unattended operation in a 'lights out' factory environment.

However, the quality of the finished work-piece, in terms of its conformance to dimensional and surface finish requirements, is strongly dependent upon the cutting conditions and, crucially, upon the state of the cutting tools used. In most systems, some form of cutting tool life management is employed but this is most frequently based on expired life criteria. Such criteria are themselves based upon cutting trials conducted under 'ideal' conditions and are therefore of limited applicability. For example, it is assumed by such systems that if a cutting

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tool leaves the stores in good condition it will remain in an acceptable condition until it has operated for a predetermined period. More sophisticated procedures exist, typically based on acoustic emission or spindle torque sensors, for dynamically sensing tool condition during operation. Such systems are potentially more useful but still only indicate that some aspect of the cutting process has changed and usually require human intervention.

Investment in cutting tools is not trivial and in a study of a large UK manufacturing company, with a tool inventory value of almost £3 million, it became apparent that some tools could be used in a less than optimum condition whilst others were needlessly replaced or refurbished.

The cutting process itself can be overseen by some form of adaptive control and several systems of differing complexity are commercially available. Most systems are relatively unsophisticated in that they control a single machining parameter, usually feed rate, in order to keep spindle torque within predefined constraints. These systems in no way compare with the sensitive control capable of being exercised by a skilled machinist. Furthermore, they are unable to dynamically react to observable changes in the condition of the work-piece as a result of the cutting process.

Work at the University of Hull is aimed at addressing the need for better control of machining processes with the objective of increased operating efficiency based on reduced scrap and rework and by a lower tool inventory. The work is primarily concerned with the application of intelligent systems to tool management and is based on the use of laser scattering techniques to detect and characterise edge defects in milling cutters (Dewhurst and Swift, 1989).

Laser Scanning Techniques

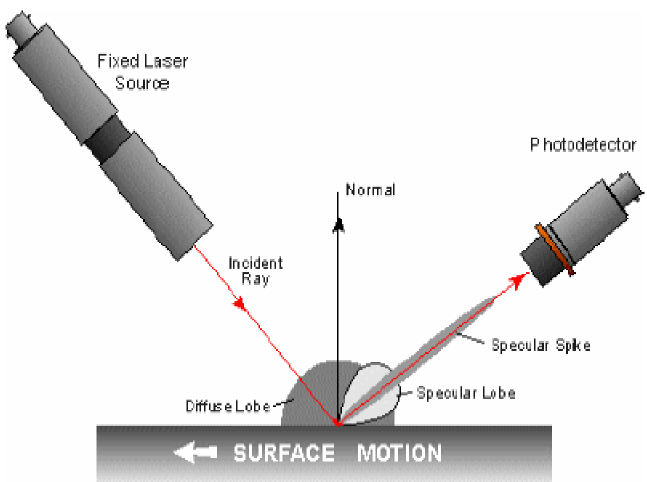


Figure 1: Theory of Laser Scattering

The principle of laser scanning (Fig. 1) is relatively simple and relies on the fact that physical features of a solid surface will reflect incident light in a way that is directly attributable to their geometry (Torrance andSparrow, 1967). Low power (<1mW) lasers are used because they provide a consistent and coherent incident light source (Schmalfuβ, 1990). Technological developments over the last decade have provided considerable opportunities for miniaturisation (Fig. 2). Suitable detectors, usually in the form of photo-diodes, are arranged to capture the reflected light patterns, which are subsequently stored and processed to extract data related to the scanned surface. By this means, intended features or defects on a surface can be recognised and assessed. The principle of operation is well-established and widely applicable and has been used by researchers at Hull as a basis for the automatic detection of defects in cutting tools (Dalgliesh *et al* (a), 1998).

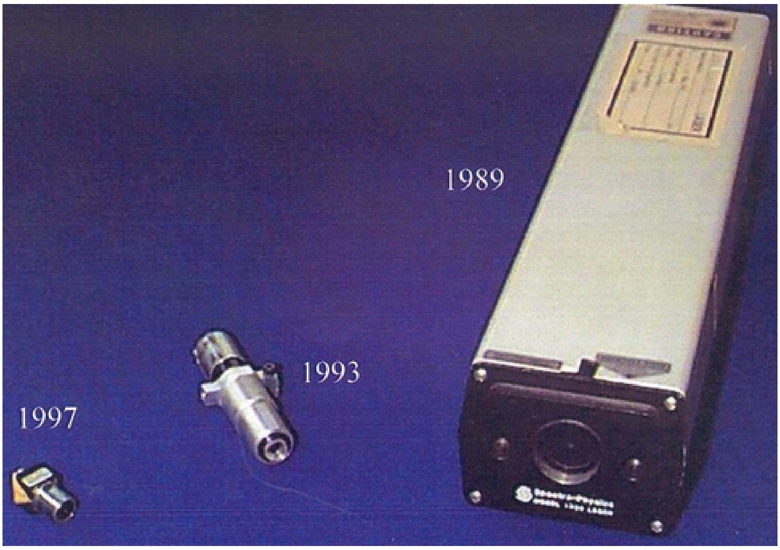


Figure 2: Miniaturisation of Laser Diodes

Milling tools have relatively complex geometry and often incorporate helical cutting edges, which have to be tracked by the laser scanner and detector. Fig. 3 shows an early prototype device for the semi-automatic inspection of end milling cutters. Computer-controlled stepper motors were used to translate and rotate the cutter under an inspection head comprising a single fixed laser and detector. A CNC 'move template', specific to a particular tool, was written to obtain the necessary combinations of rotation and translation to track the cutting edges. Such a device would be suitable for use in a central tool store to monitor edge condition before the tools were allocated to machining areas. However, a more useful implementation of the device is achieved when it is integrated with the local tool storage system of a machining centre. Fig. 4 shows an example of such an arrangement on a small CNC milling machine in the laboratory at Hull. Tools can be automatically transferred from the tool magazine to the inspection station whilst cutting proceeds with another tool. All tools are scanned prior to the commencement of the machining operation and then subsequently after each tool has been used for cutting. After inspection, the tool condition is written to the tool data file in the machine control unit (MCU) and, if significant defects are detected, a back-up tool can be used when next required.

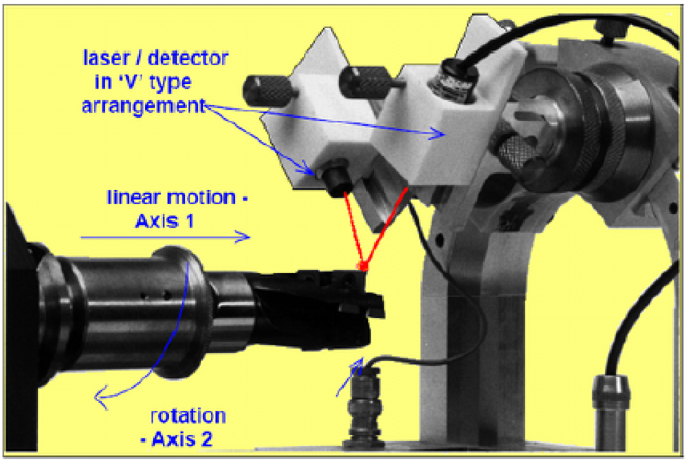


Figure 3: Prototype Device for Inspection of Milling Cutters

In-service Inspection of Cutting Tools

Laser scanning provides a good basis for cutting tool inspection systems in a tool-room or, more usefully, integrated with CNC machine tools themselves. In the early stages of this work, a demonstration system was developed to operate in conjunction with the automatic tool-changer (ATC) of a small CNC machining centre. Modifications had to be made to the ATC to allow tools, in their tapered holders, to be transferred into a separate, adjacent, inspection station. The 4-axis laser/detector system was driven by computer-controlled stepper motors along the cutting edges of a tool according to a pre-defined 'move template' (Dalgliesh *et al* (b), 1998).

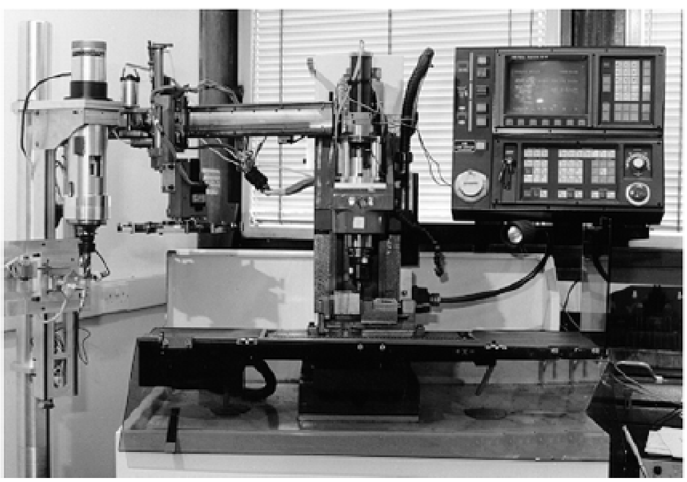


Figure 4: Integration of Laser-based Tool Inspection System with CNC Machining Centre

Tool wear patterns and defect characteristics were identified by comparison with a master trace and their severity assessed in terms of the likelihood of consequential work-piece damage. The tool database in the memory of the Machine Control Unit (MCU) could be updated to register tools unsuitable for further use. Selection of such tools would be inhibited and 'sister' tools selected, subject to availability. The principles demonstrated can be readily applied to full-size machining centres with local access to several hundred individual tools. The scanning time is typically 1–2 minutes but tools can be scanned in a variable sequence to ensure that they have been inspected well in advance of their requirement for a machining operation.

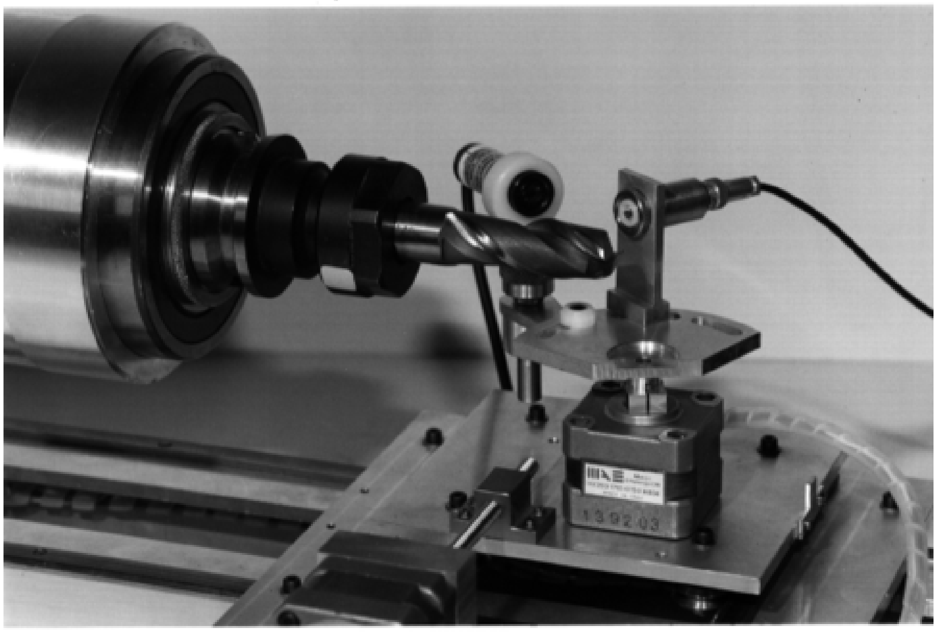


Figure 5: Close-up of Laser/Detector Assembly

Sophisticated tool management can be achieved by the use of appropriate signal-processing techniques. The digitised signal from the tool scanning sequence can be conveniently analysed using the Visual Basic programming language. Information on tool condition is captured as a linear data sequence, representing the reflected signal magnitude, in the range 0–12 Volts. The Visual Basic program is primarily designed to assess the condition of the tool edge in the critical wear zone (Zone II in Fig. 6). This is achieved by reference to control limits representing signal saturation, the physical boundary between the cutting edge and clearance face, the transition from mild wear to severe wear and variations due to signal noise.

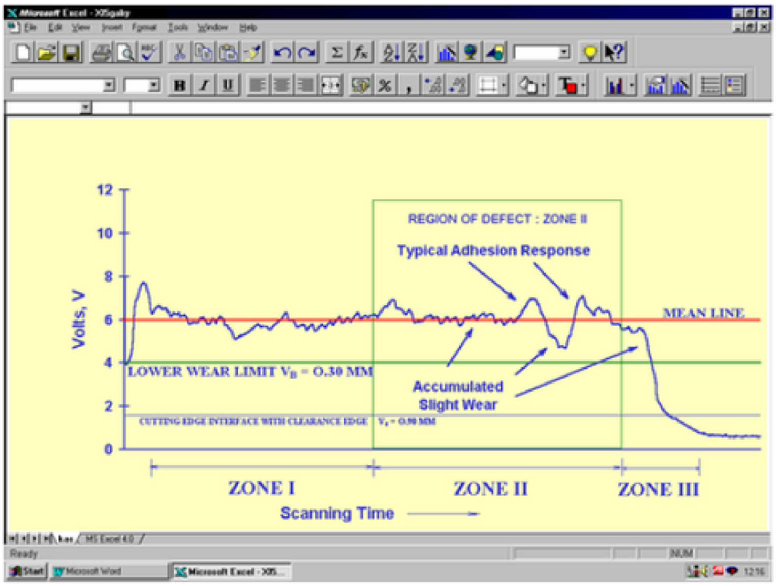


Figure 6: Screenshot of the Signal Processing Macro for a Worn Tool

The information contained in the captured traces can be used to drive algorithms to display tool condition categories based on the number of instances a particular control limit is exceeded. Any highlighted condition triggers a warning display. In the example shown in Fig. 7, a combination of work-piece adhesion and mild flank wear (<300um) is indicated. The recommended action is that the tool be ground to improve the cutting edge condition and then monitored at more frequent intervals to monitor any transition from mild to severe wear (Fig. 8).

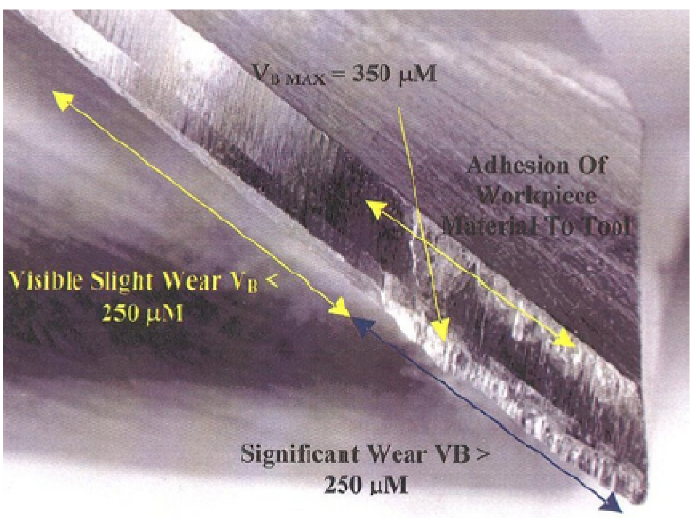
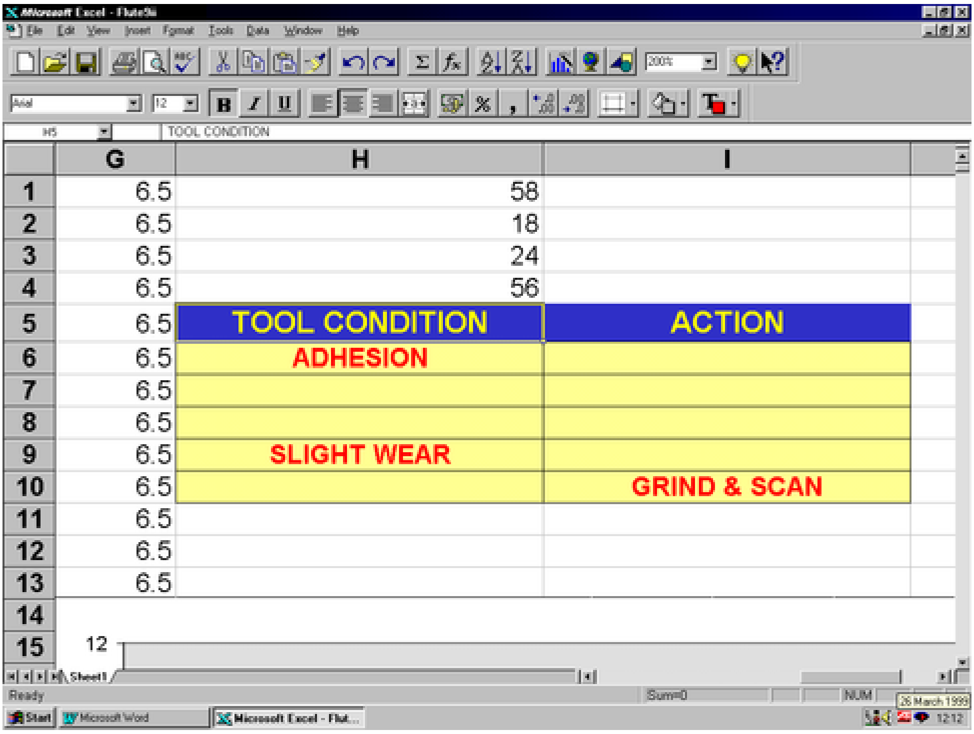


Figure 7: Visual Verification of Cutting Tool Condition



	G	H	I
1	6.5	58	
2	6.5	18	
3	6.5	24	
4	6.5	56	
5	6.5	TOOL CONDITION	ACTION
6	6.5	ADHESION	
7	6.5		
8	6.5		
9	6.5	SLIGHT WEAR	
10	6.5		GRIND & SCAN
11	6.5		
12	6.5		
13	6.5		
14			
15	12		

Figure 8: Condition / Action Table for Worn Tool

Inspection of Spindle-mounted Cutting Tools

More recent work has been focused on inspection of cutting tools held in the main spindle of a Kryle CNC vertical machining centre (Fig. 9). The optical elements of the inspection system, on the prototype system, are mounted on the bed of the machining centre and remain in place during the machining cycle to provide intermittent on-line inspection of the spindle-mounted cutting tool (James *et al*, 1999). Machining has to be interrupted to allow scanning of the tool but, on balance, the advantages of this type of inspection arrangement outweigh its disadvantages in most situations. In this respect, the principal benefit derives from the use of the controlled axes of the machine tool to provide the relative motion between the laser/detector and the cutting tool. One of the major problems to be overcome was the provision of sufficiently slow and regular rotation of the main spindle during the tool-scanning cycle. This was achieved, on the Kryle, by the provision of an auxiliary spindle drive motor but on other machine tools this has been more readily achieved via software commands to the MCU.

Figure 9: Kryle CNC Vertical Machining Centre

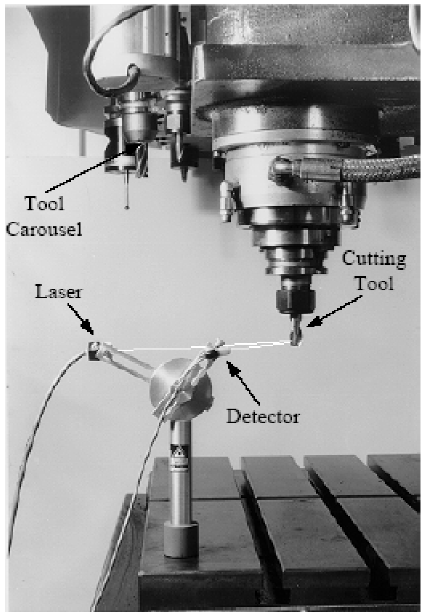


Figure 10: Close Up of Cutting Tool Inspection System

With the requirement for greater interaction between the CNC machining centre and the separate scanning system control PC, a more intelligent integrated software system had to be developed. This system has to control the machine tool axes, capture and evaluate the output from the tool-scanning system and feed back information on tool condition and required actions to the MCU. Fig. 11 is a block diagram showing the interaction between key elements of the system, in which the PC is the master controller.

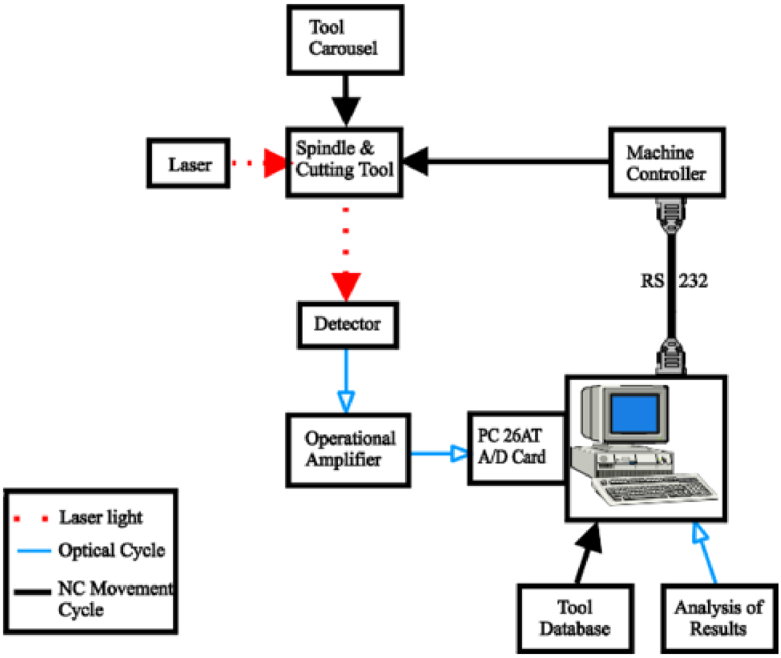


Figure 11: Block Diagram Showing Control System Interactions

The first stage of operation of the tool-scanning system is the generation of a move template to guide the laser/detector unit along the relevant cutting edges of the tool to be inspected. This is simply achieved by means of data entry into an Excel spreadsheet (Fig. 12) which generates an NC program to drive the axes of the machine tool. The data required are, typically, Helix Angle, Flute Length, Tool Diameter and Number of Flutes, all of which are readily available.

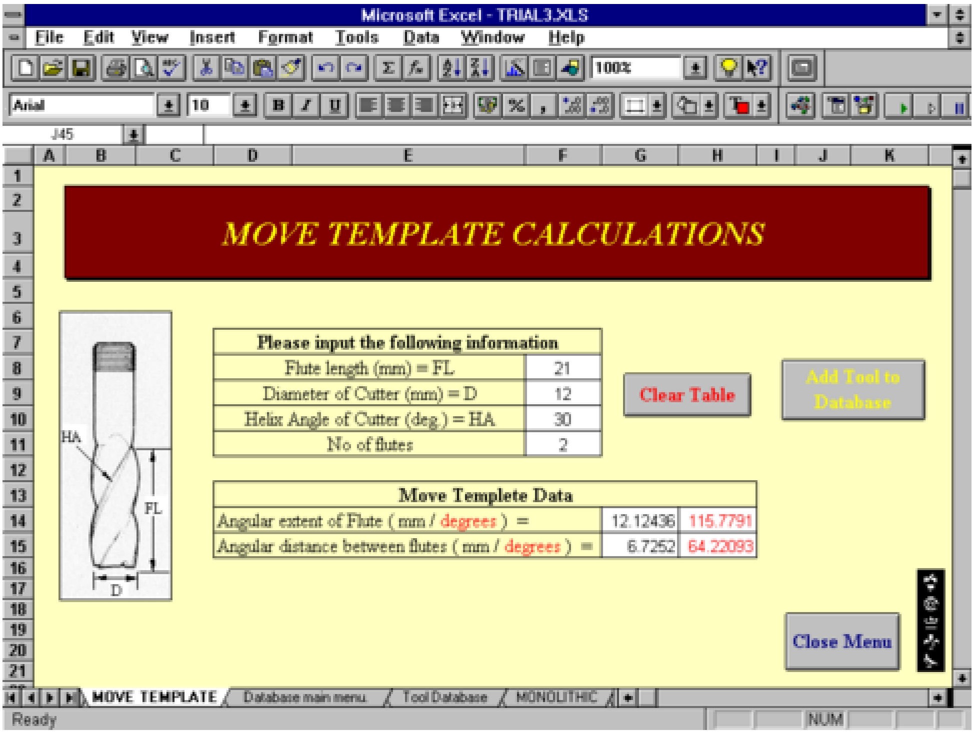


Figure 12: Screen Shot of Tool Profile Data Format

The move template for a particular tool can be transferred directly to a tool library, which holds such templates for all tools loaded into the local tool store. Move template data can thus be readily accessed as required. The following information is held for each tool:-

Tool storage location (e.g. Pocket No. in a carousel)
Tool manufacturer
Tool identification code
Diameter (mm)
Flute length (mm)
Helix angle (deg.)
Number of flutes
Angular extent of flute (deg.)
Angular distance between flutes (deg.)

When a particular tool is to be scanned, say when it is mounted in the spindle prior to cutting, it is lowered in a position to engage with the laser/detector unit in response to commands generated by the move template. The tool-scanning cycle can be automatically invoked as the cycle-start option on the MCU to allow the PC to act as the master controller. All the relevant cutting edges are then systematically inspected and the output signals passed to the PC for processing in a manner similar to that described earlier. Tool condition and recommended remedial action is dealt with as in the previous system.

An important development requirement for more general acceptance of the inspection system described is the ability to generate move templates for a variety of machining centres. This implies the need for a flexible Serial Configuration Output Program to post-process a generalised move template for different MCU's.

Conclusions

The work described here confirms the application of laser-scanning as a viable method for automatically monitoring the condition of cutting tools. It has been demonstrated that a scanning system can be successfully integrated with a machining centre such that tools held in the main spindle can be scanned via the operation of the machine tool axes and control of spindle rotation. This development removes the requirement for the separate inspection station, used in earlier implementations of the system. The physical condition of the cutting edges of tools can be deduced from the output of the laser scanning system and used to trigger the display of information to an operator. Alternatively, in unattended machining systems, the scanner can be configured to communicate directly with the machine control unit. In this way, selection of defective tools can be inhibited and consequential damage to work-pieces avoided.

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Dr. Kasim Randeree is Programme Director and Lecturer for the M.Sc. in Project Management programme at The British University in Dubai in the United Arab Emirates. He has an academic career spanning the past 15 years, with experience both in the United Kingdom and the Middle East. This work continues his interest in Engineering Design in which he holds a PhD from the UK. In more recent times, Dr. Randeree has dedicated much of his work to the development of contemporary Middle Eastern society and has worked at the United Arab Emirates University in Al Ain, The American University in Dubai as well as conducting research across parts of the Arabian Gulf and North Africa. He has a broad portfolio of research with related current interests in the legacy of early Muslim practitioners to contemporary management and the advancement of the Arab Middle East. He has numerous supporting publications both internationally and across the region.

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