Application of Ultra High Performance Manufacturing Strategies to CNC Milling

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Abstract

The application of modern multi-axis computer numerically controlled (CNC) manufacturing technology is driven by industry. The high capital cost of these resources limits educational establishments from acquiring them and therefore they largely lag behind industry. However the requirement to equip students with application knowledge of advanced computer numerically controlled (CNC) manufacturing resources remains.

Engineering education must ensure that graduating students understand and can fully embrace the technological advances in the application and programming of modern computer numerically controlled (CNC) machine tools and the associated computer aided manufacturing (CAM) systems. These dynamically advancing technologies which incorporate advanced manufacturing strategies to facilitate the programming of multi-axis machine tools need to be effectively integrated into third level engineering education.

Academics require first-hand experience of these resources to fully appreciate the skill set required to facilitate the operational deployment of these resources and to provide educational knowledge at an appropriate industrial level. To address these issues the University of Ulster has proactively engaged with a number of collaborative projects with manufacturing companies and regional technical colleges. These partnerships have significantly enhanced the ability of the University to deliver industrially focused manufacturing modules.

This paper will summarise the engineer educational benefits of collaborative, industrially focused technology transfer programmes and reports on a joint teaching development project between the University of Ulster and the Northern Regional College (NRC Ballymena) investigating the application of advanced toolpath optimisation strategies. This project focused on the application and teaching of optimised toolpath roughing and finishing strategies for 3 and 5 axis milling. The resultant CNC programs optimised the use of the machine tool, cutting tools and incorporated ‘constant tool step-over ' algorithms with dynamic feed rate control to maintain a constant material removal rate. This methodology typically reduced the manufacturing cycle time by 30-60%, extended the productive tooling life by >70%, eliminated sudden tool loading and provided stable cutting conditions. These benefits are readily replicated on all modern CNC resources and provide cost benefits to industrial and academic partners.

**1. Introduction**

The application of modern multi-axis computer numerically controlled (CNC) manufacturing technology is driven and lead by industry. Academics have an increasingly difficult challenge trying to equip themselves and educate their students with the appropriate application experience and knowledge requirements of these resources.

**2. Knowledge Transfer Schemes – KTP and Fusion**

To address this problem it is crucial for academic staff to actively participate with industrial projects and to maintain and sustain close industrial collaborative links. One way of achieving these objectives has been through graduate development programmes, Knowledge Transfer Programmes (KTP- Sponsored by Invest Northern Ireland) and Fusion (sponsored by InterTrade Ireland).

These programmes link an industrial partner with specific knowledge transfer requirements with appropriate academics and employ a graduate on a fixed term contract to address the issues. Financial assistance is provided to the company and the educational establishment and they support the graduate with combined industrial and academic expertise to address the knowledge transfer requirements. Participation with these programmes provides academic staff with an immense amount of technical and relevant industrial knowledge.

The University of Ulster has a long and well established history with these technology transfer schemes and have participated with a large and diverse range of industrial partners. These programmes play an increasingly crucial role in providing technology transfer between manufacturing companies, graduates and universities. From an educational perspective they provide relevant and current industrial experience which greatly facilitates the academics knowledge. This knowledge can be integrated into lecturing material and supported by application based case studies that can be directly incorporated into educational module content.

A sub-set of these programmes have included manufacturing companies utilising advanced multi-axis CNC resources. Example include the installation and commissioning of 13 axis Miyano ABX-THY CNC turning centres at Mann Engineering, Wexford (Fusion Project). This resource ran 3 simultaneous CNC programmes with synchronisation codes to control the three turret, twin spindle, turning centres. Live tooling was supported with both ‘C’ and ‘Y’ axis machining capabilities. This project included the utilisation of standard computer aided manufacturing (CAM) turning with the manual insertion of the appropriate synchronisation codes through to the eventual installation and application of an advanced multi-axis CAM system that could graphically simulate the entire machining process and post-process optimised CNC code to drive the machine.

Other projects include the application of 3-6 axis CNC laser profilers, 3-5 axis CNC milling centres, multi-axis CNC woodwork routers and a range of plastic manufacturing resources including injection moulders, extruders, compression moulders and vacuum formers with associated CNC routering.

Knowledge gained at this level is of immense value to academic staff helping them to appreciate and to be technically competent in the industrial application of these sophisticated resources. This direct application knowledge at an industrial level is a fundamental requirement to undergraduate / postgraduate students to ensure they understand and can apply high value added manufacturing technologies to support the requirement of modern manufacturing industry. The increasing rate of development and technological advances within CNC manufacturing resources implies that industrial collaboration should be mandatory for academic staff to ensure the effective engineering education of manufacturing to students at a university level.

**2.1 Connected Programmed**

The Connected Programme provided financial support for the transfer of knowledge between universities of regional technical colleges. A successful collaborative project was established between the University of Ulster and the Northern Regional College (NRC, Ballymena).

NRC has a long and well established manufacturing centre of excellence with major industrial collaborative links. Recent investment has complimented their centre of excellence with the installation of a DMU50 Eco-Linear, 5 axis, simultaneous CNC milling centre, Bystronic CNC laser profiler and CNC press brake along with an integrated robotic loading system.

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| dmu50evolinear_maschine.jpg | X, Y, Z Axis Travel - 500 x 450 x 400 mm  Rapid Traverse XYZ – 80,50,50 m/min  Maximum Feed Rates – 18000mm/min  Positioning ±0.005 mm  Repeatability ±0.005 mm  Max Weight On Table - 750 kg  Spindle Motor (40 / 100%) - 35 / 25 kW  Spindle Speed Range - 15-18,000 RPM  Spindle Torque (40 / 100%) -130 / 87Nm  Swivel B / C Axis 0 / 108o, 360o  Rotary speed B and C 40 / 50 rpm |

Figure (1) DMU50 Eco-Linear 5 Axis Simultaneous Milling Centre

This level of technology is unprecedented within Northern Ireland and UK educational establishments and represents a financial invest of the order £1.1M, funded by the EU INTERRG IVa Programme and the Department for Enterprise, Trade and Industry in Northern Ireland (DETI). Within the current economic climate this investment is significantly outside the financial resources of most UK and Ireland third level educational establishments.

The Connected programme was an ideal mechanism for both establishments to learn from each other and to compliment the education requirement that each needed to address.

The NRC provides excellent technician level training via the OND / HND routes and these resources are integrated into their practical and application based manufacturing courses. The University provides undergraduate and postgraduate degree qualifications in manufacturing and having access to these facilities significantly enhances and benefits the students educational experience.

Joint knowledge transfer came from the enhanced and optimised utilisation of CAM systems - MasterCAM X5 [1], Verticut [2] and Delcam PowerMill [3]. These systems fully complimented the off-line programming requirements for these resources and the deployment of ultra high performance manufacturing strategies helped establish operational excellence.

This collaborative project initiated an industrial research project with Rainey Engineering Solutions, Lisburn to prototype the development of advanced solid carbide finishing tool geometries for the manufacture of high value aerospace structures. The DMU50 milling centre provides the capability to fully test and quantify productivity enhancements, tooling productive life and surface finish analysis for the manufacture of these components. This project has been funded with the Invest Northern Ireland innovation voucher scheme.

**3. CNC Milling Developments**

CNC machine tools continue to evolve at a rapid pace and manufacturing companies are increasingly deploying the latest multi-axis machine tools to establish operational excellence.

Axis drives, spindle performance, controller technologies and all other sub-systems integrated into these resources are also developing in parallel. Examples include linear axis systems with acceleration of the order 1-3g, feedrate capability of 10-40 m/min, rapid positioning at 30-100 m/min and spindle speeds of 10-40,000 rpm. Additionally continued advances in spindle adaptors, tool holders, cutting tool materials and tool surface coatings are simultaneously taking place.

**3.1 Computer Aided Manufacturing (CAM) Software**

The CNC programming of these resources is primarily achieved with the use of computer aided manufacturing (CAM) systems that provide automatic generation of toolpaths with full graphical verification. With manufacturing industry embracing this technology they require students educated to an application knowledge level in these systems. The utilisation of these systems provides universities with an ideal opportunity to advance their application knowledge and enhance engineering education.

The teaching and application of computer aided manufacturing technologies has long been established within educational manufacturing modules. CAM systems are frequently provided to universities at a significantly reduced cost providing them with the opportunity to purchase and to potentially lead in the application and of these systems.

A fundamental problem has been that although CAM systems provide geometrically accurate toolpaths they frequently incorporate adverse cutting conditions that result in machining difficulties or limitations. Examples include variable tool engagement, variable step-over and sudden directional changes. These are typically found in traditional offset geometry roughing toolpaths and without feedrate optimisation the CNC programmer has to restrict the operational feedrate to the most difficult cutting condition.

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| mma.jpg | X, Y, Z Axis Travel - 660 x 406 x 508 mm  Rapid Traverse – 24,000 mm/min  Maximum Feed Rates – 8000mm/min  Positioning ±0.005 mm  Repeatability ±0.005 mm  Max Weight On Table - 750 kg  Peak Spindle Motor - 11 KW  Spindle Speed Range - 15-10,000 RPM  Max Spindle Torque -73Nm /1450rpm  Tools - 20 CAT Tool Carousel |

The application of new optimised milling strategies based on the concept of ultra high efficient CNC programming address these problems. Importantly for engineering education these new strategies can be readily implemented on relatively low cost CNC resources with significant operational benefits. A recent final year project at the University of Ulster utilised an entry level Hurco VM10, 3 axis CNC machining centre to investigate the operation benefits of these machining strategies. The specification of this machine tool is detailed in Figure (1).

Figure (1) - Hurco VM10 3 Axis CNC Milling Centre

**3.2 Ultra efficient machining strategies**

Optimisation of the CNC programming systems has been facilitated by the introduction of ultra efficient machining strategies including dynamic feed rate control, dynamic milling strategies (MasterCam-X5), constant step-over roughing (VoluMill – Celeritive Technologies) and a range of new 2D and 3D finishing strategies including hybrid finishing, scallop machining and high speed machining techniques (MasterCam X5, Delcam PowerMill, FeatureCAM).

Within this context a university can lead manufacturing industry and increase the awareness to students by demonstrating and highlighting the benefits attributed to CNC optimisation. These benefits include significant cycle time reduction, increased tool productive life, vibration / chatter elimination, stabilised cutting conditions, predictable tool life and reduced spindle shock loading. All of these benefits were readily achieved by the introduction of MasterCAM X5 - dynamic milling, high speed machining (HSM) algorithms and the commercial add-in VoluMill system.

Initial CNC optimisation was achieved by attempting to maintain a constant material removal rate (MRR). This procedure calculated the MRR for the toolpaths and then dynamically adjusts the traverse feedrate within a specified safe operational range in an attempt to maintain a constant material removal rate. The CAM software also examines the trajectory of the toolpath and adjusts the feedrate when abrupt changes in direction occur. This is a common problem associated with traditional offset toolpath generation, Figure (2).

New CAM roughing algorithms optimise toolpath geometry by attempting to maintain a constant tool engagement angle (TEA) [4] or a constant step-over [5]. This results in a totally different type of tool path that eliminates abrupt changes in toolpath trajectory by constantly using circular cuts. Climb milling cutting direction is maintained throughout manufacture with the tool typically retracting 0.25mm and re-positioning at maximum cutting feedrate to achieve cutting directional control. These strategies provide highly stable cutting conditions and enable the safe utilisation of large depths of cut, typically 1.0-2.0 x tool diameter with 20-50% radial engagement.

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Figure (2) Conventional Offset Roughing VoluMill Optimised Roughing

CNC application benefits by the utilisation of the full flute length of the tooling, elimination of sudden direction changes typically produced by conventional offset profile toolpaths and provide the capability to main a near constant step-over. All of these enhancements greatly enhances the productive performance of the CNC machine tool with cycle time reductions of the order 30-60%, tool productive life increases of the order 70-100% and associated benefits of reduced programming time and a right-first-time / optimise cutting strategy.

These programming techniques establish world class machining with the associated benefits of reduced tooling costs, enhanced safety and substantial time compression for manufacturing operations. Table (1) summaries the verified cutting parameters for the milling of aluminium.

Table (1) Cutting Tool Parameters for the milling of Aluminium

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| Material :- Aluminium 6061-T6 |
| Tool 12mm Keno Ripper, 3 flute, Solid Carbide |
| Spindle speed:- 10,000 RPM (maximum spindle speed on Hurco VM10 |
| Feedrate 3800 mm/min |
| Axial depth of cut 14mm / 1.15 x Tool Diameter |
| Radial width of cut 3.6mm / 30% radial engagement |
| Material removal rate 12 x 3.6 x 3800 = 164,160 mm3/min |

With the Hurco CNC mill programmed using the constant step-over roughing algorithm and using these cutting parameters the operational spindle loading registered at a maximum 45-50% with no sudden or spike loading encounter. Stabilised cutting conditions were maintained throughout the program, with minimum edge burr formation and a tool life of 40+ hours machining without an significant tool wear.

With manufacturing companies increasingly under pressure to improve efficiency, reduce operational costs and ensure maximum utilisation of their expensive CNC manufacturing resources this level of CNC optimisation becomes increasingly important. Therefore it becomes an educational requirement to incorporate this level of operational excellence into manufacturing modules to realistically emulate the requirements of modern manufacturing.

Industrial manufacturing companies may have limited time or opportunity to investigate or experiment with these new cutting strategies. This provides an excellent opportunity for universities to extend the educational scope by increasingly incorporating and evaluating new optimised CNC machining strategies. These world class manufacturing philosophies are increasingly important for industrial companies to secure high value added work, control cost, increase their competitiveness and to differentiate themselves from competitors.

The ability to programme at this level with total confidence in the application represents a very significant benefit to the academic, dynamically demonstrated the capabilities of the machine tool and providing an optimisation theme to manufacturing modules.

**4. Conclusion**

Collaborative links via industrial based technology transfer programmes (KTP and Fusion), the Connected Programming (linking universities and regional technical colleges) and the educational application and knowledge of advanced CAM system strategies provides a framework for advancement in the delivery of manufacturing education. All three elements are fundamentally crucial for the effective knowledge transfer and teaching of advanced CNC manufacturing.

Industrial collaborative projects enhanced the engineering educational process by providing real case study material along with access to state-of-the-art manufacturing resources.

Regional technical college collaboration provided bi-directional technology transfer and direct access for training, demonstrating and development work on resources that are financially unobtainable within the University of Ulster.

Keeping abreast with the latest CAM software is a demanding and challenging particularly with the rate of change and introduction of new optimisation CNC toolpath strategies. However this provided university lead application knowledge that can significantly enhanced the utilisation and business performance of all CNC resources.

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