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A Roadmap for STEP-NC Enabled Interoperable Manufacturing

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Abstract:

STEP-NC is the result of a ten-year international effort to replace the RS274D (ISO 6983) G and M code standard with a modern associative language. The new standard connects CAD design data to CAM process data so that smart applications can understand both the design requirements for a part and the manufacturing solutions developed to make that part. STEP-NC builds on a previous ten-year effort to develop the STEP standard for CAD to CAD and CAD to CAM data exchange, and uses the modern geometric constructs in that standard to specify device independent tool paths, and CAM independent volume removal features. This paper reviews a series of demonstrations carried out to test and validate the STEP-NC standard. These demonstrations were an international collaboration between industry,

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academia and research agencies. Each demonstration focused on testing and extending the STEP-NC data model for a different application.

Key words: ISO 10303, ISO 14649; STEP; STEP-NC; data model; manufacturing processes; product data.

1. Introduction

The language for programming Numerically Controlled (NC) machine tools has remained fundamentally unchanged since the early 1950s when paper tape was the most popular medium for moving data between computers. The capabilities of CNC machines have improved significantly with the invention of minicomputers, and later microcomputers. Multi-axis, multi-tool, and multi-process machines are now commonly seen in manufacturing sites, but they are programmed using the same G&M codes, formalized as ISO 6983 [1], that were used to program their archaic ancestors. Meanwhile the ever-growing capabilities of CNC machines have made process planning and CNC programming more difficult. Off-line software tools for Computer-aided Design (CAD), Computer-aided Process Planning (CAPP), and Computer-aided Manufacturing (CAM) are now frequently used for efficient and proven NC code generation.

The computer software and hardware capabilities now available at machine tools make it possible to graphically simulate tool motion and material removal, and to use adaptive control for on-line improvement of manufacturing process parameters [2]. Industry vendors and users are seeking a common language for the entire product development lifecycle including design, manufacturing, measurement, and other data pertaining to the product. STEP provides a mechanism that is capable of describing product data, independent from any particular software or hardware system. The nature of this description makes it suitable not only for neutral file exchange, but also as a basis for implementing, sharing and archiving product databases. ISO 10303 – Application Protocol (AP) 203 [3] is the first and perhaps the most successful AP developed to exchange design data between different CAD systems. Going from geometric data, as in AP 203, to manufacturing features, as in AP 224 [4], is an important step towards STEP-based CAD/CAM/CNC systems. Of particular significance to manufacturing is STEP-NC AP 238 [5], an extension of STEP utilizing feature-based concepts for CNC machining [6].

This paper presents the on-going research efforts of a team from academia, government and industry to enable interoperable manufacturing using STEP-NC. STEP-Manufacturing is one of the teams meeting under Working Group 3 (WG3) of ISO TC184/SC4- the standards group responsible for STEP. The team meets three times a year at locations in the USA, Europe, and the Far East. Since the year 2000, it has carried out multiple demonstrations to validate the STEP-NC standard. In the next section, the background of STEP-NC, its modeling language, and the STEP-Manufacturing team is introduced. In Section 3, the timeline and content of the STEP-NC demonstrations is presented. Remarks and conclusions are drawn in Section 4.

2. Background

The capabilities of CNC machines have improved significantly during the past half century. However, the CNC machine tool programming language has remained almost unchanged. In order to produce faster, more accurate and more autonomous machine tools smart data is necessary. The challenges to realize the vision of smart data for smart machines are a) the resistance of vendors to changes in the data standard, b) the disruption caused by the implementation of a paradigm change – a business challenge, and c) the development of the data models themselves – a technical challenge. To overcome the business challenge, it is indispensable for vendors and users to work together. To tackle the technical challenge, the primary focus is on validation. This means setting up realistic pilot tests that show that the new standard is indeed doing what it is supposed to. The research carried out by the STEP-Manufacturing team addresses these challenges. The members of the team include manufacturing industry vendors of CAD/CAM/CNC systems and users such as Boeing and Airbus. The group has conducted a series of successful tests and demonstrations that involve STEP-NC data model development, implementation, and validation. This section first introduces the STEP-NC effort to realize manufacturing interoperability; and then the background of the STEP-Manufacturing group is presented.

2.1 STEP-NC

STEP, the Standard for the Exchange of Product Data, is a large and powerful set of ISO standards; all under ISO 10303. The overall objective of STEP is to provide a mechanism that describes a complete and unambiguous product definition throughout the life cycle of a product [6].

A typical use of STEP can be given in the following scenario. An automobile engine designer working with a commercially available CAD system designs an engine block. The CAD system's native representation of the design is proprietary to the vendor of the system, but a STEP output function has been included within the CAD system that translates the proprietary representation into a representation using the STEP application protocol for configuration controlled design (AP 203). The AP 203 representation is saved in a STEP data file using Part 21 of STEP. The engine block design is sent to a manufacturing plant by sending the STEP Part 21 file for the design. At the manufacturing plant, a manufacturing engineer using a CAD system from a different vendor tells the CAD system to read the STEP file. This is possible because the second CAD vendor has also implemented STEP AP 203. The system has a function that read the STEP file and builds a representation of the design in the second CAD system's native format. With the design now resident in the CAD system, the manufacturing engineer goes to work figuring out how to manufacture the engine block. If the manufacturing engineer wants to suggest a change in the design, he or she can have the CAD system write a STEP AP 203 Part 21 file and send it back to the designer. It is also possible to use STEP to communicate manufacturing information at the feature level (AP 224) and at the operation level (AP 238) [7].

Fig. 1 describes a manufacturing data exchange scenario enabled by STEP. Geometric representation data described in STEP AP 203 or another format are translated into machining features defined in AP 224. The machining feature definitions are used as inputs to macro process planning applications (e.g. AP 240 for machining, AP 223 for casting, and AP 229 for forging). Micro process planning for machining (AP 238) and inspection (AP 219) are then carried out for each of the aforementioned application processes. In such a system, the need for data conversion is eliminated [8].

STEP-NC is the application of STEP to NC machines. Its title is “STEP Data Model for Computerized Numerical Controllers”, representing common data specifically aimed at NC programming. STEP-NC has been and continues to be a global effort with the goal of providing a data model for a new breed of CNC communication and machine tool control. Within ISO, two different subcommittees (SC1 and SC4) of TC 184 have been contributing to the development of this standard. SC1 focuses on the control of machines, while SC4 focuses on industrial data. Since numerical control programs for machining are data for the control of industrial machines, there is a natural overlap between SC1 and SC4.

The ISO 14649 set of standards, which are subtitled “Data model for computerized numerical controllers,” were developed by SC1. The models are written in EXPRESS and are Application Reference Model (ARM) type models, in that they use domain terminology to describe machining functionality. ISO 14649 has the following Parts that became international standards in 2004.

- ISO 14649-1: Overview and fundamental principles [5];
- ISO 14649-10: General process data [9];
- ISO 14649-11: Process data for milling [10];
- ISO 14649-12: Process data for turning [11];
- ISO 14649-111: Tools for milling [12] ;
- ISO 14649-121: Tools for turning [13];

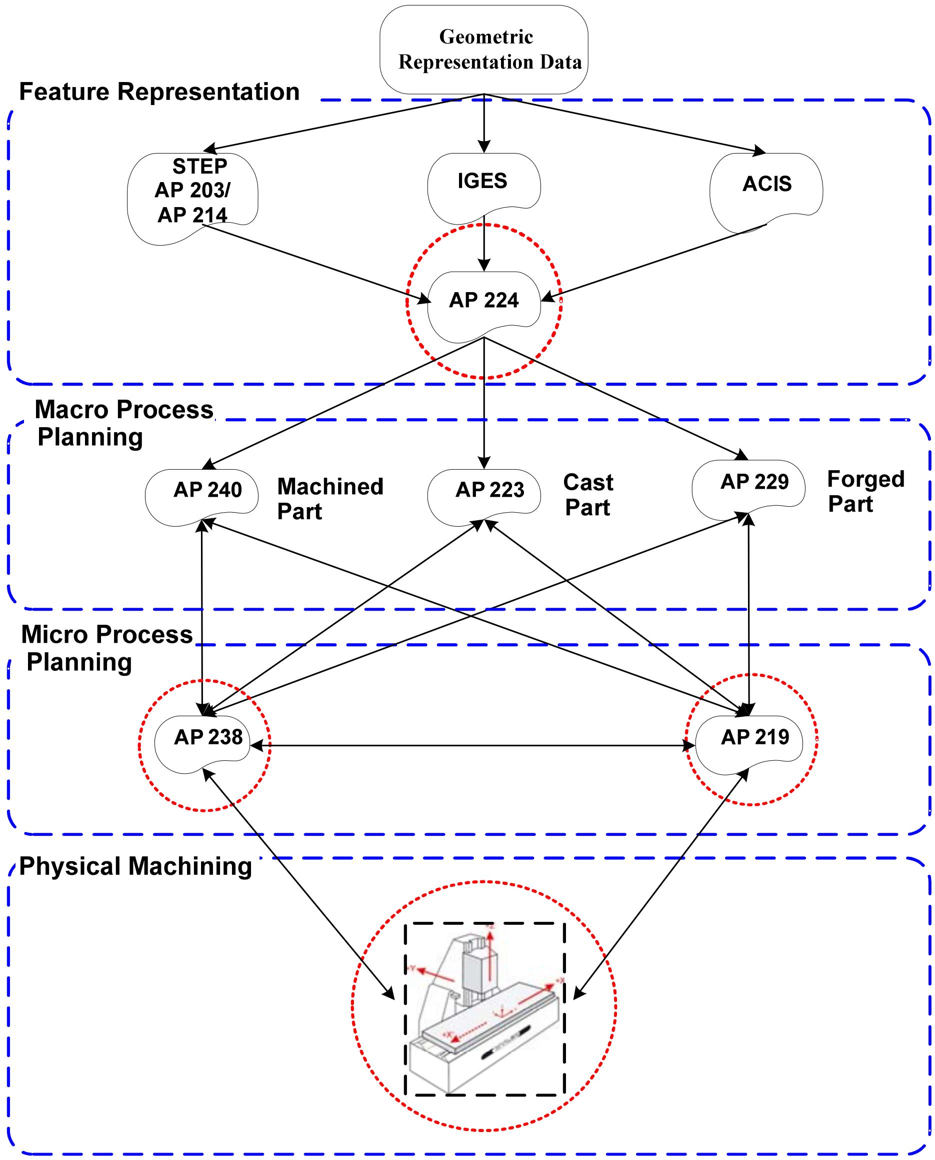


Fig. 1 Design-Manufacturing data exchange enabled by STEP [14]

These Parts are arranged hierarchically, in that Part 11 uses Part 10 and Part 111, while Part 12 uses Part 10 and Part 121. Part 10 provides a set of basic capabilities for process planning for machined parts. Part 11 and 12 specialise these capabilities for milling and turning, respectively. SC1 now continues the development effort on these standards with the aim of producing a second edition of the ISO 14649 standard containing updated models for the above, harmonized cutting tool models with other ISO standards (i.e. ISO 13399 cutting tool data representation and exchange) and new data models for machine tools, additive manufacturing and measurement of parts.

STEP-NC has many benefits over G&M code [15-17] (shown in **Fig.** 2):

- STEP-NC provides a complete and structured data model, linked with geometrical and technological information, so that no information is lost between the different stages of the product development process.
- Its data elements are capable of describing task-oriented NC data.
- The data model is extendable to further technologies and scalable (with Conformance Classes) to match the abilities of a specific CAM, SFP (Shop Floor Programming) or NC system.
- Machining time for small to medium sized job lots can be reduced because intelligent optimization can be built into the STEP-NC controllers.
- Stand-alone post-processers are no longer required, as the interface does not require machine-specific information.
- Machine tools are safer and more adaptable because STEP-NC is independent from machine tool vendors.
- Modifications at the shop-floor can be saved and fed back to the design department since bi-directional information flow from CAD/CAM to CNC machines can be achieved.

It has been predicted that STEP and STEP-NC will reduce the time required to program a CNC by 35%, reduce the number of drawings that have to be sent from design to manufacturing by 75% and decrease the time required to machine parts on CNC tools by 50% by enabling faster machines to be used for small to medium-size job lots [18]. The ISO standard committees are continuing to extend STEP-NC to new technologies and to incorporate refinements discovered during use. The STEP-Manufacturing team has been conducting STEP-NC demonstrations to validate the applicability of the various sections of the standard in the industry. In Section 3, these demonstrations are reviewed in detail.

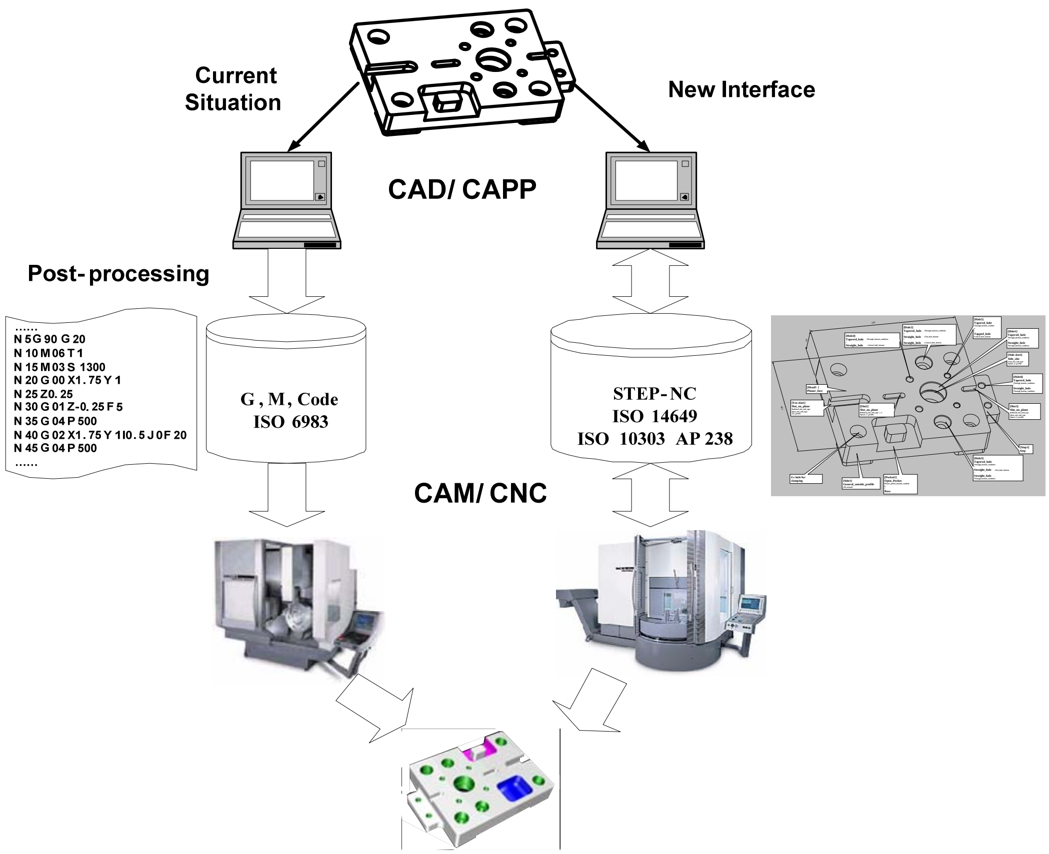


Fig. 2 Comparison of G&M code and STEP-NC data

2.2 STEP-Manufacturing and AP 238

STEP-Manufacturing is a team within Working Group 3 of the ISO TC184/SC4 committee that is testing the integrated version of STEP-NC defined by ISO10303-238 and also known as AP 238 [19]. Both ISO 10303 AP 238 and ISO 14649 are commonly referred to as "STEP-NC". Unlike ISO 14649, which is divided into separate Parts as described above, AP 238 incorporates the equivalent of all the Parts of ISO 14649 (except Part 1) with a few modifications into a single model. The model is then mapped to the STEP integrated resources to obtain an implementation model – the Application Interpreted Model (AIM model). Although ISO 14649 uses the EXPRESS language for data modelling, the full inheritance model of EXPRESS was not employed by the SC1 committee in developing the ISO 14649 data model [20]. The data modelling rules in the EXPRESS language were only lightly used in ISO 14649. The integration between ISO 14649 and STEP integrated resources was not planned by SC1 because the data described in the ARM was believed to be easier for a person to read and hand-edit using a text editor and can be parsed more quickly. However, the SC4 team continued all the research and demonstrations in the integrated way by using the AIM model. The benefits of this method are:

a) Both ARM and AIM models describe data that is too difficult for an average machine tool operator to hand edit so there will have to be graphical interfaces on the CNC. The integrated STEP model makes these interfaces more powerful because each working step can be shown in the context of the part feature it manufactures, the current geometry of the part and the tolerances required by that geometry. In the ARM model these features, geometry and tolerances are not available so they cannot be shown.
b) The SC4 integrated resources are normalized to make them easily extendible. If specific weaknesses are identified then the models can be extended without requiring all of the existing applications that use those models to change.
c) The SC4 integrated resources allow a greater range of representations to be used for the machine tool functionalities so more kinds of applications can use the data. For example, applications that want to visually check for correctness can distinguish between images of geometry that were planned to be in the model and images of geometry that were not planned to be in the model because every function that needs to be modelled including the workpieces, cutting tools and fixtures can be given an image.

The difference is illustrated by the link between features, geometry and tolerances enabled by the integrated model. In the AP 238, the tolerance data is defined by the Geometric and Dimensional Tolerancing (GD&T) model developed for AP 203 edition 2 [21], AP 214 and AP 224. Hence an application program can traverse the integrated data from a feature, to the faces in that feature, to the design tolerances that apply to those faces, to the datum that define the tolerances, to the plane that defines each datum, to another feature that when machined defines that datum plane and so on. Table 1 summarizes the differences.

Table 1: Summary of differences between the STEP-NC models [20]

	STEP Compliance	EXPRESS compliance	3D Geometry	Design Integration	Complexity
AP-238	Full	Full	Required	Full	More
ISO 14649	Partial	Partial	Optional	Little	Less

The richness of AP 238 data model brings in the fundamental business benefits of STEP-NC and hence can lead to greater acceptance in manufacturing industry. If the STEP-NC model includes the STEP tolerance model then there will be greater traceability between design and manufacturing. Similarly, if the STEP-NC model uses the STEP model for manufacturing features then CNC programming systems will be able to receive these features from design or manufacturing. Thirdly, if the CNC machine tool receives the design product model then there are many quality checks that can be performed on the machine tool such as determining if the selected tool and speeds and feeds will produce the right surface finish.

The research work carried out by the STEP-Manufacturing group can be divided into two parts: AP 238 data model development and industrial demonstration. The group continuously works on developing the AP 238 data model for various types of machine tools and manufacturing operations such as traditional 3-axis and 4-axis CNC machines, state-of-the-art 5-axis CNC machines, mold workpieces, machining process optimization, etc. In the demonstrations, requirements for new data model components are identified, implemented and tested with industry partners. In the next section, the demonstrations carried out by the STEP-Manufacturing team are reviewed.

3. Demonstrations of STEP-NC Enabled Manufacturing

The core of STEP-NC is the ISO 14649 model for CNC control developed by European ESPRIT and IMS STEP-NC projects beginning in 1999 [22]. These projects were led by Siemens with contributions from the University of Aachen and the University of Stuttgart in Germany, Komatsu and FANUC in Japan, Heidenhain in Switzerland, and the Pohang University of Science and Technology in Korea [23, 24]. Integration of the CNC model into

STEP to produce ISO 10303-238 began in the USA with the funding of the Model Driven Intelligent Control of Manufacturing (MDICM) project by the National Institute of Standards and Technology (NIST) Advanced Technology Program (ATP) in 1999. The work was performed by STEP Tools, Inc [18], in conjunction with an Industrial Review Board [20]. The new protocol was assigned the number AP 238 and its committee draft was released for technical review in 2001.

To date, there have been fourteen STEP-NC demonstrations. Each was an international collaboration between academia, industry and government research agencies. The sequence of demonstrations can be grouped into five phases as shown in Table 2. The details of each demonstration are discussed in the following sections.

Table 2: Summary of STEP-NC enabled interoperable manufacturing demonstrations

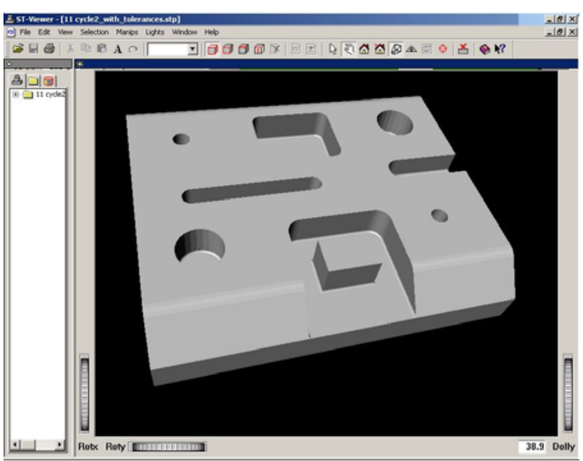
Phase	Demonstration Dates	Capabilities Shown	Purpose
1	November 2000 February 2002 January 2003 June 2003	Tool path generation from manufacturing features	Faster Art-To-Part
2	February 2005	CAM to CNC data exchange without post processors	CNC Interoperability
3	May 2005 June 2006 July 2007	Integration of CAD GD&T data (as defined in AP-203 e2) with CAM process data (as defined in ISO 14649)	Integrated Machining and Measurement
4	December 2007 March 2008 October 2008	Cutting tool modeling (as defined in ISO 13399). Cutting cross section modeling	Feed speed optimization
5	May 2009 September 2009 June 2010	Tool wear modeling Machine tool modeling	Tool life management

3.1 STEP-NC Enabled Faster Art-to-part Manufacturing

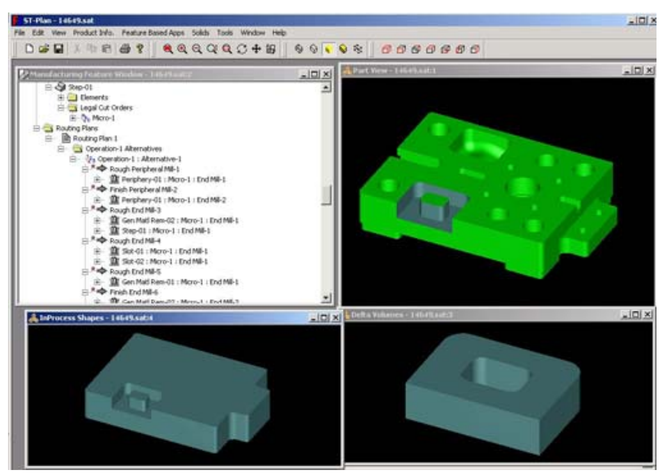
The first phase of STEP-Manufacturing group's research work consisted of four demonstrations and focused on verifying and validating STEP-NC manufacturing feature definitions by generating tool paths from those definitions. These demonstrations were funded by the ATP program and termed the "Super Model Project".

The first demonstration was held in November 2000 at the Benet Laboratories of Watervliet Arsenal, USA. This demonstration used the FB Mach system to make feature-based STEP-NC data, and a Bridgeport Machine Tool controller to machine the part. FB Mach is a computer-aided manufacturing system developed by Honeywell FM&T for the US Department of Energy. In the demonstration it read a STEP AP 203 file from a CAD system, an operator used its advanced feature recognition capabilities to compute a manufacturing plan, and the result was written as a STEP AP 224 file containing all the information required to make a part (shown in **Fig.** 3 (a)).

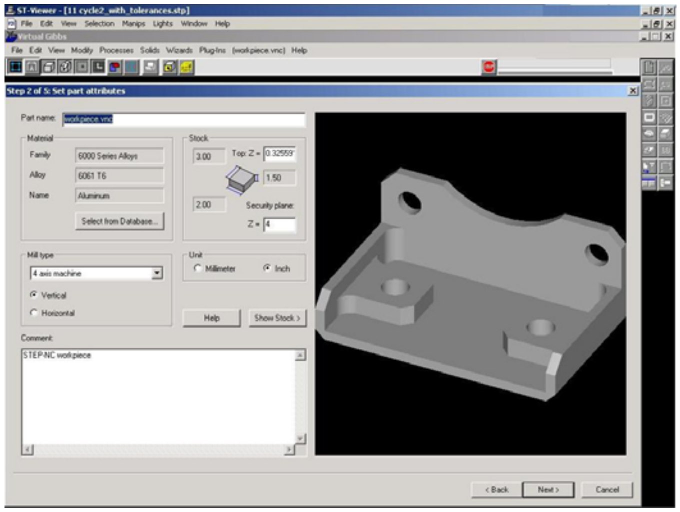
Custom software read FB Mach data and converted it to AP 224 manufacturing features. A Bridgeport Controller modified by Electro-Mechanical Integrators (EMI) read the AP 224 manufacturing data, extracted the information necessary for a milling machine to make the part, and presented that information in a form that is easy to process on the PC based control. This demonstration tested feature recognition to convert AP 203 to AP 224, and tool path generation from the STEP-NC manufacturing features defined in AP 224.



(a) 2001 demonstration



(b) 2002 demonstration



(c) 2003 demonstration

Fig. 3 STEP-NC Super Model Project demonstrations

The second demonstration continued to work on verification of the AP 238 committee draft using the more complex workpiece shown in **Fig.** 3 (b). After this demonstration, the differences between the AP 224 and ISO 14649 machining feature definitions were harmonized in the AP 238 draft standard. In January, 2003, the third demonstration was held at the NASA Jet Propulsion Laboratory (JPL) in Pasadena, California, USA. STEP Tools Inc. worked with JPL to demonstrate the machining of a part using full fidelity STEP-NC product data as direct input to a multi-axis CNC milling machine. In the demonstration an AP 203 file of the workpiece shown in **Fig.** 3 (c) was converted into AP 238 CNC-independent control data with tolerances set using JPL crib sheets and an automated wizard for defining setup and fixtures. A more complex feature recognition process with compound features, together with a piloted tool path generation using GibbsCAM was also tested in this demonstration.

In June 2003, a follow-up demonstration was held at NIST in Gaithersburg, Maryland, USA. For the first time, the STEP-NC demonstration focused on a complex surface model provided by Boeing that was milled on a 5-axis CNC machine tool. A plug-in program was developed for both MasterCam [25] and GibbsCAM [26] software to generate toolpaths and output CNC code from a STEP-NC file. The bi-directional exchange of machining process plans between two different CAM software systems was realized as shown in **Fig.** 4.

In October 2004, STEP-NC AP 238 was completed as a Draft International Standard (DIS) and was submitted for business case review by all the member countries of the ISO. This represented the end of the first phase of STEP-NC demonstrations.

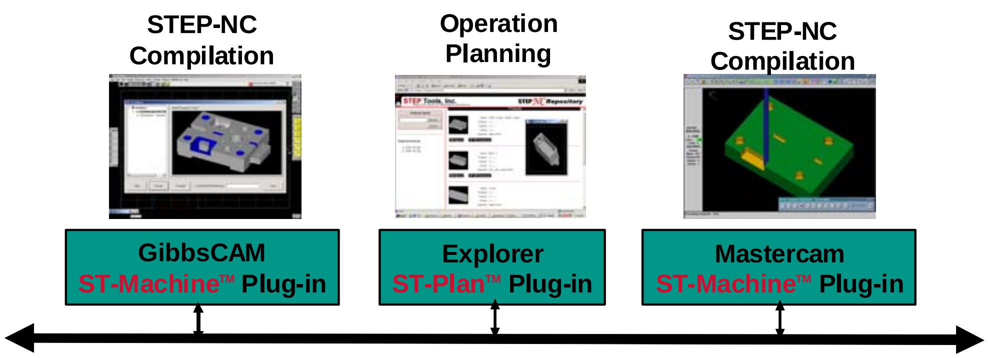
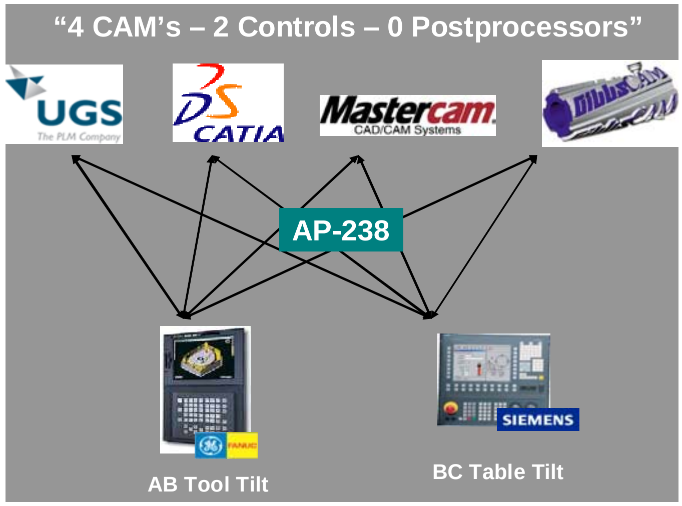


Fig. 4 Bi-directional information exchange between MasterCAM and GibbsCAM

3.2 STEP-NC CNC Tool path Interoperability Demonstration

Upon submission of STEP-NC AP 238 to ISO, the STEP-Manufacturing group started the second phase of demonstrations by verifying the business case for the first Conformance Class (CC 1 of 4). The demonstration was held in February 2005 in Orlando, Florida. Four CAD/CAM systems were used to produce CC1 toolpaths for milling the two 5-axis test parts (shown in **Fig. 5**).

Four major industrial CAD/CAM systems produced AP238 machining programs for milling two 5-axis test parts. The controls were configured for two CNC machines with different geometries. The first was an AB tool tilt machine. The second was a BC table tilt machine. In the demonstration, each AP 238 program produced by the four CAM systems was run on both controls without any post processing. The demonstration showed that AP 238 data are portable between machine and control configurations, assuming each machine tool has the capabilities required by the program such as cutting tools with the right dimensions, a tool bed with sufficient size, and motors with the required power [27]. In addition, Boeing cut complex 5-axis parts on a variety of machines at their Tulsa facility in order to validate scalability. A part was also cut on a machine at NIST in Gaithersburg, USA. With several of the major commercial CAM software companies' participating, these demonstrations successfully showcased the value that the STEP-NC standard was initially designed for – interoperability between commercial software for manufacturing.



(a) 4 CAM’s -2 Controls – Postprocessors system

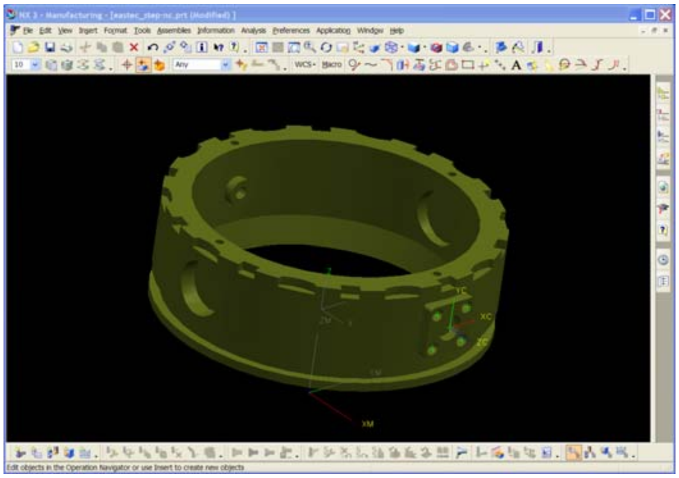
(b) 5-axis workpieces

Fig. 5 STEP-NC tool path interoperability test

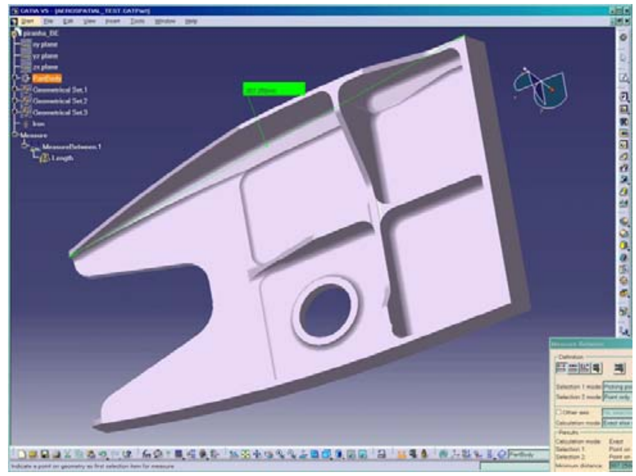
3.3 STEP-NC Integrated Machining and Measurement Demonstrations

The third phase of STEP-NC demonstrations consisted of three tests from 2005 to 2007. It focused on the integration of CAD GD&T data (as defined in AP 203 edition 2) with CAM process data (as defined in ISO 14649).

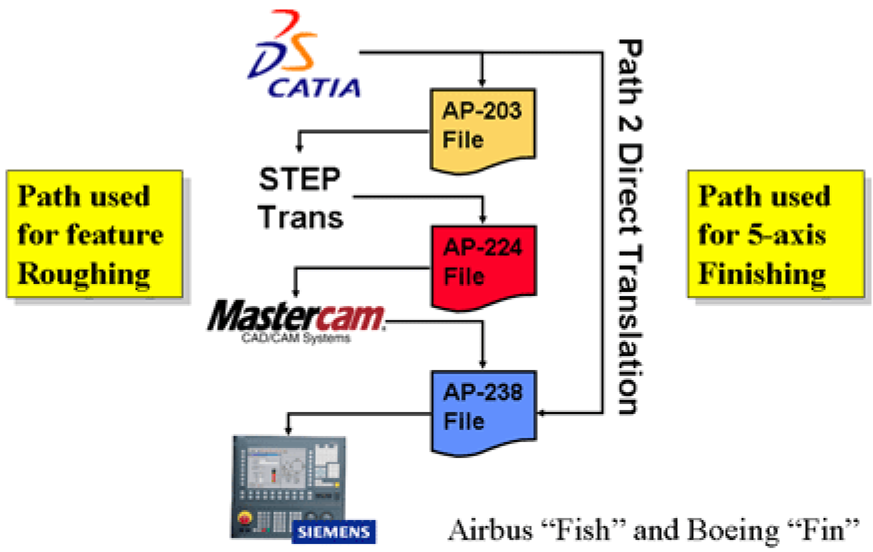
The first of these demonstrations was held in May 2005 at Springfield, Connecticut, USA. An engine casting test workpiece was provided by Pratt and Whitney (**Fig. 6** (a)).



(a) Casting engine test workpiece



(b) 5-axis Fishhead workpiece



(c) International interoperable manufacturing test scenario on airplane workpieces

Fig. 6 Phase 3 STEP-NC manufacturing demonstrations

The workpiece was first cut into a rough state using toolpaths computed from STEP manufacturing features by an intermediate CAM system. Then the workpiece was finished using toolpaths directly from the original design system. The final result was a STEP-NC AP 238 file containing all the geometry, feature, and tool path information used during the entire process. After roughing and semi-finishing machining, a probing operation was used to adjust a final finishing pass. The finishing was done using cutter contact toolpaths. Two

CAM systems were utilized in this demonstration: the roughing paths were created by a UGS NX system and the finishing paths by MasterCAM.

In June 2006, a live 5-axis STEP-NC machining demonstration was hosted by Airbus at Toulouse, France. A STEP-NC enabled interoperable manufacturing scenario was tested. The 5-axis workpiece was designed in France (as an AP 203 file) shown in **Fig. 6** (b), the process was planned in the UK (as an AP 224 file), toolpaths were generated in the USA (as an AP 238 file), and the part was machined in France. The demonstration process is shown in **Fig. 6** (c).

With the success of the 2006 demonstration, an integrated machining and measurement test was carried out in the following year in July 2007 at Ibusuki, Japan. GD&T definitions from AP 203 edition 2 were added to the “fishhead” workpiece data set using a graphical user interface. Machine-independent toolpaths for high speed machining and high-level probing paths were generated and saved in an AP 238 file. Three machining and measurement tests were carried out simultaneously in the USA, France, and Sweden. Low-level Dimensional Measuring Interface Standard (DMIS) measurement commands were generated from the AP 238 file for in-process measurement operation.

In April 2007, STEP-NC AP 238 was published as an international standard as ISO 10303-238.

3.4 Feed and Speed Optimization and Tool Life Management through STEP-NC

The fourth phase of STEP-NC research and demonstrations focused on further developing the AP 238 data model. Based on extensive discussions during a STEP meeting held in December 2007 in Dallas, new information was added to the AP 238 data model. The information included: high-level inspection process planning information [14], traceability information [28], and cutter cross sectional information for feed and speed optimization [29]. In March 2008, a demonstration was held in Sweden. At the demonstration it was decided that STEP-NC should integrate cutting tool description definitions from ISO 13399 [30] so that semantic associations between tolerances, machining operations, and the cutting tools can be represented. This kind of information on machining descriptions is commonly represented in documents (**Fig. 7**) and managed in Product Data Management (PDM) systems but without detailed integration.

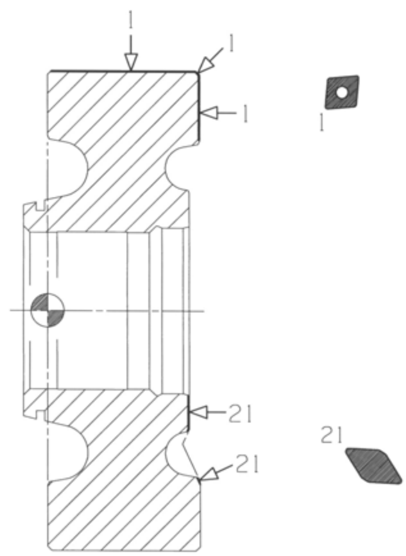


Fig. 7: Typical PDM documentation for how cutting edges are to be applied to a part.

A demonstration at Scania, Sweden, utilized the detailed integration of product, process, and resources in AP-238 to simplify cutting tool compensation during machining and enable automatic calculation of tool wear compensation values based on the differences in measured and nominal part dimensions (an illustrative video of this demonstration is attached in Appendix A). An association between product geometry surfaces, GD&T representation, manufacturing feature occurrences and machining processes was first computed (**Fig. 8**). A tolerance stack was then derived for the workpiece so that the precedence between surfaces that were machined by different tools could be taken into consideration. Actual values for the tolerances were measured using hand-held wireless callipers, applied to the tolerance stack and used to compute tool length and diameter compensation values to enable more accurate machining.

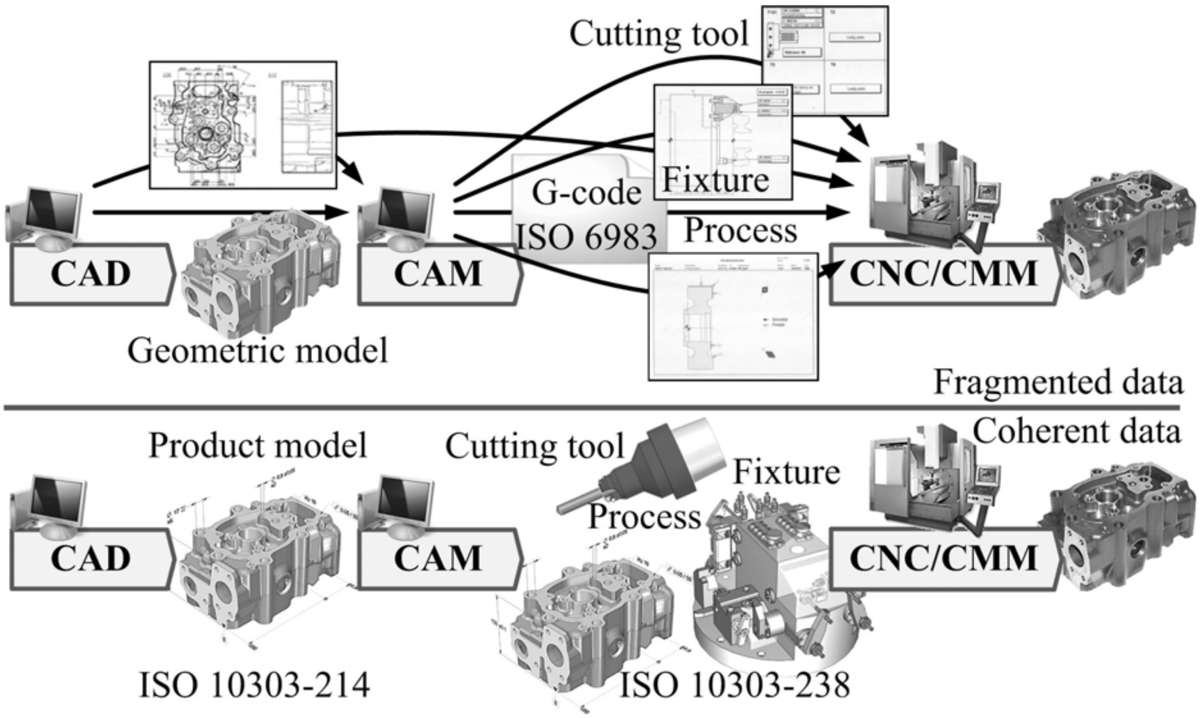
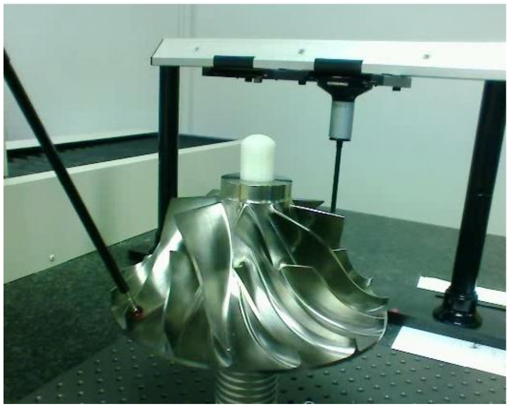
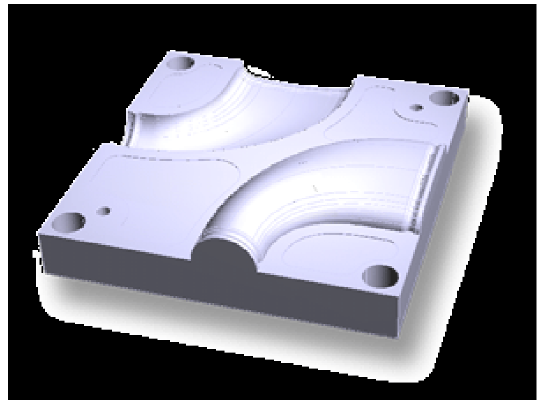


Fig. 8: Comparison between STEP-NC based coherent data exchange and traditional fragmented data flow

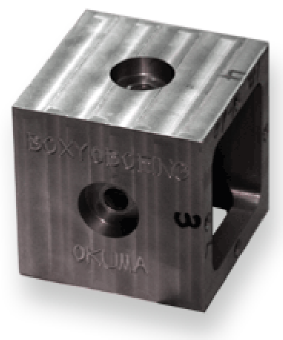
This demonstration showed that the information requirements of machining descriptions can be met via views of STEP-NC data. Viewing different machining descriptions from the same data eliminates the potential problem of inconsistency between the machining descriptions and the described machining process. The activity of creating machining description and/or maintenance of scripts for automatic generation of those documents is also shortened when views of STEP-NC integrated data can be utilised [31].

The extended cutting tool description data model was tested at the October 2008 demonstration at Hartford, Connecticut, USA. A titanium impeller workpiece was used as the testing example shown in **Fig. 9** (a). A scanning probe was used to provide cutting tool compensation information during the machining process.





(a) Impeller example workpiece (b) Mold example workpiece



(c) Gear box test part

Fig. 9 STEP-NC demonstrations of phases four and five

Feed and speed optimization can significantly improve manufacturing efficiency and reduce costs. Therefore, the STEP-Manufacturing team augmented the AP 238 data model with cutter cross sectional area definitions and the data model was verified in a demonstration held in May 2009 at a Boeing facility in Renton, Washington, USA. The machining of a mold workpiece, shown in Fig. 9 (b), was demonstrated. The same AP 238 file for the mold was machined at different sites using different machine tools. Different types of measurement devices – CMM touch trigger probe and laser scanning probe – were used for tolerance checking. The tolerance information was saved in an AP 203 edition 2 file. A test AP 238 file interpreter was developed by Fanuc and integrated to a CNC machine that was used to machine the mold example workpiece. During this demonstration, it was decided that further extending AP 238 to cover tool wear modelling and machine tool modelling should be the focus of the next phase of demonstrations.

A new test workpiece based on a gear box was designed by KTH for the fifth phase of demonstrations shown in **Fig.** 9 (c). Information modelling for tool wear and machine tools were developed in the demonstration held at Bath, UK, in September 2009. The new gear box test workpiece was used to test the newly extended data model. This test workpiece was also employed to test multiple setups (setups for 3, 4, and 5-axis machine tools) and the applicability of using AP 238 file for alternate machining plans for alternate tooling. To further validate the tool wear and machine tool data model, the latest STEP-NC demonstration was held in June 2010 at Gaithersburg, Maryland, USA. The focus was on the use of STEP-NC for tool wear management. At the demonstration, the tool wear and consequent machine loads were predicted from the STEP-NC data and verified using a dynamometer.

Prior to the demonstration the Boxy workpiece was used to test collaborative process planning. Data files were linked together using STRL's. An STRL is a URL that connects several STEP-NC files together. It contains a URL address, an action and a query. The query defines a subset of a STEP-NC project that is to be viewed, copied, planned, machined, measured, optimized or simulated. The action describes how the data is to be used and a STRL is a way for users to e-mail these commands to each other. For example one user could ask another user to look at a potential error in a project at a location defined by an STRL, or a contractor could ask a supplier to rough machine a part using a program identified by a STRL, or a group of suppliers can link their systems to make a distributed simulation.

Some potential applications for STRL's include:

- to link a new program with an existing program,
- to associate the machining process data of multiple parts in an assembly for concurrent engineering,
- to enable distributed simulation of roughing and finishing machining processes for the same workpiece,
- to enable interoperable process plan exchange for horizontal and vertical machines,

- to enable cutting tool database optimization by linking a ISO 13399 database to a toolpath generator,
- to enable feed speed optimization by linking STEP-NC to MT Connect.

In the planning for the Gaithersburg demonstration STRL's were used to link the master model for Boxy with new models containing new and improved methods for machining the different features. The improvements were made at KTH and as each was completed its data was copied into the master model.

4. Current Status of AP 238 Data Model

Among the aforementioned five phases of demonstrations, phases one and two validated tool path generation and CAM to CNC data exchange without post processors by using the AP 238 data model. During the following demonstrations, various opportunities to enhance and optimize manufacturing processes were discovered by the team; therefore the AP 238 data model was modified and augmented accordingly. It is, hence, useful to summarize all of the corrections and new features from the several years of implementation. The following is the list of changes that have been proposed by the STEP-Manufacturing team for AP 238 edition 2:

- Tool path reference direction – add an optional tool_reference_direction curve to augment tool axis curves. This attribute is used for asymmetric tools such as composite tape laying heads, where two direction vectors are needed to properly align the tool.

```
ENTITY cutter_location_trajectory
SUBTYPE OF (trajectory);
basiccurve:                bounded_curve;
its_toolaxis:              OPTIONAL bounded_curve;
its_toolref_direction:     OPTIONAL bounded_curve;
surface_normal:            OPTIONAL bounded_curve;
path_maximum_deviation:    OPTIONAL length_measure;
tool_axis_maximum_deviation:OPTIONAL plane_angle_measure;
END_ENTITY;

ENTITY cutter_contact_trajectory
SUBTYPE OF (trajectory);
basiccurve:                curve_with_surface_normal;
```

```
its_toolaxis:               OPTIONAL bounded_curve;
its_toolref_direction:      OPTIONAL bounded_curve;
its_contact_type:           OPTIONAL contact_type;
path_maximum_deviation:     OPTIONAL length_measure;
tool_axis_maximum_deviation:OPTIONAL plane_angle_measure;
END_ENTITY;
```

- Gage placement for simulation – add gage_placement and tool_end_placement to tool_usage to allow any origin convention. The new information provides a way to accurately mount a tool product model on a machine tool product model for display and simulation.

```
ENTITY tool_usage;
its_id:                     label;
its_position:               OPTIONAL identifier;
its_carousel:               OPTIONAL identifier;
its_product:                OPTIONAL workpiece;
its_library_reference:      OPTIONAL externally_defined_representation;
gage_placement:             OPTIONAL axis2_placement_3d;
tool_end_placement:         OPTIONAL axis2_placement_3d;
END ENTITY;
```

- Tool path transform on Workplan – add a tool path transform attribute to workplan to enable more significant reuse of machining operations. The transform also make it possible to move tool paths from all workingsteps or nested workplans at once.

```
ENTITY workplan
SUBTYPE OF (program_structure);
its_elements:               LIST[0:?] OF executable;
its_channel:                OPTIONAL channel;
its_setup:                  OPTIONAL setup;
its_effect:                 OPTIONAL in_process_geometry;
its_minimum_machine_params:OPTIONAL machine_parameters
its_accuracy_requirements: OPTIONAL SET [1:?]OF
                            dm_accuracy_requirement_global;
toolpath_orientation:       OPTIONAL axis2_placement_3d;
WHERE
WR1: SIZEOF(QUERY(it <* its_elements | it = SELF)) = 0;
END_ENTITY;
```

- Enable/Disable Executable – add an attribute to store the enabled/disabled state of an executable. This makes is possible to keep many alternates in a file for different tooling configurations. When a part is to be built the workingsteps that correspond to the available tooling can then be selected for the machining.

```
ENTITY executable
ABSTRACT SUPERTYPE OF (ONEOF(workingstep, nc_function,
                             program_structure);
its_id:                      identifier;
enabled:                     OPTIONAL BOOLEAN;
as_is:                       OPTIONAL Workpiece;
fixture:                     OPTIONAL Workpiece;
removal:                     OPTIONAL Workpiece;
to_be:                       OPTIONAL Workpiece;
END_ENTITY;
```

- Cross section parameters for feed and speed optimization – add new entities to represent cross-section parameters for feed and speed optimization. The entities define curves that give a parameterized description of material removal cross section area along the tool path.

```
ENTITY trajectory
ABSTRACT SUPERTYPE OF (ONEOF(cutter_location_trajectory,
                           cutter_contact_trajectory, axis_trajectory))
SUBTYPE OF (toolpath);
its_direction:                     OPTIONAL BOOLEAN;
its_material_removal_depth:        OPTIONAL material_removal_measure;
its_material_removal_overcut:      OPTIONAL material_removal_measure;
its_material_removal_total_volume:      OPTIONAL volume_measure;
cross_section_area_flank_parameters:    OPTIONAL bounded_curve;
cross_section_area_plunge_parameters:   OPTIONAL bounded_curve;
END_ENTITY;
```

- Define touch_probe as a real tool – change the touch_probe entity from a stand-alone entity into a subtype of tool to enable a connection between a probe and its shape geometry.
- Datum and datum_target reference to workpiece – add an attribute to the datum and datum_target entities to refer to a workpiece.

```
ENTITY Datum
ABSTRACT SUPERTYPE;
its_workpiece:               Workpiece;
END_ENTITY;
```

```
ENTITY Datum_target;
id :                         STRING;
its_workpiece:               Workpiece;
END_ENTITY;
```

- Full workpiece for in-process geometry – change in-process geometry from just a shape_representation reference to a full workpiece reference to allow a full range of product properties, features and tolerances to be connected with workpiece.

```
ENTITY executable
ABSTRACT SUPERTYPE OF (ONEOF( workingstep, nc_function,
                              program_structure));
its_id:                    identifier;
enabled:                   OPTIONAL BOOLEAN;
as_is:                     OPTIONAL Workpiece;
fixture:                   OPTIONAL Workpiece; -- deleted
removal:                   OPTIONAL Workpiece;
to_be:                     OPTIONAL Workpiece;
END_ENTITY;
```

In addition to these changes, new entities have been developed for machine tool modelling, workpiece setup, and part properties. The following machine_parameter entity defines requirements for the machine tool.

```
ENTITY machine_parameters;
  feedrate:                       OPTIONAL speed_measure;
  spindle_speed:                  OPTIONAL rot_speed_measure;
  spindle_power:                  OPTIONAL value_with_unit;
  spindle_torque:                 OPTIONAL value_with_unit;
  number_of_control_axis:         OPTIONAL INTEGER;
  number_of_simultaneous_axis:    OPTIONAL INTEGER;
  positioning_accuracy:           OPTIONAL length_measure;
  table_indexing:                 OPTIONAL BOOLEAN;
  table_length:                   OPTIONAL length_measure;
  table_width:                    OPTIONAL length_measure;
  axis_travel:                    SET [0:?] OF machine_axis_travel;
  work_volume_length:             OPTIONAL length_measure;
  work_volume_width:              OPTIONAL length_measure;
  work_volume_height:             OPTIONAL length_measure;

WHERE
    WR1: (0 = SIZEOF(axis_travel)) OR
    ((NOT EXISTS (work_volume_length)) AND
     (NOT EXISTS (work_volume_width)) AND
     (NOT EXISTS (work_volume_length)));
END_ENTITY;
```

In a parallel effort, the ISO Working Group 7 of Subcommittee 1 of the Technical Committee 184 continued their work on developing the data model for ISO 14649. The majority of the work in this working group has been focused on realisation of a data model for representation of machine tools. **Fig.** 10 shows the scope of the data model.

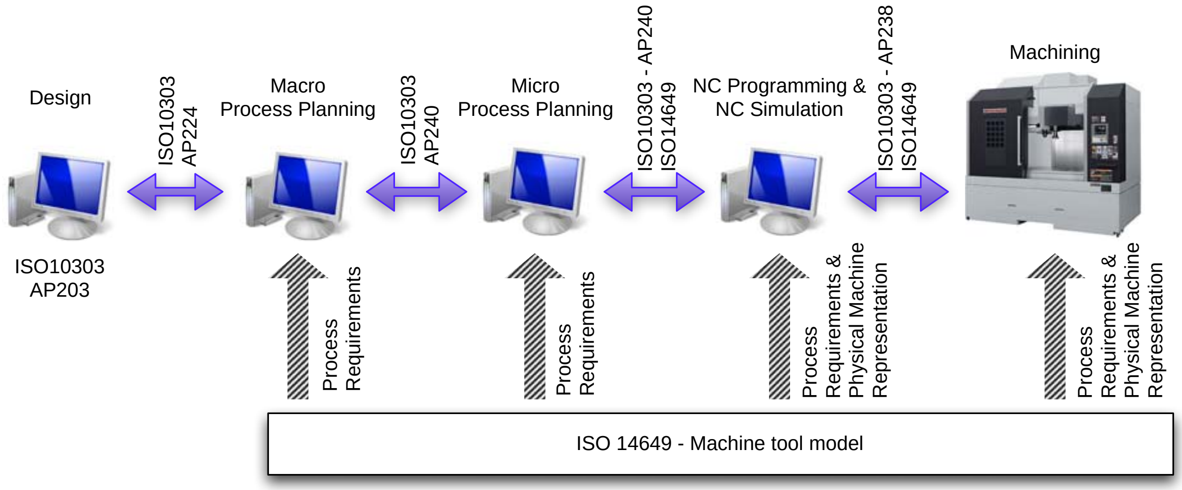


Fig. 10 Scope of the machine tool data model developed in ISO 14649

The data model is envisaged to provide the necessary entities to capture manufacturing resource requirements while creating process plans at different levels. This is in harmony with the STEP-in, STEP-out, STEP-throughout vision of TC184. In addition the data model will provide entities to capture a complete functional representation of machine tools within the scope of process planning and machining. Information regarding the kinematic structure of the machine, process capabilities, physical dimensions, energy requirements of machine components, controller capabilities and interfaces with cutting tools (as represented in ISO13399 and ISO14649) and jigs and fixtures are contained within the data models. An approach for applying these data models on top of the AP 214 standard have been presented [32], which enables reuse of the same generic product data model for manufacturing resource modelling within domains such as process planning, factory design, investment and maintenance.

5. Remarks and Future Demonstrations

The RS 274D (ISO 6983) G and M code standard was developed more than fifty years ago when punched paper tape was commonly used for transferring data. Although the capabilities of CNC machines have improved significantly, the programming language used to control those machines has remained almost unchanged.

In this paper we have reported on international efforts to develop a modern associative language to connect the CAD design data used to determine the machining requirements for an operation with the CAM process data used to determine how to meet those requirements. STEP-NC builds on a previous ten year effort to develop the STEP neutral data standard for CAD data, and uses the modern geometric constructs in that standard to define device independent tool paths, and CAM independent volume removal features.

Industrial use of STEP-NC has shown evidence of significant cost savings, higher quality, and reduced time-to-market. In the rapidly changing economy that is increasingly globalized, collaborative, and distributed, easily exchangeable manufacturing information will become vital for manufacturing industry to gain new market share. Such manufacturing information needs to be interoperable and integrated so that it can be handled by different CAM and CNC systems without the inherent limitations of post-processing. The STEP-Manufacturing team has been working for a decade to define and validate such information for industry.

The next phase of the work will focus on two related activities: on-machine simulation and volume compensation. In on-machine simulation the enhanced machining data in a STEP-NC file is used to check, validate or predict the machining. Run time checking can verify that the machining will continue to operate without collisions when the actual tools are substituted for simulated tools. Run time validation can perform a similar function but go further by checking the tolerance and surface finish constraints. Run time prediction is the most aggressive and uses various algorithms to predict, optimize and correct the machining so that the part is completed more quickly, more accurately and with minimum operation costs and energy consumption.

Volume compensation and machine simulation share a requirement for run time computation of material removal volume. In volume compensation the tool paths are expanded to better meet the tolerances on a part. Typically tool paths are computed to meet the nominal (as designed) dimensions but if tolerances have been defined then there will be a range of allowed dimensions with the nominal being somewhere in the middle. Cutter compensation is used today, but the compensation is limited to moving tool contact line to the left or right of the direction of movement. In STEP-NC the compensations can be moved in many more directions and the range of devices that can measure a part on the machine tool is increasing. They include many types of computer vision systems, laser scanning systems and ever more accurate touch probing systems. Future STEP-Manufacturing demonstrations will be examining a range of options for modifying tool paths to meet tight tolerances using techniques that can be programmed for automatic or semi-automatic operation.

This paper has reviewed the STEP-NC demonstrations carried out by the STEP-Manufacturing team. These demonstrations were results of international collaborations between industry, academia and research agencies. Each demonstration focused on extending the STEP-NC data model for different manufacturing applications. The demonstrations were grouped into five phases. The first phase of demonstrations verified the manufacturing feature definitions in the AP 238 data model and demonstrated CAM-independent tool path generation. Upon the last demonstration of this phase, AP 238 was submitted to ISO for international standard review in 2004 and was published in 2007.

The second phase focused on validating CAM to CNC data exchange without post processors, which proved the interoperability of STEP-NC. During the third phase, CAD GD&T data was added to CAM process information to enable closed-loop machining. This phase of STEP-NC demonstrations were closely related to the development of AP 203 edition 2 standard, which was able to provide semantic GD&T representation data in CAD files. The fourth and fifth phase of demonstrations focused on extending the STEP-NC data model for tool wear, cutting tool and machine tool modelling. The newly augmented information was able to provide rich information for feed and speed optimization and better tool life management. With a STEP-NC data model driving the NC operator interface new industrial benefits have been explored. Machining descriptions that are easy understandable for not only the NC operator, but also the process planner, tool suppliers and others enable efficient, collaborative development and operation of machining processes.

All these demonstrations have shown that STEP-NC is able to provide comprehensive information for intelligent machine tool control. The information includes product and process data, manufacturing resource data, and manufacturing control data. The applications of STEP-NC are significant and the STEP-Manufacturing team is continuing its efforts to demonstrate the efficacy of STEP-NC for enterprise integration, data archiving, and solving challenging manufacturing problems. Through the testing and demonstration, the STEP-Manufacturing team has improved and augmented the AP 238 data model for different types of manufacturing applications. The second edition of AP 238 is under preparation to be submitted to ISO for peer review.

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Appendix A