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ORIGINAL ARTICLE

A roadmap for STEP-NC-enabled interoperable manufacturing

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Abstract The STEP-NC—AP 238 and ISO 14649 standard is the result of a 10-year international effort to replace the RS274D (ISO 6983) G and M code standard with a modern associative language that connects the CAD design data used to determine the machining requirements for an operation with the CAM process data that is used in creating a machining solution to satisfy these requirements. STEP-NC builds on the previous 10 years effort to develop the STEP neutral data standard for CAD data, and uses the modern geometric constructs in that standard to specify device independent tool paths, and CAM independent volume removal features. STEP-Manufacturing, Team 24 in Working Group 3 (WG3) of ISO TC184/SC4, is developing and validating the STEP-NC standard in liaison with Working Group (WG7) of ISO TC184/SC1 who provides the domain-specific input (ISO 14649) used within the standard. This paper reviews the demonstrations carried out by STEP-Manufacturing over the past 10 years. These demonstrations have been international collaborations between industry, academia, and research agencies. Each demonstration focused on extending the STEP-NC data model for a different application.

Keywords 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 computer

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numerically controlled (CNC) machines are commonly seen in manufacturing sites. However, most CNC machines are still using the same GOTO codes, namely G&M codes formalized as the ISO 6893 [1] standard that was used to program their archaic ancestors. This is principally because there is no standard method to get 3D product and process data into the control.

The ever-growing capabilities of CNC machines have made the process planning and programming tasks more difficult and more complex. Thus, off-line software tools for computer-aided design (CAD), computer-aided process planning (CAPP), and computer-aided manufacturing (CAM) are required for efficient and proven NC code generation. Many such systems are used to manage technical product data for manufacturing processes in industry.

The software and hardware capabilities now available at machine tools makes it possible to graphically simulate the tool motion and the material removed, and to use adaptive control for on-line improvement of manufacturing process parameters [2]. However, each system has its own proprietary data format so the same information has to be entered multiple times into multiple systems leading to redundancy and errors.

Industry vendors and users are seeking a common language for the entire product development lifecycle that can describe 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 features, as in AP 224 [4], is an important step toward enrichment of data handling to enable 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 the STEP-Manufacturing group in STEP-NC standard development and STEP-NC enabled interoperable manufacturing. STEP-Manufacturing is one of the teams meeting under Working Group 3 (WG3) of ISO TC184/SC4. Team members are from academia, government, and industry. The team meets three times a year at locations in the USA, Europe, and the Far East. Since 2000, numerous demonstrations have been carried out to validate portions of the STEP-NC standard. In the next section, the background of STEP-NC standard, its modeling language, and the STEP-Manufacturing group is introduced. In Section 3, the timeline 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 of the century. However, the CNC machine tool programming language has remained mostly unchanged. In order to achieve faster, more accurate, and more autonomous machine tools that are driven by product and process models and responsive to the manufacturing enterprise, smart data is essential for smart machines. The challenges to realize the vision of smart data for smart machines are (a) the resistance of vendors to standardization—a business challenge; and (b) the development of the data models themselves—a technical challenge. To overcome the business challenge, it is indispensable to involve vendors and users together and pull for a standard for it to be successful. To tackle the technical challenge, the primary focus is on the validation of standards. This means setting up realistic pilot tests that show that the standard is indeed doing what it is supposed to. The research carried out by the STEP-Manufacturing group well addresses these two challenges. The members of the STEP-Manufacturing group include manufacturing industry vendors of CAD/CAM/CNC systems and users such as Boeing. 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 standard 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 Model 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 module 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 module 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 writes 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 manufacturing information at the operation level (AP 238) [7].

Figure 1 describes the data—manufacturing data exchange scenario enabled by STEP. The geometric representation data described in STEP AP 203 or other formats 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 [9].

STEP-NC is the application of STEP methods to NC machines. Its title is "STEP Data Model for Computerized Numerical Controllers", representing a 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 intelligent CNC controllers. 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.

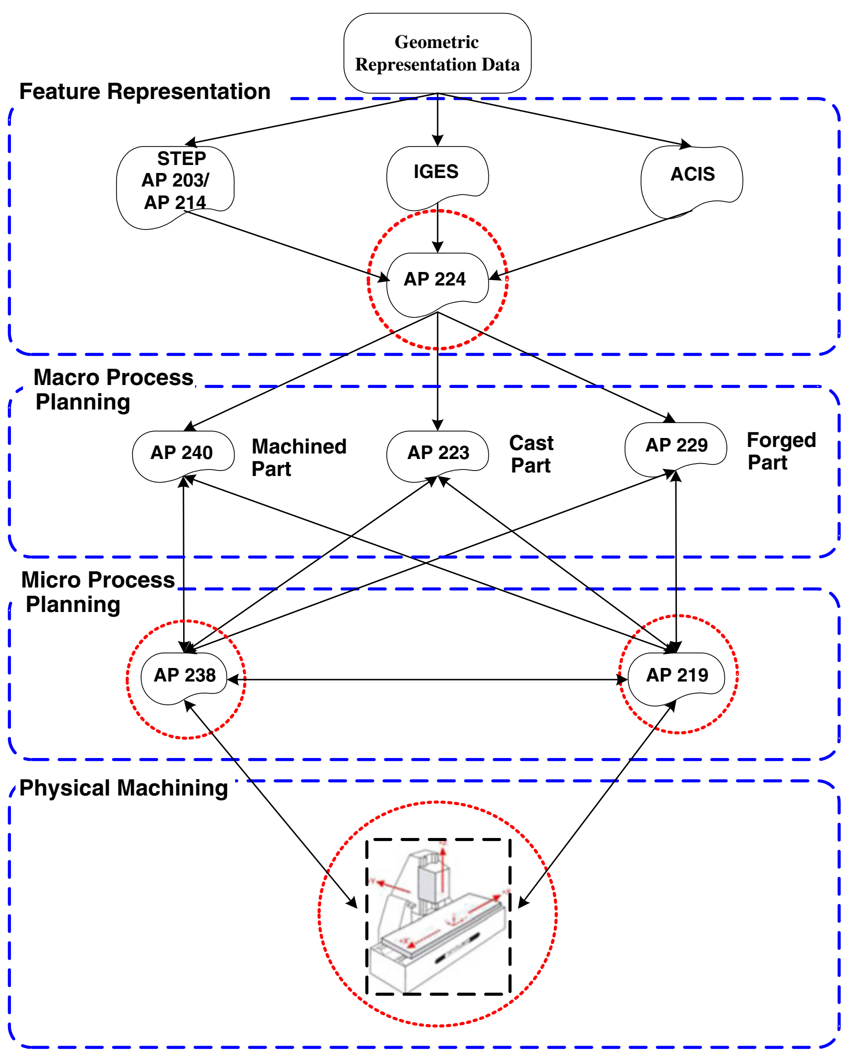


Fig. 1 Design–manufacturing data exchange enabled by STEP [8]

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 [10]
- ISO 14649–11: Process data for milling [11]
- ISO 14649–12: Process data for turning [12]
- ISO 14649–111: Tools for milling [13]
- ISO 14649–121: Tools for turning [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. Parts 11 and 12 specialize 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) and new data models for machine tools, additive manufacturing, and measurement of parts.

Comparing STEP-NC with G&M code, there are many benefits [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 adequate enough to describe 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 systems.
- Machining time for small- to medium-sized job lots can be reduced because intelligent optimization can be built into the STEP-NC controllers.

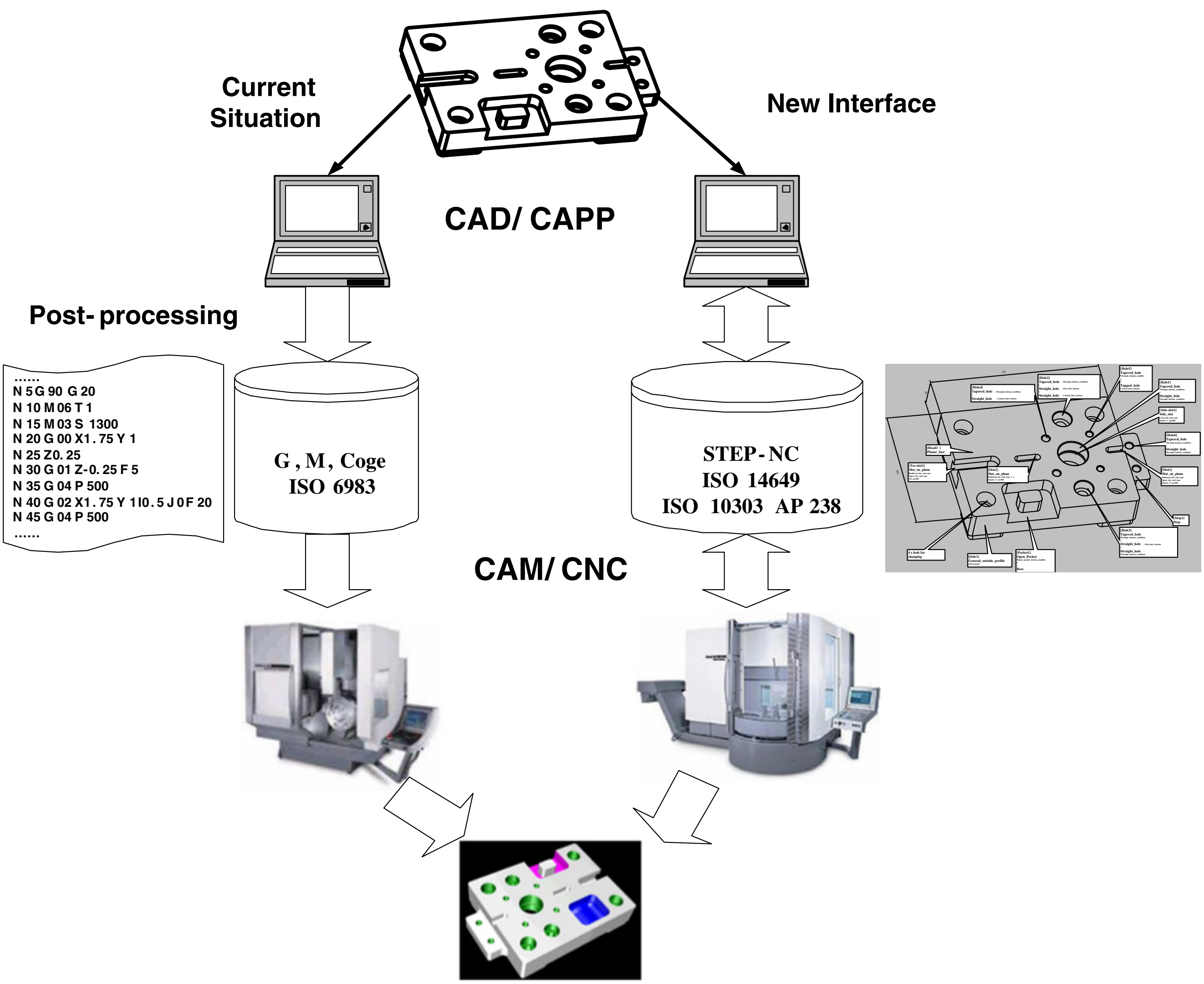


Fig. 2 Comparison of G&M code and STEP-NC data

- Post-processor mechanism will be eliminated, 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.
- Modification at the shop-floor can be saved and fed back to the design department hence 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-sized job lots [18]. With the inception and continuation of the work within the ISO standard committees to extend STEP-NC to new technologies and to incorporate refinements discovered during use. The STEP-Manufacturing group has been conducting continuous 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.

2.2 STEP-Manufacturing working group and AP 238

The SC4 manufacturing working group (also known as the STEP-Manufacturing group) is a team within Working Group 3 of the ISO TC184/SC4 committee. The STEP-Manufacturing group has adopted ISO 14649 as the ARM for AP 238 [19]. Both of 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 in 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 as the data modeling language, the full inheritance model of EXPRESS was not employed by the SC1 committee in developing the ISO 14649 data model [20]. The data modeling 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 that the data described in the ARM is believed to be easier for a person to read and hand-edit using a text editor and can be parsed more quickly which is an important advantage for high-speed machining. 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. High-speed CNC machines have made extensive use of caching. By using another level of caching they will overcome the problem of slow-parsing.
c. The SC4 integrated resources are normalized to make them easily extendible. If specific weaknesses can be identified then they should be extended for manufacturing. However, the editors of the STEP APs such as AP 224, AP 219, and AP 240 in addition to AP 238 have not yet identified any weaknesses.

The difference between the models is illustrated most clearly by the link between features, geometry, and tolerances. In the AP 238 data model, 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. This allows an application program to traverse the 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. The differences between the ISO 14649 and AP 238 data models are summarized in Table 1.

The richness of AP 238 data model affects the fundamental business benefits of STEP-NC and hence leads 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

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

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 is to extend and integrate STEP-NC with the manufacturing industry. The research efforts can be divided into two parts: AP 238 data model development and industrial demonstration. The group works on continuously developing the AP 238 data model for various types of machine tools and manufacturing operations such as traditional three- and four-axis CNC machines, state-of-the-art five-axis CNC machines, mold workpieces, machining process optimization, etc. The new portions of data model are implemented and tested with industry partners, which is also known as the demonstrations. Extensions and refinements of STEP-NC data model are often discovered and improved during demonstrations. 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 begun in 1999 [22]. These 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 14 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.

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. 3a).

Custom software read the data written by FB Mach and converted it to AP 224 manufacturing features. A Bridgeport

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

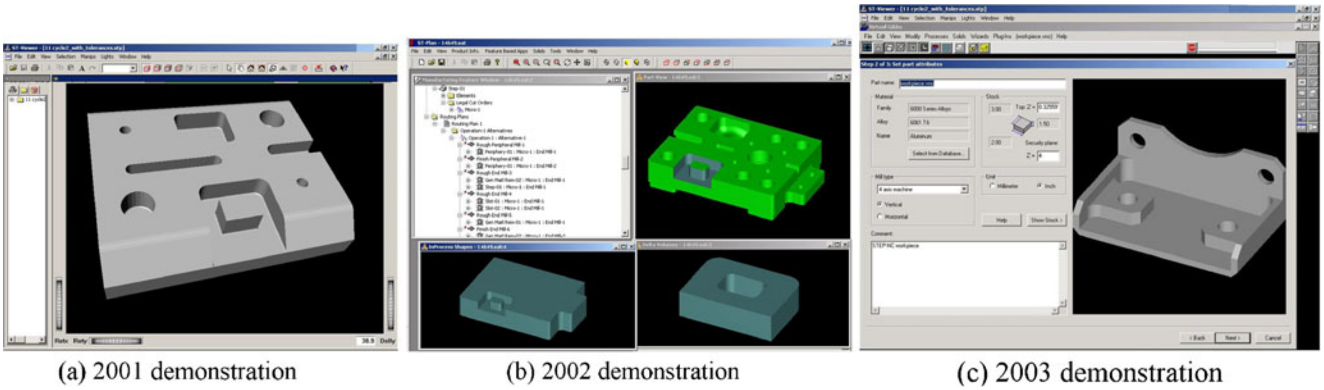


Fig. 3 STEP-NC Super Model Project demonstrations. **a** 2001 demonstration, **b** 2002 demonstration, and **c** 2003 demonstration

Controller modified by electro-mechanical integrators read the manufacturing data, found 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.

The second demonstration continued to work on verification of the AP 238 committee draft with a more complex workpiece shown in Fig. 3b. The difference of machining feature definitions between AP 224 and ISO 14649 were harmonized in the AP 238 draft standard after this demonstration. 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. 3c 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 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 five-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.

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

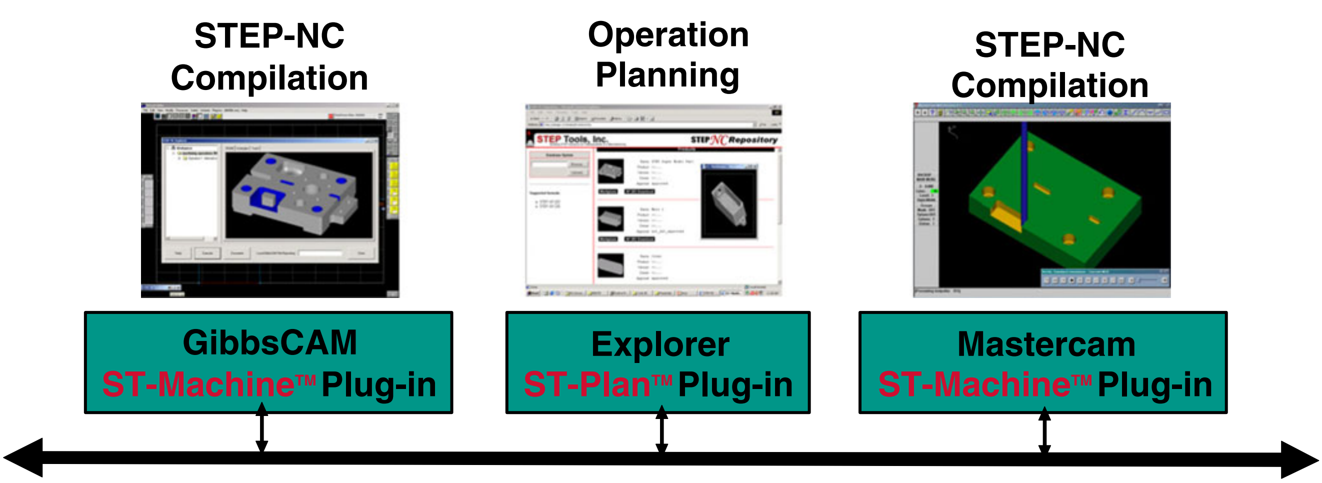
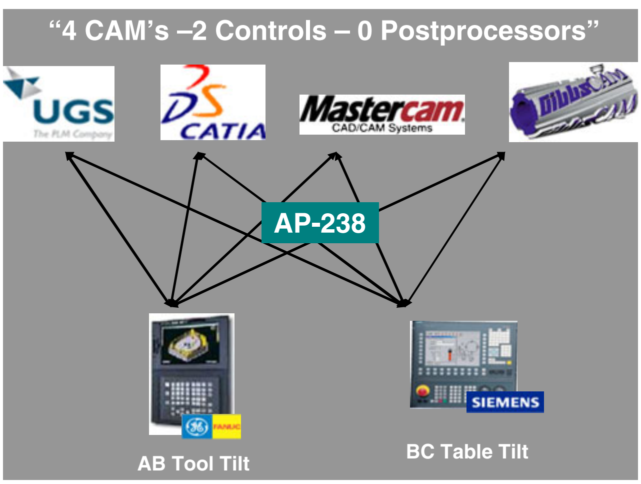


Fig. 4 Bi-directional information exchange between MasterCAM and GibbsCAM

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 two five-axis test parts (shown in Fig. 5).

Four major industrial CAD/CAM systems produced AP 238 machining programs for milling two five-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 parts on a variety of machines at their Tulsa facility, and a part was cut on a machine at NIST in Gaithersburg, USA. This demonstration showed the value that the STEP-NC standard was initially designed for—realizing interoperability between commercial software for manufacturing. With most of the major commercial CAM software companies' participating, the demonstration successfully showcased the future vision of an interoperable manufacturing scenario.



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

(b) 5-axis workpieces

Fig. 5 STEP-NC tool path interoperability test. **a** Four CAM’s–two controls—postprocessors system. **b** Five-axis workpieces

3.3 STEP-NC integrated machining and measurement demonstrations

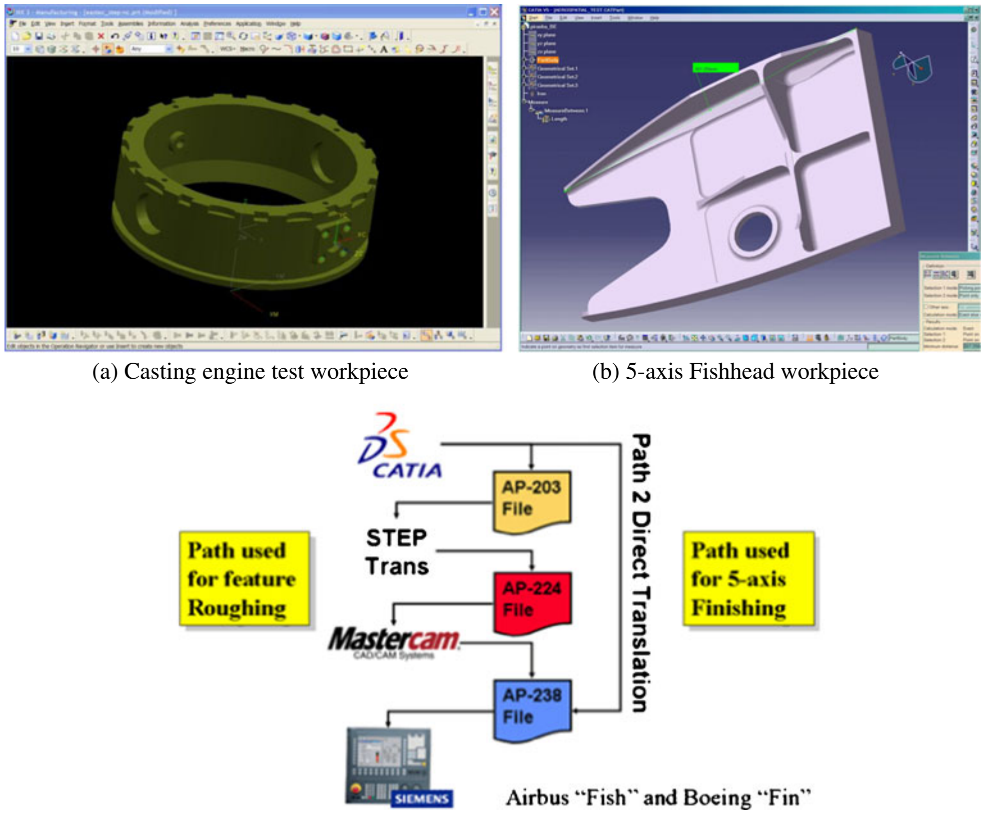
The third phase of STEP-NC demonstrations consisted of three tests from 2005 to 2007. This phase of demonstration focused on the integration of CAD GD&T data (as defined in AP 203 edition 2) with CAM process data (as defined in ISO 14649).

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

The workpiece was first cut into a rough state using toolpaths computed from STEP manufacturing features by an intermediate CAM system. Second the workpiece was finished using toolpaths directly from the original design system. The final result was a STEP-NC AP 238 file containing all 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 participated in this demonstration: the roughing paths were created by a UGS NX system and the finishing paths by MasterCAM.

In the following June 2006, a live five-axis STEP-NC machining demonstration was hosted by Airbus at Toulouse, France. A STEP-NC enabled interoperable manufacturing scenario was tested. The workpiece was designed in France (as an AP 203 file) shown in Fig. 6b, 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. 6c.

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



(a) Casting engine test workpiece

(b) 5-axis Fishhead workpiece

(c) International interoperable manufacturing test scenarioon airplane workpieces

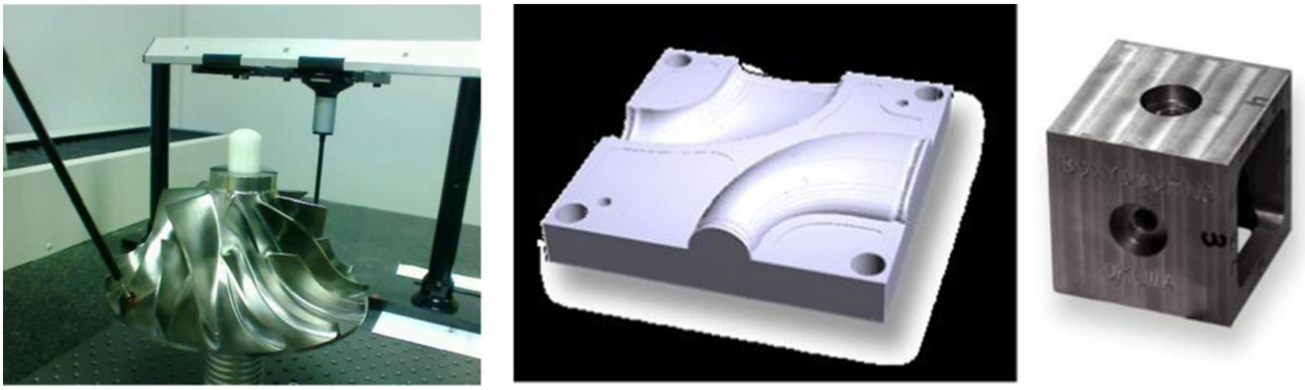
Fig. 6 Phase 3 STEP-NC Manufacturing demonstrations. **a** Casting engine test workpiece. **b** Five-axis Fishhead workpiece. **c** International interoperable manufacturing test scenario on airplane workpieces

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 the demonstration 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 [8], traceability information [28], and cutter cross-sectional information for feed and speed optimization [29]. In the following March 2008, a demonstration was held in Sweden. The previously tested five-axis workpiece (shown in Fig. 6b) was used to test the newly extended AP 238 data model with cutting tool data. At the demonstration it was decided that STEP-NC should integrate machine tool description definitions from ISO 13399 [30] so that semantic associations between tolerances, machining operations, and the cutting tools can be represented. This helped simplify tool compensation for more accurate machining. 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. 7a. A scanning probe was used to provide cutting tool compensation information during the machining process.

Feed and speed optimization is considered to be a very important area to improve manufacturing efficiency and reduce cost. Hence, the STEP-Manufacturing group augmented the AP 238 data model with cutter cross-sectional area definitions and the data model was verified in the demonstration held in May 2009 at Boeing facility in Renton, Washington, USA. The machining of a mold workpiece, shown in Fig. 7b, was shown in this demonstration. The same AP 238 file for the mold was machined at multi-sites using different machine tools. Different types of measurement devices—CMM touch trigger probe and laser scanning probe—were used for tolerance checking, where the tolerance information was saved in an AP 203 edition 2 file. An AP 238 file interpreter was developed and integrated to a Fanuc CNC machine that was used to machine the mold example workpiece. During this demonstration, it was perceived that further extending AP 238 to cover tool wear modeling and machine tool modeling should be the focus of the next phase of demonstrations.

A new test workpiece based on a gear box was designed for the fifth phase of demonstrations shown in Fig. 7c. Information modeling 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 three-,



(a) Impeller example workpiece (b) Moulding example workpiece (c) Gear box test part

Fig. 7 STEP-NC demonstrations of phases four and five. **a** Impeller example workpiece. **b** Moulding example workpiece. **c** Gear box test part

four-, and five-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.

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 issues have been discovered by the STEP-Manufacturing group; therefore the AP 238 data model was modified and augmented accordingly. It is, hence, necessary to summarize all of the corrections and new features from the past several years of implementation and testing for the second edition of AP 238. The following is the list of changes that have been proposed by the STEP-Manufacturing group 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 locate tool product model on the machine 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 tool path transform attribute to workplan. This allows more significant reuse of machining operations. 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 into the file such as selecting part of a program for 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 entity to represent cross-section parameters for feed and speed optimization. The entity defines a curve that gives 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 touch_probe entity from a stand-alone entity into a subtype of tool. It enables a connection between a probe and its shape geometry.
- Datum and datum_target reference to workpiece—add attribute to datum and datum_target entities to refer them to the workpiece.
- Full workpiece for in-process geometry—change in-process geometry from just shape_representation reference to full workpiece reference. This allows full range of product properties, features, and tolerances to be connected with workpiece.

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

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

```
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;
```

Apart from these changes, some new entities have been developed for machine tool modeling, workpiece setup, parts property, etc. The following is the machine_parameter entity that defines information of a 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 realization of a data model for representation of machine tools. Figure 8 shows the scope of the data model.

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 general. In addition, the data model will provide entities to capture a complete functional represen-

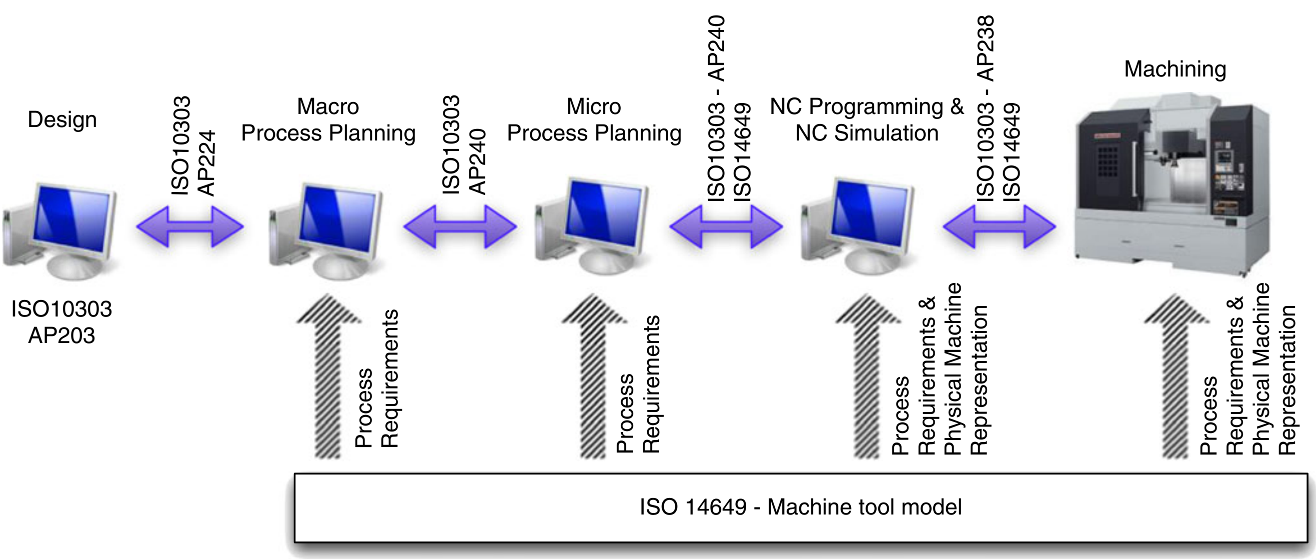


Fig. 8 The scope of machine tool data model developed in ISO 14649

tation of machine tools. These representations of physical manufacturing resources will be used in NC programming and simulation and by future generations of CNC controllers. 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.

In addition to the machine tool model, the working group has started the work to develop the second edition of ISO14649. In the second edition, more technologies will be covered in the scope of the standard and advances in other parts of STEP (such as advances in recording geometric tolerances) will be incorporated in the standard.

5 Remarks and future demonstrations

The RS 2274D (ISO 6983) G and M code standard was developed more than 50 years ago when paper tape was used for transferring data. Although the capabilities of CNC machines have improved significantly, the programming language remained almost unchanged. International efforts have been devoted 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. STEP-NC is part of the result from these efforts. It builds on the previous 10 years 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 tedious 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 less tool wear.

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 to 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. Future STEP-Manufacturing demonstrations will examine a range of options for modifying tool paths to meet tight tolerances.

This paper has reviewed the STEP-NC demonstrations carried out by the STEP-Manufacturing team. These demonstrations have been 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 of STEP-NC demonstrations 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 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 modeling. The newly augmented information was able to provide rich information for feed and speed optimization and better tool life management.

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. During the several years of testing and demonstration, the STEP-Manufacturing group has also 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 the ISO committee for peer review.

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