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Category B

STEP-NC Plate Cutting and Marking Demonstration
NSRP Panel Project
Final Report



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Contents

1	Introduction.....	3
2	Background.....	3
2.1	What is STEP-NC.....	4
3	Data Preparation.....	8
3.1	Creating Basic Data.....	8
3.2	Adding Manufacturing Preparation Data.....	12
4	CNC Machine Interface	13
5	Demonstration	14
6	Plate Cutting and the Second Edition of STEP -NC AP-238.....	15
7	Conclusion	16
8	References	17

1 Introduction

The scope of this STEP-NC concept demonstration was to implement a proof of concept prototype that connects a shipyard design system to a plate cutting machine using the STEP-NC standard. For this project, STEP Tools implemented a functioning prototype in which machining data is converted to STEP-NC from actual shipbuilding data sources and used for cutting and marking at a shipyard facility.

The key activities of this project were as follows:

- Electric Boat provided plate data from their existing design system. This included AP203 geometry for plate shape and CATIA APT to describe the marking and cutting process. The process data included straight and bevel cuts, line and text marking.
- From this input, STEP Tools constructed STEP-NC AP238 CC2 data to describe plate and process, and annotated it with additional manufacturing data for plate piercing, lead-in, lead-out, etc.
- STEP Tools constructed prototype interfaces to drive ESAB plasma cutter and laser marking machines from AP238 data.
- STEP Tools cut and marked plate at Electric Boat Quonset Point facility using the STEP-NC data and prototype ESAB interface on May 9, 2007.
- The results of this project were presented at the NSRP meeting in San Diego on May 16, 2007.

The following sections will provide some history and motivation for STEP-NC, and describe the above activities in greater detail.

2 Background

The language used to describe part programs for Computerized Numerical Controls (CNC) is 40 years old. It was designed in an era when paper tape was the most popular medium for moving data between computers and the logic necessary to process simple commands was just about affordable for a CNC machine. Today the average microprocessor can easily process 3D data and CNC machining is the only operation in the design-to-manufacturing pipeline that is not using full-fidelity product and process information.

In design and manufacturing, many systems are used to manage technical product data. Each system has its own data formats so the same information must be entered multiple times into multiple systems leading to redundancy and errors. The problem is not unique to manufacturing but more acute because design data is complex and three-dimensional leading to increased scope for errors and misunderstandings between operators. The

National Institute of Standards has estimated that data incompatibility is a 90 billion dollar problem for manufacturing industry [1].

Over the years many solutions have been proposed. The most successful have been standards for data exchange. The first ones were national and focused on geometric data exchange. They included SET in France, VDAFS in Germany and the Initial Graphics Exchange Specification (IGES) in the USA. Later a grand unifying effort was started under the International Standards Organization (ISO) to produce one International Standard for all aspects of technical product data and named STEP for the Standard for Product Model Data [2]. Nearly every major CAD/CAM system now supports a STEP protocol. Figure 1 shows some applications.

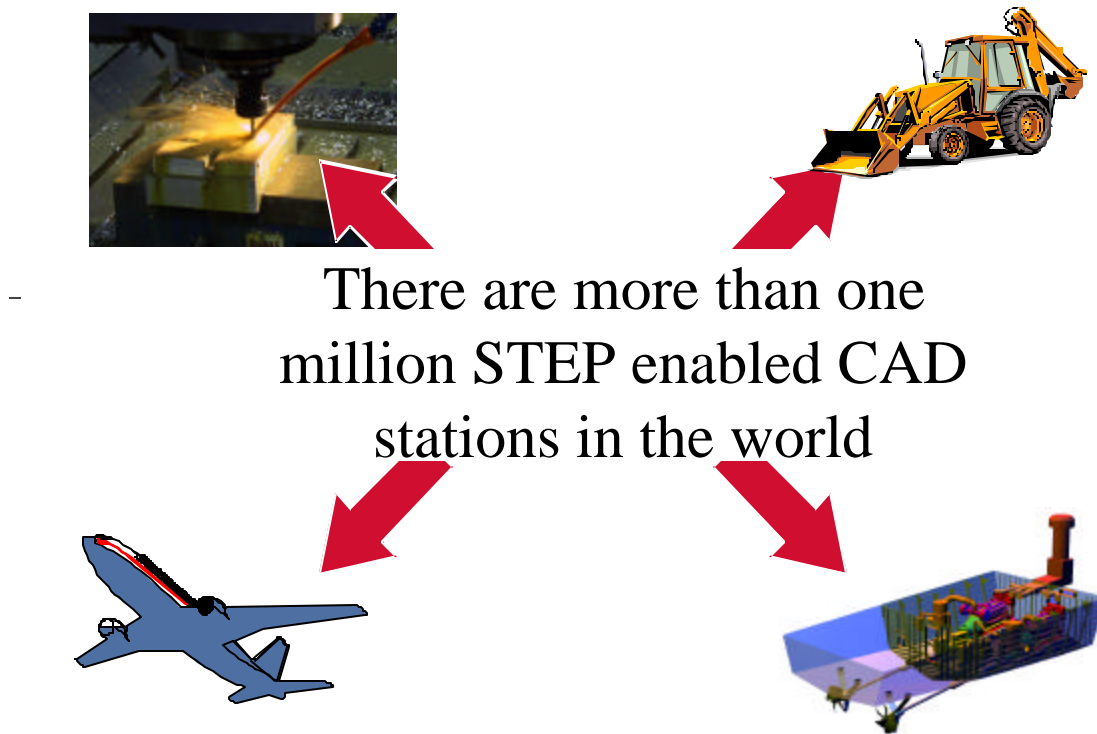


Figure 1. Data Exchange using STEP and STEP-NC

The idea for STEP-NC started in a joint European and Japanese project. The first model they produced was for the data necessary to control milling machines and subsequently they developed models for controlling turning, EDM and Cutting machines. The developers represented Siemens, the University of Aachen and the University of Stuttgart in Germany, Komatsu and Fanuc in Japan and Heidenhein in Switzerland [3].

2.1 What is STEP-NC

Figure 2 shows how design data is communicated to manufacturing in current practice. Design creates the specification for a product as a 3D model. Detailing decides the manufacturing requirements for the product by making a drawing. Path planning generates tools paths. Manufacturing controls production.

The job of design is performed using a CAD (Computer Aided Design) system, the job of detailing is performed using a drawing (Computer Aided Design Detailing) system, the job of path planning is performed using a CAM (Computer Aided Manufacturing) system, and the job of manufacturing is controlled using a CNC system. In most cases CAD and CADD functions are combined into one system, and in many cases the CAD, CADD and CAM functions are combined into a single integrated CAD/CAM system. In all cases, however, the CNC function is performed by a separate system.

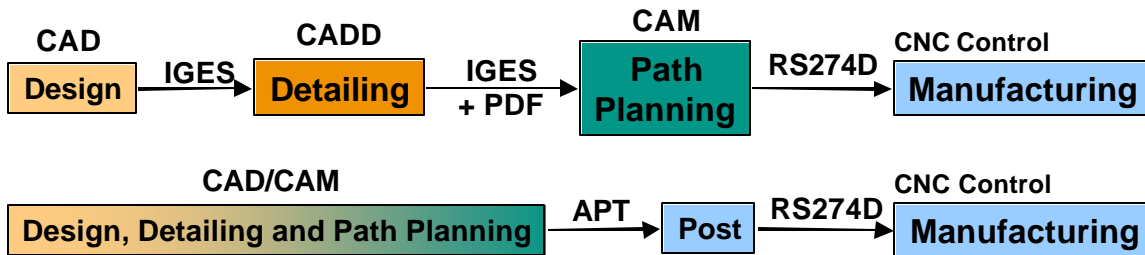


Figure 2. Current Practice in Design to Manufacturing Data Exchange

Figure 3 gives a graphical illustration of the major features and shortcomings of the RS274D machine control standard. Also known as ISO 6983, RS274D defines a sequence of codes for controlling the cutting head of a machine tool. “G” codes are used to define linear or circular tool movements and “M” codes are used to define ancillary operations such as controlling the flow of coolant. As shown in the figure, RS274D programs are quite limited.

Development of RS274D stopped about 30 years ago. Machine tool vendors have since filled the vacuum by adding special codes to their version of the RS274D language to control special features of their machines. This has led to a situation where there are many partially incompatible flavors of RS274D. The biggest CAM vendors now estimate they support 4,500 RS274D flavors using tools known as post processors. For industry these flavors mean that RS274D programs are not portable between machines.

STEP-NC extends STEP to include manufacturing control information. Figure 4 contains an illustration of the information defined by STEP-NC as an EXPRESS-G diagram [2]. In the top left corner the geometry defined by AP-203 is shown as a single box labeled geometry. Below this a series of machining features are defined and also shown as boxes.

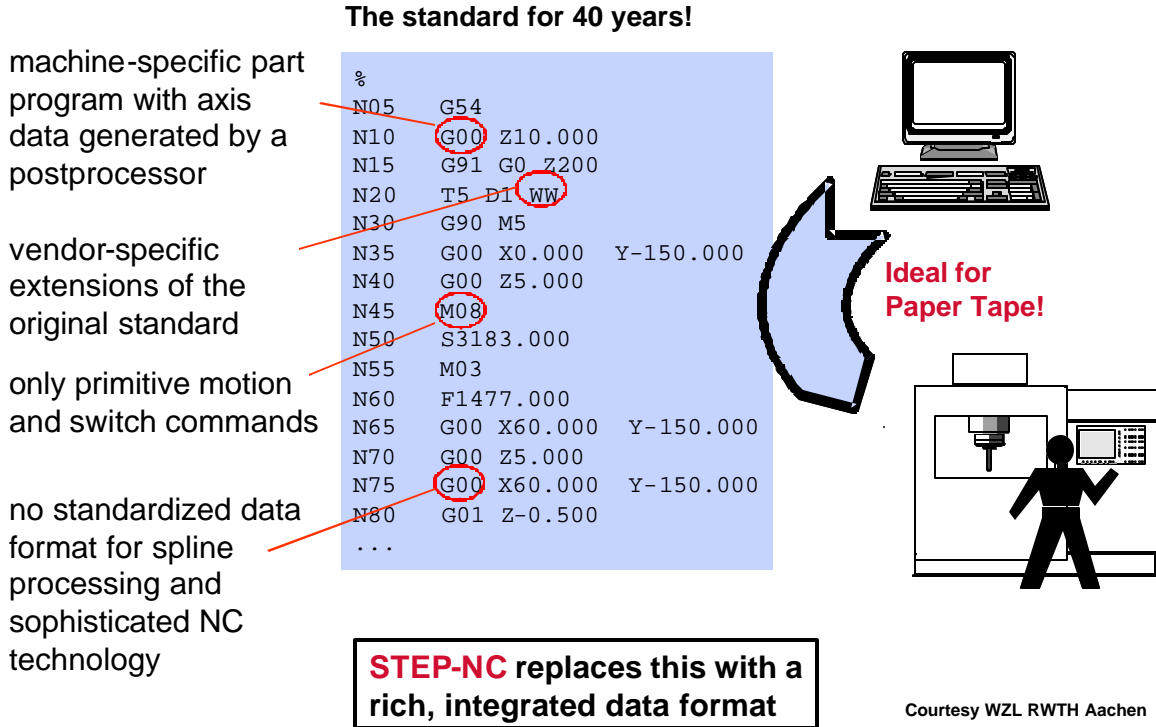


Figure 3. Illustration of the RS274D Standard

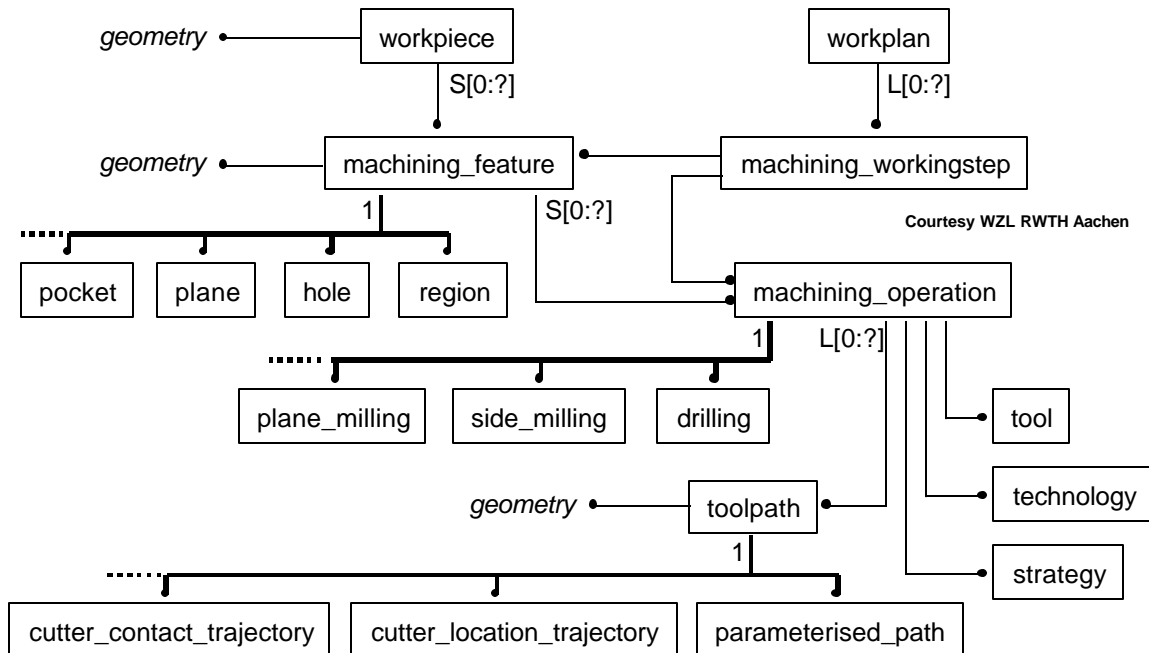


Figure 4. Information Diagram for STEP-NC

The features are the same as those defined in AP-224 [4]. The rest of the diagram outlines some of the new information defined by the STEP-NC model for milling. Similar models for turning and EDM have been developed and others are anticipated for bending, CMM inspection, robotic assembly and other operations.

The root of a STEP-NC part program is a work plan. Each work plan contains a series of working steps. Each working step applies a machining operation to a manufacturing feature, for example, a rough milling operation to a pocket. The same machining operation may be used in several working steps and several working steps may be necessary to complete a feature. For example, completion of a pocket may require a roughing operation to be followed by a finishing operation. The diagram does not show the details but work plans may be nested, they may be made conditional on the result of a probing operation, and they can be organized to run concurrently on machines with multiple cutting heads.

In STEP-NC each operation can access any of the information in the part program. This is one of the key advantages of STEP-NC because it means an operation knows its tooling requirements, the parameters of the feature, the geometry of the feature, the tolerances of the feature, any necessary strategy and technology information, and so on. Therefore, algorithms can be written to make the machine tool faster and more intelligent and these algorithms can be run on the controller while the machine is running to give the operator more intelligent advice and improve safety.

A STEP-NC program describes Cutter Location (CL) data for its tool paths. This means those tool paths are described in the coordinate space of the part, not the coordinate space of the axes of the machine tool being used to make the part. Therefore, STEP-NC tool path data are portable between CAM and CNC systems.

The BCL data format also defined portable data paths, but unlike BCL, STEP allows the CAD geometry and CAM process data used to generate the tool path data to be included in the exchange file. This geometry was not available when BCL was defined because CAD systems had not yet been give STEP interfaces. We believe the addition is crucial to the success of STEP-NC for plate cutting because the geometry and CAM process data will allow us to generate new tool paths when necessary within the context of the receiving CAM system.

STEP-NC can be used for plate cutting and pipe bending as well as for milling and turning. On May 5 of 2004 STEP Tools gave a demonstration of plate cutting at Bath Iron Works using data supplied by NGSS Ingalls. The results of the first demonstration were published in the Journal of Shipyard Production [5]

Last, but not least, the Northrop Grumman Information Technology division has done an analysis of how STEP-NC can be applied to shipbuilding and presented its results and recommendations to the NSRP [6].

3 Data Preparation

3.1 Creating Basic Data

The input to the demonstration was plate data in the form currently used by a shipyard. After some initial discussion, the simple support structure shown in Figures 5 and 6 was chosen as a test part. Electric Boat created plate data for the test part using their existing design system and provided AP203 geometry for plate shape and CATIA APT to describe the marking and cutting process.

The process data included straight and bevel cuts, line and text marking. The shape and marking for the STEP1 and STEP2 parts shown below were very similar, but within the APT process data, the STEP1 contained only simple moves, near side marking and far side marking. The APT for the STEP2 part was more involved because it described a double 45deg bevel along one edge of the part.

Both parts had a full selection of marking operations: line marking in several line styles, plain text marking at different angles, and part number marking where the part id had to be gathered from the workpiece product data. The markings were done on both near side and far side of the part.

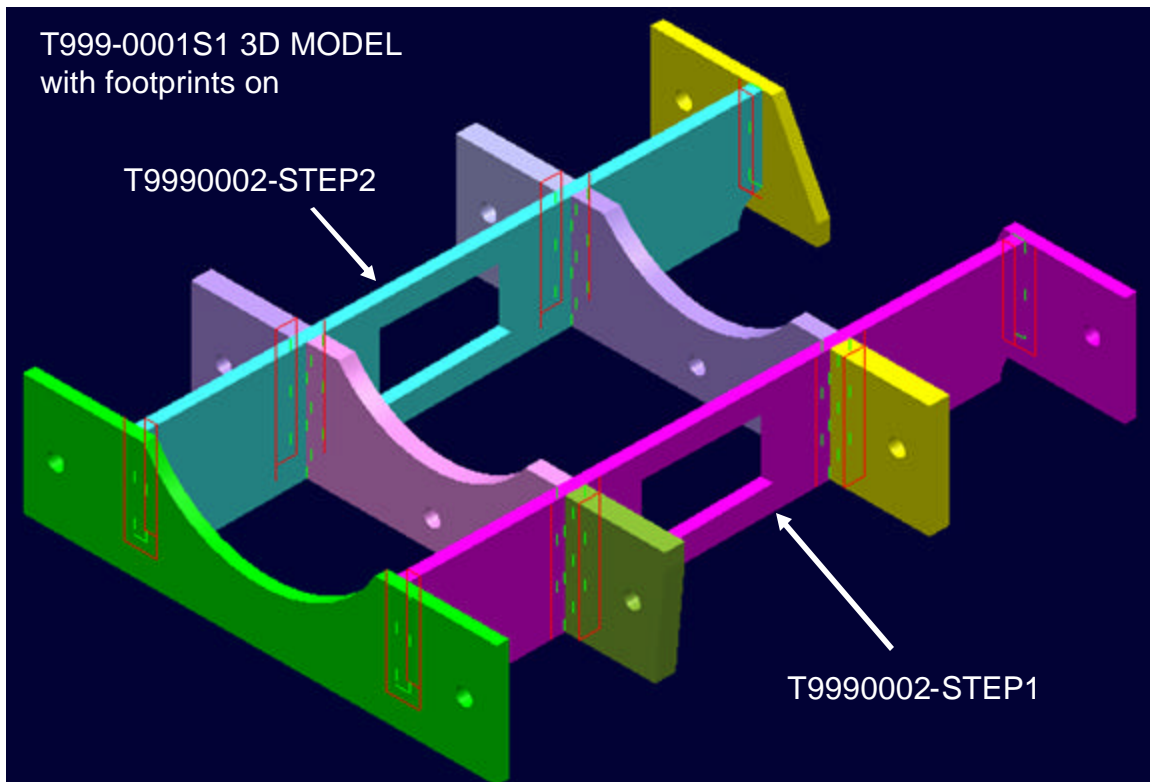


Figure 5. Original CATIA Geometry Data

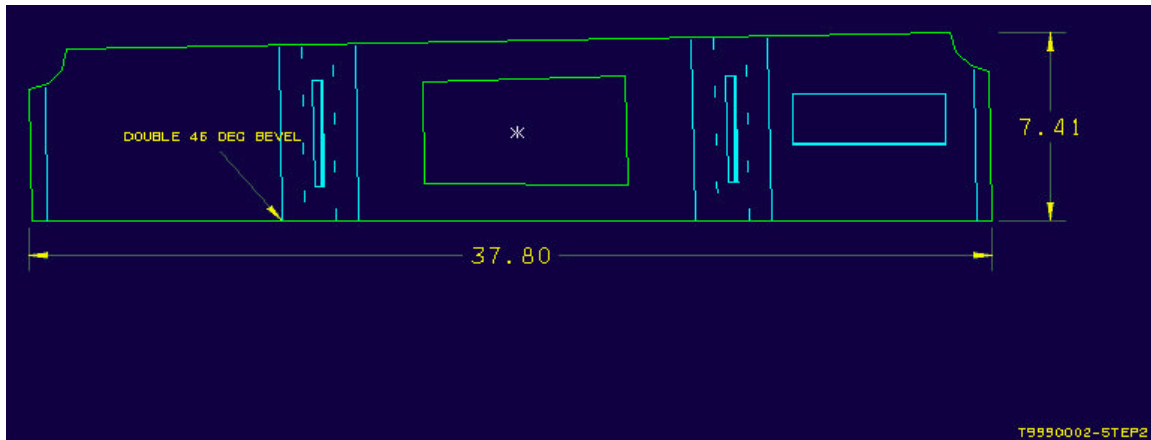


Figure 6. T9990002-STEP2 with far side footprints visible

The first task in creating the STEP-NC data was to read the APT and create STEP-NC workingsteps and operations. We used a tool previously developed for converting APT code for milling and turning, and extended it to recognize a number of cutting and marking-specific commands. A list of these plate-specific commands is shown below.

- ANGLEL - Set cutting head angle left for beveling.
- ANGLER - Set cutting head angle right for beveling.
- AREA
- AUTOPS - Ignored, appears at the beginning of a circle/arc element.
- CYCLE/BEVEL GX3 style bevel pass
- CYCLE/BOTTOM Bottom bevel pass on multi-pass edge
- CYCLE/DUMMY Dummy cycle to define part perimeter
- CYCLE/FAR Far side single-pass bevel
- CYCLE/LABEL Old style part label (GX4 marker support)
- CYCLE/LAND Land pass on multi-pass edge
- CYCLE/NEAR Near side single-pass bevel
- CYCLE/OXFUEL Oxyfuel - GX3 only
- CYCLE/PLABEL Near side laser marked part label
- CYCLE/PLABELF Far side laser marked part label

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- CYCLE/PLASMA Straight cut pass. No bevels on the part
- CYCLE/PMARK Near side punchmarked/laser marked geometry
- CYCLE/PMARKF Far side laser marked geometry
- CYCLE/STRGHT Straight cut single pass entity on bevel part
- CYCLE/TAB Straight cut pass to cut tabs
- CYCLE/TEXT Near side laser marked text
- CYCLE/TEXTF Far side laser marked text
- CYCLE/TOP Top bevel pass on multi-pass edge
- FROM - Set starting location
- GRAIN N
- HEAD/OFF - Turn Laser or cutting head off
- HEAD/ON - Turn Laser or cutting head on
- HITEL - Set bevel height left
- HITER - Set bevel height right
- INDIRV - IN DIRection Vector for arc cuts. It defines the direction of the cut. It's a vector starting (0,0,0) at the start point of the circle/arc and ending at a point 10% into the arc in the direction of cut.
- INTRNL - For beveling, indicates when a corner is internal. It relates to cut sequencing, not geometry.
- LFONT - Select line font to use
- LKERF - Indicates left kerf. Due to the dynamics of a plasma torch, plate cutting is done with left kerf, without exception.
- MANGLE - Set orientation angle of marked text
- MARK - Specify text to mark, as numeric ASCII codes
- NOTE
- TFONT - Select text font to use

- TLON - Marks the beginning of a circle/arc cut. Always immediately follows an INDIRV command

The first edition STEP-NC model cannot hold the cutting and marking process parameters defined by these commands, so we used the Extended_Nc_Function construct to hold the necessary data.

Using this technique, we created the initial AP-238 process data. One side effect from the use of Extended_Nc_Function was the workplan being broken into many small workingsteps separated by the functions. This is a temporary issue however. When the STEP-NC model is extended for plate cutting, the parameters will move into Technology and Operation constructs and the process will be organized into workingsteps at more semantically interesting places. In particular, the various CYCLE commands in APT describe information that can be used to group the process data in the STEP-NC model into logical operations.

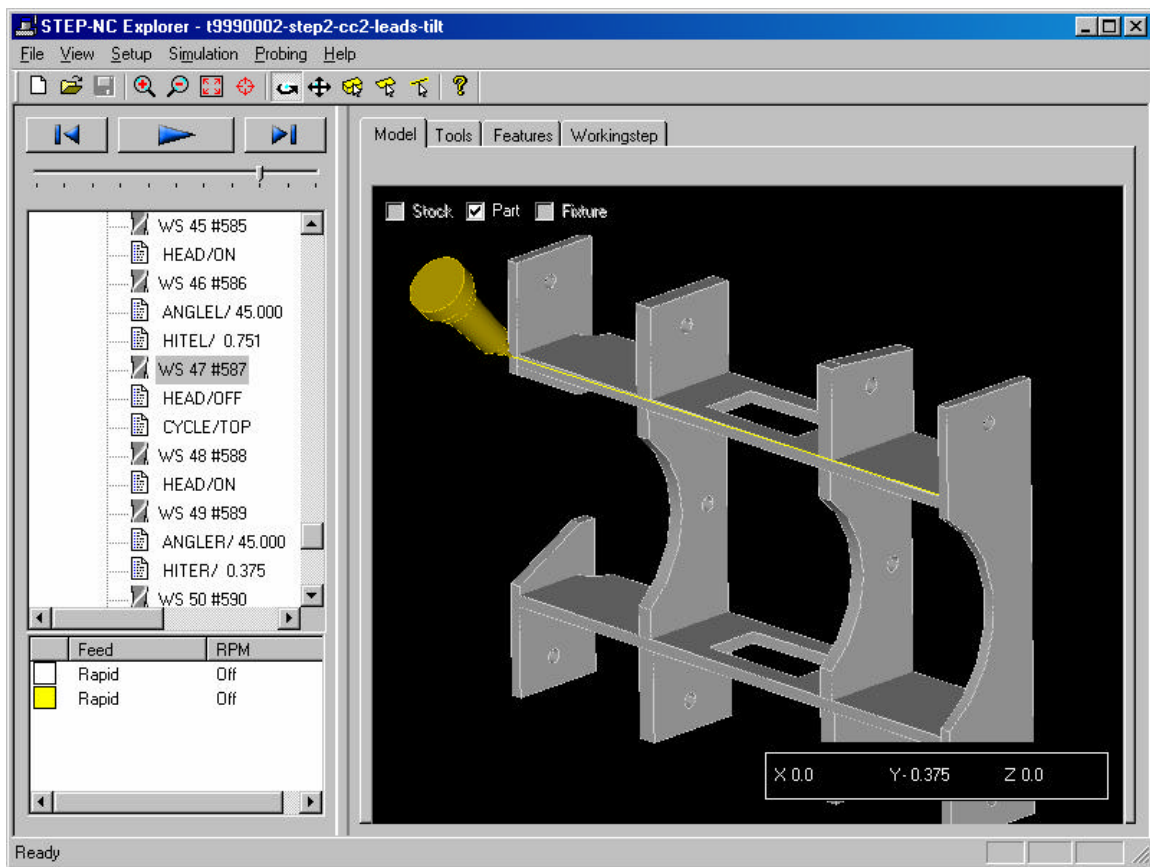


Figure 7. STEP-NC Data with Combined Geometry and Process

Once the STEP-NC process data was constructed, the AP-203 geometry for plate shape was added so that the process could be seen in context. The geometric placement of the workpiece geometry had to be modified to match the location of the process data. The process data was located at the origin, but the workpiece shape was located almost 100 yards away, presumably taken from a larger ship assembly.

3.2 Adding Manufacturing Preparation Data

At this point, we had a STEP-NC description of the process and geometry, but additional manufacturing preparation data was needed before the information was suitable for cutting parts. The data was as-designed, with cuts starting and ending right on edge of the part, however, lead ins and lead outs are normally required to avoid gouging the part.

When using plasma to cut plate, an arc must first melt through (pierce) the plate, as shown in Figure 8, which tends to splash molten metal and make an irregular hole. To avoid gouging the part edge, this is normally done a few inches away, in unused metal, and then the torch moves into the normal cut once a stable arc has been established.

This is also important when cutting bevels because piercing is done perpendicular to the plate, and a lead-in gives the cutting head time to traverse into the correct bevel angle.

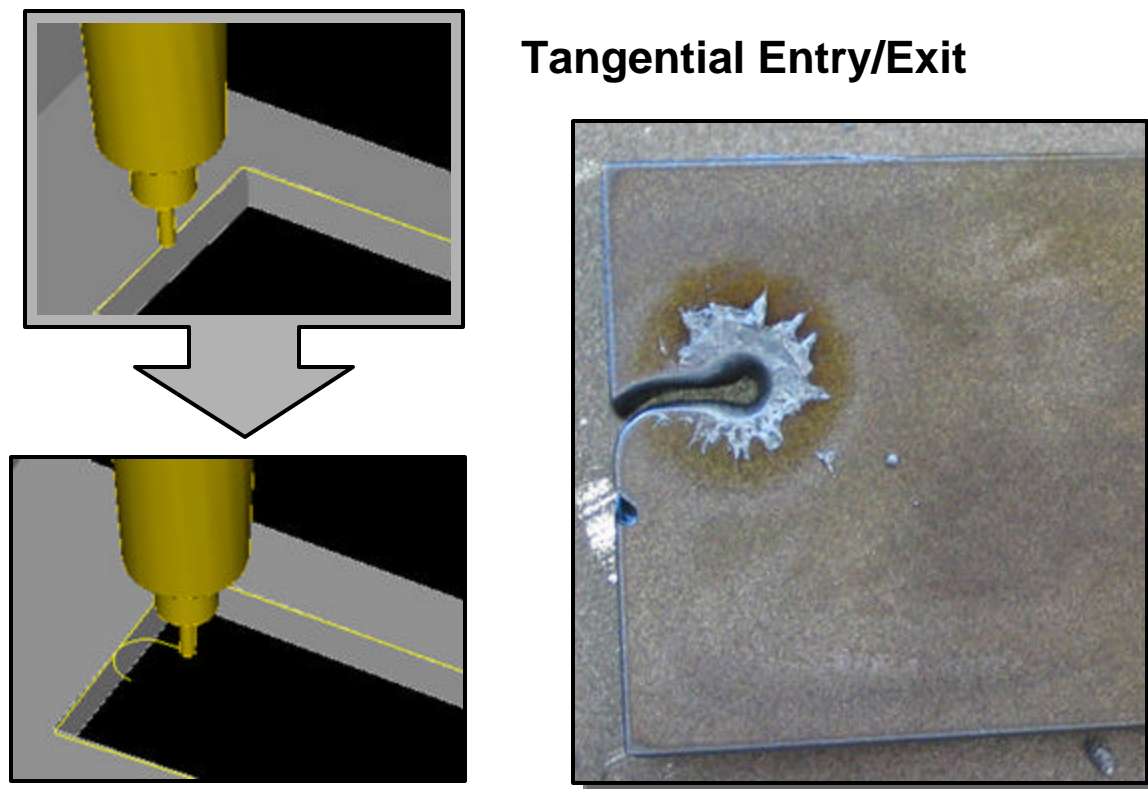


Figure 8. Tangential Entry/Exit for an Interior Cut

We created utilities to add these lead ins and lead outs to the STEP-NC data. Figure 8 shows the original cut data for the interior of a plate. Using the tools we developed, we added lead in and lead out moves that merged tangentially into the original cut. The photo shows the pierce and resulting cut from the actual plate.

Figure 9 shows the original cut data for the double 45 degree bevel cut on the part. Using the tools described above, we added linear lead-ins that allowed the head to pierce the plate and rotate into the correct position.

In the original data, the cutting head angle was specified by the ANGLEL/ANGLER parameters described in the previous section, rather than by the normal STEP-NC tool axis mechanism. As part of the manufacturing preparation data, we also added a tool axis vector to the STEP-NC toolpaths so that the beveling can be seen more clearly, as in the “after” images of Figure 9.

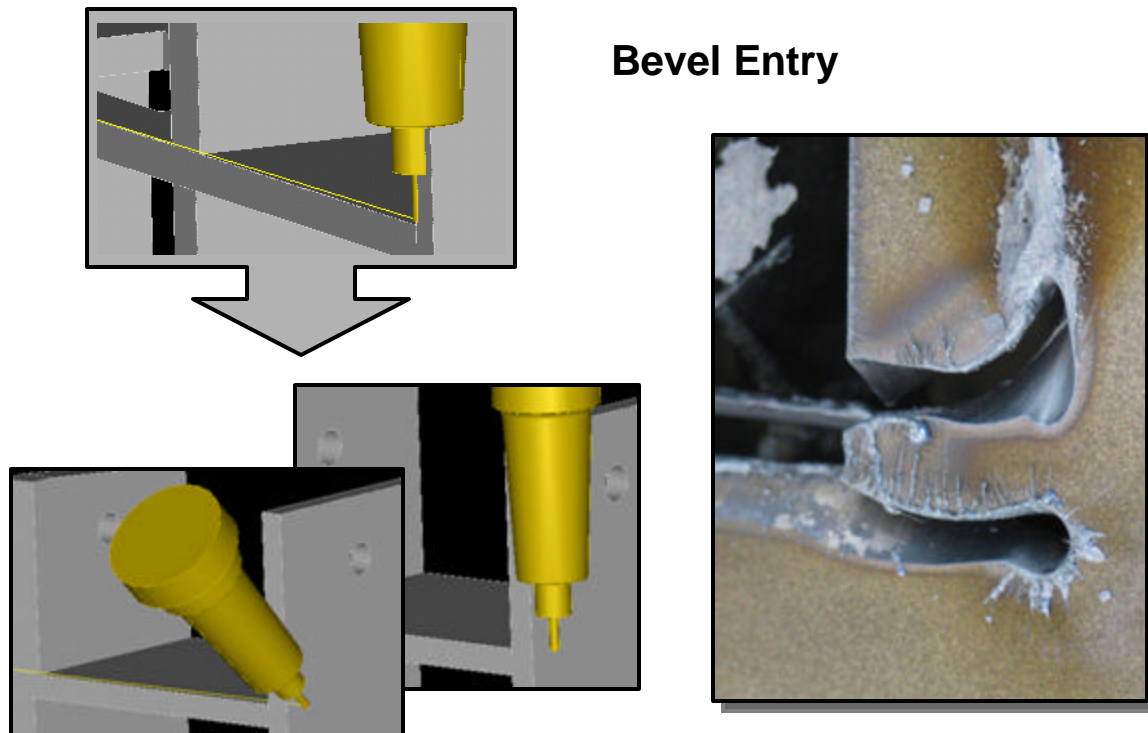


Figure 9. Pierce and Lead-In for Double Bevel

Today, this manufacturing preparation data is added by nesting systems like Optimization, Majestic, or Sigmanest. In the future, these systems can read and write STEP-NC, or other stand-alone utilities can operate on the STEP-NC data to add lead in/out moves, or other technology specific information.

4 CNC Machine Interface

To demonstrate cutting and marking, the CNC controls at the designated site had to be updated to accept STEP-NC input. This was done by adding a layer of software above the existing control that converts the STEP-NC process data into the native codes of the control.

The laser marking machine and plasma cutting machine selected for the demonstration were driven by ESAB controls. These controls required many unique codes and had a number of operational peculiarities, like ordering of codes and required decimal points, so close contact with EB personnel was required to understand them and create the AP-238 CNC interface. Some APT and ESAB codes are rather obscure. For example, laser marking the text “-STEP11” was given by the following in the source APT:

MARK/ 45, 83, 84, 69, 80, 49, 49, 0, 0

The marked text is represented as numeric ASCII values and must be converted to character values for output. The corresponding ESAB code for marking the text is shown below:

```
F100.0  
G89D003  
G81D0.375  
G82D271.1  
G80  
(-STEP11)  
D004  
M75
```

The STEP-NC program describes all of the operations that apply to the test plate, but no one machine can do all of these operations in one pass. In order to cut and mark the test plate, the laser marker first marks one side of the plate then the plate is flipped and the laser marks the far side of the plate. Next, the plate is moved to a separate machine for cutting. The STEP-NC CNC interface must create three separate ESAB programs, as shown in Figure 10, to cover near-side marking, far-side marking and cutting.

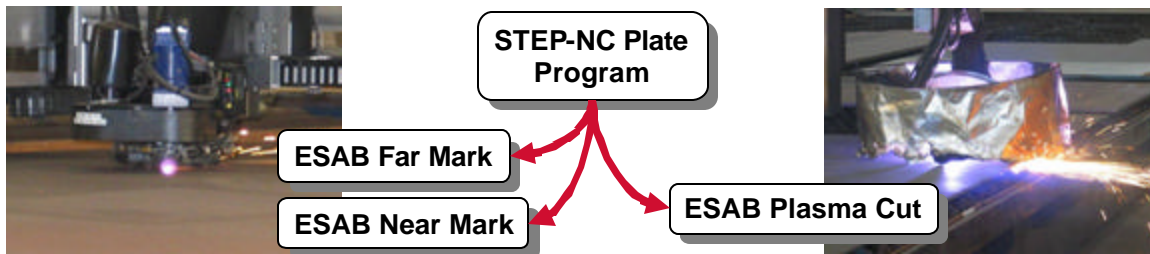


Figure 10. STEP-NC Cutting and Marking Interface

Splitting the process into three separate programs was not difficult because of the CYCLE annotation that was present in the original source data. In future work, however, it will be preferable to do this when creating the STEP-NC data rather than at the CNC. A single STEP-NC part program will still hold all of the operations, but they will be organized into three nested sub-workplans for near marking, far marking, and cutting. This will make the data easier to understand and manipulate.

Finally, the CNC interface had to transform the coordinate systems and origins to accommodate the local conventions for setup and registration of the plate, as well as the flipping of the plate between marking of the near and far sides. In addition, the part had to be located on the material with appropriate borders for lead-ins and to avoid the edge of the plate.

5 Demonstration

On May 9, 2007, the test part was marked and cut at the Electric Boat Quonset Point facility. Before the demonstration, the cutting and marking programs were tested

extensively on an ESAB simulator. On the actual machine tools, the cutting process worked smoothly. Proving that a simulator is no substitute for actual experiment, when the marking programs were tested, a minor issue was discovered with the ordering of one of the ESAB marking codes (specifically that G141 to set the marking line style must occur before turning the laser on with M74). This was corrected on site.



Figure 11. Test Part Cut at Demonstration

The test part was successfully cut and marked using the STEP-NC description, and is shown in Figure 11.

6 Plate Cutting and the Second Edition of STEP-NC AP-238

There is growing consensus in industry that STEP-NC is a better, language for CNC machining because it enables higher accuracy machining, integrated measurement with machining, and easier workload balancing. Therefore, extensions are being developed to further enhance these qualities.

A metrology extension is being developed by the High-Level Inspection Process Plan (HIPP) team lead by NIST with participation by Boeing, Lockheed Martin, Honeywell, Caterpillar and John Deere and others. An early experiment has already shown that DMIS programs can be generated from AP-238 programs proving that STEP-NC allows measurements to be made on both CMM's and CNC's. The HIPP team is examining how other DMIS functionality can be integrated into AP-238. The next ISO TC184/SC4 meeting in Ibusuki Japan in July 2007 will review a draft of the new metrology model. The model is being validated in an experiment in which the same 5-axis machining and measurement program is being run at sites in France, Sweden, and the USA.

A traceability extension is under development to enable verification that a part has been machined correctly [7]. STEP-NC makes CNC traceability more practical because the trace can be explained using the high level concepts in the STEP-NC model. A draft of this model will also be presented in Ibusuki and some early results will be demonstrated in Sweden and Spain in the Fall of 2007.

This project has demonstrated that a STEP-NC model for plate cutting allows plate cutting data to be made more portable and functional. If appropriate action is taken, then the new plate cutting model can also be included in the second edition of STEP-NC AP-238. To meet the schedule, the model should be agreed upon during the Fall of 2007 so that it can be mapped into the STEP integrate resources during the Winter and included in the Draft International Standard of the Second Edition to be published in the late Spring or early Summer of 2008.

7 Conclusion

The demonstration showed that STEP-NC AP-238 can be built from existing shipyard data sources, and can be used to drive plate cutting and marking. Figure 12 shows the design to manufacture pipeline as it exists today and how the pipeline will appear when based on STEP-NC technology.

Today, the design system creates nominal plate cutting descriptions that are sent as APT to a nesting system like Optimization, Majestic, or Sigmanest. The nesting system performs many functions in addition to nesting. It adds lead ins, lead outs, other manufacturing preparation information, and then produces machine specific G-codes as a post-processor. If the nesting system does not perform one of these functions well, then there is usually no option except to wait for improvements from the system vendor.

A process based on STEP-NC will be considerably more flexible. The nesting systems will continue to provide nesting and manufacturing preparation functions, however, the open STEP-NC data backbone means that other stand-alone utilities can be added where necessary to improve specific functions.

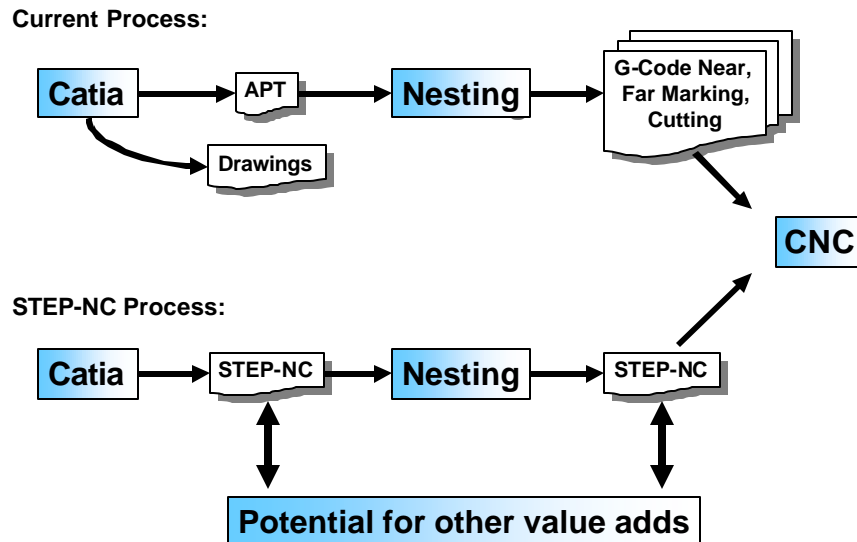


Figure 12. Current Process vs. STEP-NC Process

For example, the height of the plasma torch is controlled by a feedback loop, but this can be disrupted when passing over a previous cut causing the head to dip and resulting in

some irregularities in the cut. For maximum quality, the feedback loop should be turned off briefly when passing over a previously cut region. This information is not in the original shipyard source data and many nesting systems are not very good at detecting path intersections, so a STEP-NC application can be written to analyze the cuts and annotate the toolpaths so that the feedback loop is turned off for the appropriate interval.

The key area for future work is to combine the results of this demonstration with the observations of the previous NSRP Northrop Grumman STEP-NC panel project [6]. Ideally, the new work will make a draft ARM information model in time for inclusion in the second edition of AP-238 in the Fall of 2007. The model must extend the STEP-NC Technology and Machine_functions to contain descriptions for cutting and marking parameters. It must also extend the Operation concept to characterize workingsteps into cutting and marking operations.

The addition of plate cutting to the STEP-NC standard will maximize the portability and functionality of Navy data for plate cutting. Increased portability will allow for better balancing of the machining workload among shipyards and reduce the number of plate cutting machines required. Enhanced process visualization will lead to fewer mistakes and reduce scrap. Improved accuracy will enable process improvements that lead to more automation within the yards.

To support the development of the second edition, we recommend that the Navy and shipyards review the plate cutting model at the next NSRP meeting in Groton in August 2007, and at the International STEP meeting in Dallas in November 2007. We also recommend that the model be validated at a second yard using the design and manufacturing systems of that yard, and that a data exchange then takes place between the two yards so that a plate designed at the first yard is captured as STEP-NC data and used to control cutting machines at the second yard and vice versa.

8 References

- [1] S. B. Brunnermeier and S. A. Martin, "Interoperability Cost Analysis of the U.S. Automotive Supply Chain," RESEARCH TRIANGLE INSTITUTE, March 1999, <http://www.rti.org/publications/cer/7007-3-auto.pdf>
- [2] ISO 10303-1:1994 Industrial automation systems and integration Product data representation and exchange - Overview and Fundamental Principles, International Standard, ISO TC184/SC4, 1994.
- [3] Suh, S.H., Cho, J.H., and Hong, H.D., 2001, "On the architecture of intelligent STEP compliant CNC," *Int'l J. Computer Integrated Manufacturing*, Vol. 15, No. 2, January 2002, pp. 168-177
- [4] Hardwick, M. "On STEP-NC and the complexities of product data integration", *ACM/ASME Transactions on Computing and Information Science in Engineering*, Vol.4, No1, March 2004

- [5] Hardwick, M, “Improving Shipyard Manufacturing Processes using STEP-NC”, with B. Kassel, B. Crump and S. Garret, *Journal of Ship Production*, Karen Hansen Editor, Society of Naval and Marine Engineers, August 2005.
- [6] Richard, K., *STEP-NC for Steel Production, Final Report*, NSRP Systems Technology Panel, September 29, 2006
- [7] J. Garrido and M. Hardwick, “A traceability information model for CNC manufacturing”, *Computer Aided Design*, Vol.38, No.2, pp540-551, 2006.