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ORIGINAL ARTICLE

A STEP-based machining data model for autonomous process generation of intelligent CNC controller

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Abstract

As the key component of intelligent CNC machine tool, CNC controller is expected to provide various intelligent functions, among which, autonomous process planning is one of the most important functions. However, current machining data models are not very suitable to support this function. G&M code gives movement and auxiliary instructions directly, making the CNC controller just an executor. A new standard STEP-NC, providing semantically rich information, aims to overcome the drawbacks of G&M code. However, information in the data model specified in STEP-NC is not very suitable for intelligent CNC controller autonomous process planning because of the lack of important machining requirements. Also, in STEP-NC model, machining strategies, which are supposed to be decided by CNC controller, have already been included. Namely, decision right is not totally handed over to the controller. To solve these problems, a STEP-based machining data model is proposed in this paper. The machining data model is an ARM, and it is designed as the machining task input of intelligent CNC controller. It can provide necessary workpiece information for intelligent process planning functions based on knowledge base. With the consideration of interoperation with design stage, STEP data format is used in the machining data model. Detailed structure and implementing method is introduced. In order to verify the feasibility of this data model, generation method of machining task complied with this data model and process plan generation based on the machining task have been put forward through a case. Results show the machining task complied with this data model can provide sufficient information for the autonomous process planning function of CNC controller.

Keywords Machining data model · STEP · Intelligent CNC controller · Process planning

1 Introduction

With the rapid development of social economy and information technology, requirement about intelligent manufacturing has been put forward. Machine tool is one of the most important equipments in manufacturing industry. As the brain of machine tool, CNC controller is the key component for realizing intelligent functions.

Among all intelligent functions, autonomous intelligent process planning is one of the most important functions, which can ease human burden and ensure machining quality. Currently, most of the CNC controllers are using G/M code [1] as machining data model, which makes CNC controller just as an executor with no intelligent process planning ability [2]. In order to make CNC controller more intelligent, CNC controller should have the ability to realize autonomous process planning then control manufacturing process according to product design requirements and manufacturing resources.

To realize intelligent process planning, which is a key component of an intelligent CNC controller, not only architecture and process planning method, but also machining data model which gives machining task input should be studied. However, the problem is that there is not a very suitable machining data model which can carry required information to support intelligent process planning function of the CNC

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controller. G/M code focuses on underlying axis movement and auxiliary instruction, which makes it as a bottleneck and cannot fulfill the demands of intelligent CNC systems [3]. STEP-NC data model [4] was proposed two decades before but has not totally handed over decision right to intelligent controller because of the existence of process information and the lack of machining requirements like geometric tolerance and surface quality.

In this paper, a STEP-based machining data model for autonomous process generation of intelligent CNC controller is proposed to solve the problems. This feature-based machining data model is aimed to provide necessary workpiece information as the machining task for the intelligent CNC controller using process knowledge base for process planning, which was introduced in the earlier paper of our group [5].

The rest of the paper is organized as follows. Research background is reviewed from two aspects in Sect. 2. In Sect. 3, requirements of the machining data model are analyzed; according to demands of intelligent CNC controller, an overall structure is presented. Detailed design of the machining data model is illustrated in Sect. 4. Section 5 demonstrates the generation method of the machining task complied with the proposed data model and process plan autonomous generation using the machining task through a case. Section 6 are the conclusions.

2 Research background

CNC machining data model should cover necessary information of the workpiece in order to support intelligent process planning function. In addition, machining data model is the input data model of CNC controllers which describes machining task. Related works on intelligent process planning integrated CNC controller and machining data model are discussed as follows.

2.1 Research on intelligent process planning integrated CNC controller

Processing planning bridges design and manufacturing and has a great influence on processing time, product quality, and cost efficiency. Researches about intelligent process planning method have been carried out to ease the workload of human experts and provide a more efficient, lower cost, better-quality process plan [5–11]. In these researches, rule-based expert system, intelligent algorithms are widely used.

In these rule-based expert systems [6, 7], process knowledge is explicitly represented through rules. However, most developments concentrate on feature recognize and logical reasoning, and lack of dynamical and adaptive learning capability [8]. Given many uncertain and ambiguous even contradictory factors are involved in process planning, substantial expert knowledge is required. It is a heavy work to define rules manually in a rule-based expert system. Therefore, intelligent algorithms such as fuzzy logic [8], artificial neural network (ANN) [9], ~~and~~ genetic algorithm [10], and hybrid approach [11] are adopted in some researches as they can automatically acquire rules through data. However, ANN has advantages in solving small-scale problems; processing planning requires a complex and large network model, which is difficult to develop and train as the machining condition changes. Genetic algorithm is easily trapped in the local optimum and tends to emerge premature convergence. Moreover, these algorithms have narrow applicability and low accuracy because of the fossilization and finiteness of training data. To overcome the training data limitation of traditional process planning methods, intelligent process planning based on big data points out a new direction. Ye et al. presented an approach to design and develop CNC machining process knowledge base using cloud technology, which has ability to deal with ever-growing knowledge effectively by using Hbase and MapReduce [5].

However, most of these intelligent process planning methods are independent of CNC controller. Although machine tools have the abilities for high-speed and high-precision machining these days, because of the lack of intelligent process planning function, CNC controller just executes the process planning result. This means CNC controller not only cannot have a full understand of the machining task, but also do not have enough information to support other intelligent functions. Therefore, it is necessary to integrate intelligent process planning function into CNC controller to reduce the time cost and data loss caused by information exchange between process planning stage and CNC machining stage.

Besides process planning methods, to integrate intelligent process planning function into CNC controller, architecture of CNC controller is crucial. Conventional CNC controller (as shown in Fig. 1) usually uses G&M code, as the machining data model. This makes the CNC controller just as an executer, which exactly executes the underlying command described in G&M code.

In recent years, STEP-NC data model is developed in order to make CNC controller have more intelligent functions including autonomous process planning. STEP-NC compliant controllers can be summarized into three types, as shown in Fig. 2. Most of the proposed prototypes have been reviewed by Xu et al. [12] and Rauch et al. [13].

- CNC controller with STEP-NC interface

This type designed a post-processor, which is used to interpret STEP-NC data model and convert it to G&M code. The designed structure makes conventional CNC control compatible with STEP-NC interface. Wang et al. designed a function-block-based mapping mechanism to accept STEP-NC data and translates it into the type of G-code [14].

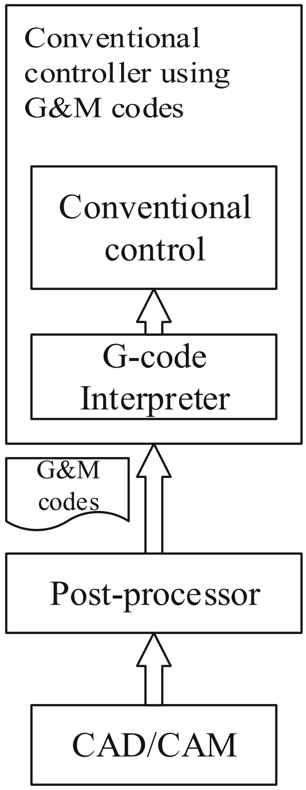


Fig. 1 Conventional CNC controller [18]

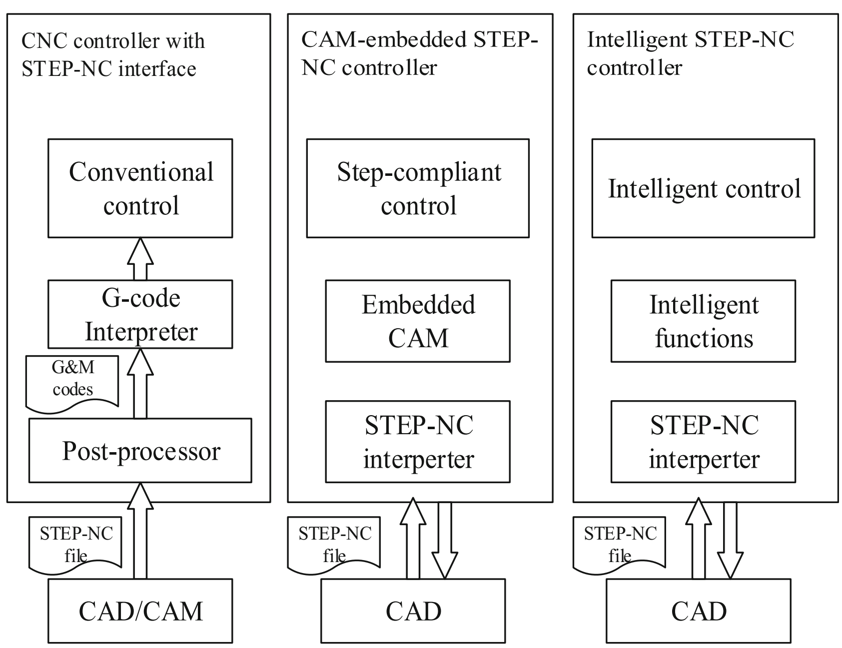
- CAM-embedded STEP-NC controller

In this type of STEP-NC controller, CAM module is embedded. Instead of converting STEP-NC file into G&M code, the controller can directly generate motion instructions according to the processing information and resource information in STEP-NC. Xu presented a STEP-compliant CNC machine tool that demonstrated a G-code free machining scenario [15]. His work mainly included retrofitting an existing machine with CompuCam's control system, which is programmable with 6K motion control language, and development of a STEP-compliant NC converter named STEPcNC.

- Intelligent STEP-NC controller

This controller is designed to perform the machining task autonomously and realize intelligent function including real-time control, integrated active quality control, process planning, and inspection [16], with the support of semantically rich information in STEP-NC file. Some researches about intelligent controllers have been done according to this data model [2, 16–21]. Suh et al. presented a conceptual framework for intelligent CNC controller as a paradigm for STEP-compliant CNC. The architecture was composed of SFP/TPG modules, control modules, and database module [17]. Then, the framework for autonomous STEP-compliant CNC (ASNC) was proposed; through the operational scenario, they showed that the CNC can be "autonomous" by using process sequence graph PSG [2]. Finally, a comprehensive prototype, "Korea STEP-NC" was formed [18], which was composed of five modules: PosSFP [19], PosTPG, PosTPV, PosMMI, and PosCNC. After that, they first presented STEP-compliant CNC system for turning system named TurnSTEP [20]. Zhang presented a conceptual framework of multi-agent-based intelligent STEP-NC controller [21]. In this controller, 14 agents could co-operate closely to carry out various functions including process planning, NCK/PLC, and decision-making.

Fig. 2 Three types of STEP-NC compliant controller [18]



In these three types of controller, although STEP-NC data model with rich CAD/CAM information has been adopted, the first two structures only give support to the new STEP-NC standard and do not have intelligent functions other than tool-path generation. The third structure is expected to perform the machining task autonomously with an efficient mechanism to take full advantage of the semantically rich information of the data model [2]. However, because of the existence of process planning information and lack of necessary machining requirements such as geometric tolerance and surface texture in STEP-NC, the controller does not have full rights for autonomous process planning. In order to integrate intelligent process planning function into CNC controller, a data model which can fulfill complete autonomous machining process planning is needed.

2.2 Research on machining data model

Machining data model is one of the key factors to implement intelligent CNC [17], because the realization of intelligent process planning function is based on the full use of the workpiece information. So far, ISO 6983 known as G&M code still dominates most CNC machine tools. With this data model, the controller faithfully executes NC program in which movement and auxiliary instructions are indicated. Gradually G&M code limits the development of integration and intelligence of CNC system due to its poor portability and interoperability [22].

To overcome the shortcomings of G&M code, STEP-NC is developed by vendors, users and academic institutes all over the world to provide a data model for next generation intelligent CNCs. This new developing standard is an extension of STEP [23] in NC area. ISO 14649 [4] specified the application reference model (ARM) of STEP-NC. The application interpreted model (AIM) of STEP-NC was explained in ISO10303-238 [24]. STEP-NC data model presents information relevant to machining, including geometry description, task description, processing description, and resource description in a hierarchical structure.

STEP-NC has many advantages:

- It provides a data model that is concise and clear and has mechanism to guarantee the data consistency.
- Instead of specifying axis movement, STEP-NC provides a manufacturing feature-oriented data model for representing the processing plan and execution strategy for NC machining with a detailed structured data interface [12]. This semantically rich information could support intelligent functions of CNC controller.
- STEP-NC file uses a natural format, which provides interoperability and could support seamless integration between CAD/CAM/CNC systems.

Based on these advantages, many researches have been done to utilize STEP-NC to realize integration of CAD/CAM/CNC systems and interoperable manufacturing. To support feature-based process planning for interoperable STEP-NC manufacturing, Nassehi et al. developed a software platform entitled integrated platform for process planning and control (IP^3AC) [25]. To support intelligent process control, Kumar et al. proposed a STEP-NC compliant framework, in which self-learning algorithms were used to enable the manufacturing system to learn from previous data and results in eliminating the errors and consistently producing quality products [26]. Zhang et al. developed a STEP-compliant process planning system (PPS) with surface roughness chosen as the process planning object to demonstrate the feasibility of interoperable CNC manufacturing based on STEP-NC [27]. Newman et al. provided a strategic view of how interoperability could be implemented across the CAx chain with STEP and STEP-NC standards [28]. In order to reuse the shop-floor process knowledge, Zhang et al. developed a universal process comprehension interface (UPCi) to interpret CNC part programs written in different languages and represented it into STEP-NC format [29–31]. Suh et al. proposed a method of transforming a G/M code into a STEP-NC file [32].

However, with the trend that autonomous process planning function is integrated into CNC controller, as the input of CNC controller which describes machining task, STEP-NC needs to be extended for these reasons:

- Machining requirements, which make a big difference to process planning, have not been adequately addressed in STEP-NC standard. Mostly because STEP-NC lacks the mechanism to coordinate with other STEP APs such as AP 219 [33] where geometric tolerances are defined. In these years, some researches have been carried out to integrate tolerance information to product data model. Kang proposed a schema to represent tolerance information for process planning [34] and focused on a proper data structure to store various types of tolerance and surface finish data using STEP AP224.
- Although the aim of the standard is to support intelligent functions of CNC controller, decision right has not been fully handed over to the controller because processing information like working steps and machining strategies can also be indicated in a STEP-NC file. For intelligent CNC controller with autonomous process planning, machining strategies are supposed to be decided by the controller, and they are unnecessary input.

To solve problems mentioned above, a new machining data model is required. This paper proposes a machining data model for intelligent CNC controller's autonomous process planning. In this machining data model, necessary workpiece information is represented in a neutral format based on STEP.

Before going into details of the proposed data model, requirement and overall structure of machining data model for intelligent CNC controller are briefly described.

3 Requirement analysis and overall design

3.1 Requirement analysis

In order to meet the requirements of intelligent CNC controller, two aspects should be taken into consideration in machining data model design. First are the essential data items, which cover the need for intelligent decision. The second one is data description format. They are described as in the following.

3.1.1 Essential data items

For intelligent controller to realize autonomous process planning function, first it needs to know what the material and geometric shape of the rawpiece and finished workpiece. Then, the machining process requirement should be given according to the design purpose. Essential data items of the machining data model can be classified as follows:

- Material information. Material of the workpiece to be machined. The material characteristics that have a great impact on process planning should be included.
- Geometry information. Description of the shape of rawpiece and finished workpiece needs to be included. The information should be intuitive and concise for the controller to understand what to machine.
- Machining requirements. Machining requirements include accuracy requirements like dimensional tolerance, geometric tolerance, and surface texture requirement. This information specifies the quality requirements that finished workpiece should meet.

Allover, the data model, which works as the primary basis of process planning, should clearly describe the original and final state of the part to be machined; thus, the intelligent controller could have a full understanding of the machining task.

3.1.2 Data format

Because of the variation of data format, human interpretation is inevitable from CAD to downstream applications such as process planning. While, through a neutral interface, which is independent to resource and platform, data exchange between and manufacturing stage will be much more efficient and interoperability can be improved. Data format about data model includes two parts, data format of data model description and data format of data model implementation.

- The requirement of data model description format is the language adopted to describe the machining data model should be able to represent complex entity clearly with consistent semantics. Considering the diversity and complexity of the parts, data model should have the ability to be easily extended.
- For the data format of data model implementation, which specifies the exchange of information through text files, the interoperability and portability can be improved with the advantages of current standard STEP, which could provide a neutral interface. Meanwhile, it should provide support to implementation of the integration of life cycle bidirectional data flow.

3.2 Overall structure of the machining data model

To fulfill the requirements above, a machining data model exactly for intelligent CNC controller autonomous process planning is designed. The structure of the machining data model is shown in Fig. 3. It is consisted of a workpiece, which describes the finished workpiece information, rawpiece information, the requirement of machining task, and other relevant information. The finished workpiece (hereinafter referred to as workpiece) information, which is described by a set of manufacturing features, is the main body of the data model. Manufacturing features (e.g., cylinder, cone, etc.) are abstracted from geometric shape features and applied as the carrier of machining faces and machining requirement information. Information covered in the model is explained separately as follows:

- *Workpiece information* is the top-level of the machining data model; it describes the general information of machining task. Other information in the model is used to represent workpiece information structurally.
- *Rawpiece information*, which presents shape and geometric dimension and tolerance (GD&T) of rawpiece, is the original status of the workpiece. A recursive description is adopted; the rawpiece is of type workpiece itself, because the rawpiece of this stage might be a workpiece of the last processing stage.
- *Material information* includes the material identifier, standard number, and important property such as yield strength. This information is needed while determining the cutting tool and processing parameters such as cutting speed, because of the difference of machinability according to different materials.
- *Geometry information* describes the underlying geometry and topology information like surfaces, lines, and points; it is an exact description of the finished workpiece geometry.

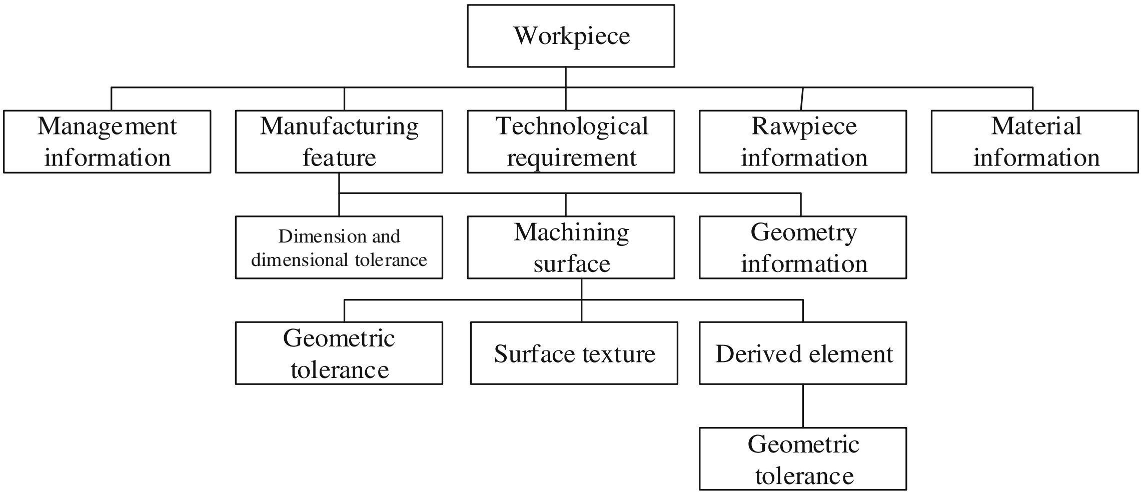


Fig. 3 Overall structure of the machining data model

- *Manufacturing feature information* representing features of a specific shape is abstracted from geometric shape and has manufacturing meaning.
- *Dimension and tolerance information* defines the dimension, dimensional tolerance, and geometric tolerance, which are necessary parameters to do process planning. Dimension and dimensional tolerance information is directly attached to manufacturing features. However, geometric tolerance information is difficult to represent through manufacturing features. They are designed as the attribute of machining surface and derived element.
- *Machining surface and surface texture information* describes machining surfaces in manufacturing features and their surface texture requirements like roughness and waviness.
- *Technological requirements information* such as deburring requirement is used as a note text defined by users.
- *Management information* includes product ID, designer, design date, etc.

With above information, the data model enables required representation of the machining task for intelligent CNC process planning.

4 Design of the machining data model

According to overall structure design of the machining data model for intelligent CNC controller, to represent machining task information concisely and clearly, the data model is defined using EXPRESS. EXPRESS formalized in ISO 10303-11 is a widely used language that can describe the complexity of a 3D object and easily extend the data model. An EXPRESS data model can be defined in two ways, textually and graphically. The graphical representation of EXPRESS data model is known as EXPRESS-G representation. This data model is designed as an ARM to provide a functional view of the data. Detailed data model definition of overall schema, manufacturing feature, geometric tolerance, machining surface, and surface texture are introduced in this section in both EXPRESS-G and EXPRESS representations.

4.1 Overall schema

A schema is designed to describe the whole data model. The simplified overall schema is shown in Fig. 4. To express the machining data model, essential entities are created. The top-level entity is workpiece, which is defined by following EXPRESS statements. It has several attributes such as its_id, its_material, its_rawpiece, its_geometry, its_features, other_technical_requirements, its_management_info, etc., and each attribute refers to corresponding entity.

```
SCHEMA machining data model;
ENTITY workpiece
    its_id: identifier;
    its_material: material;
    its_rawpiece: OPTIONAL workpiece;
    its_geometry: OPTIONAL advanced_B_rep;
    its_features: LIST [0:?] OF manufacturing_feature;
    other_technical_requirements: OPTIONAL SET
    [0:?] OF technical_requirement;
    its_management_info: OPTIONAL management_info;
END_ENTITY;
```

4.2 Manufacturing feature

Manufacturing feature describes region of material removed during processing. It abstracts geometric

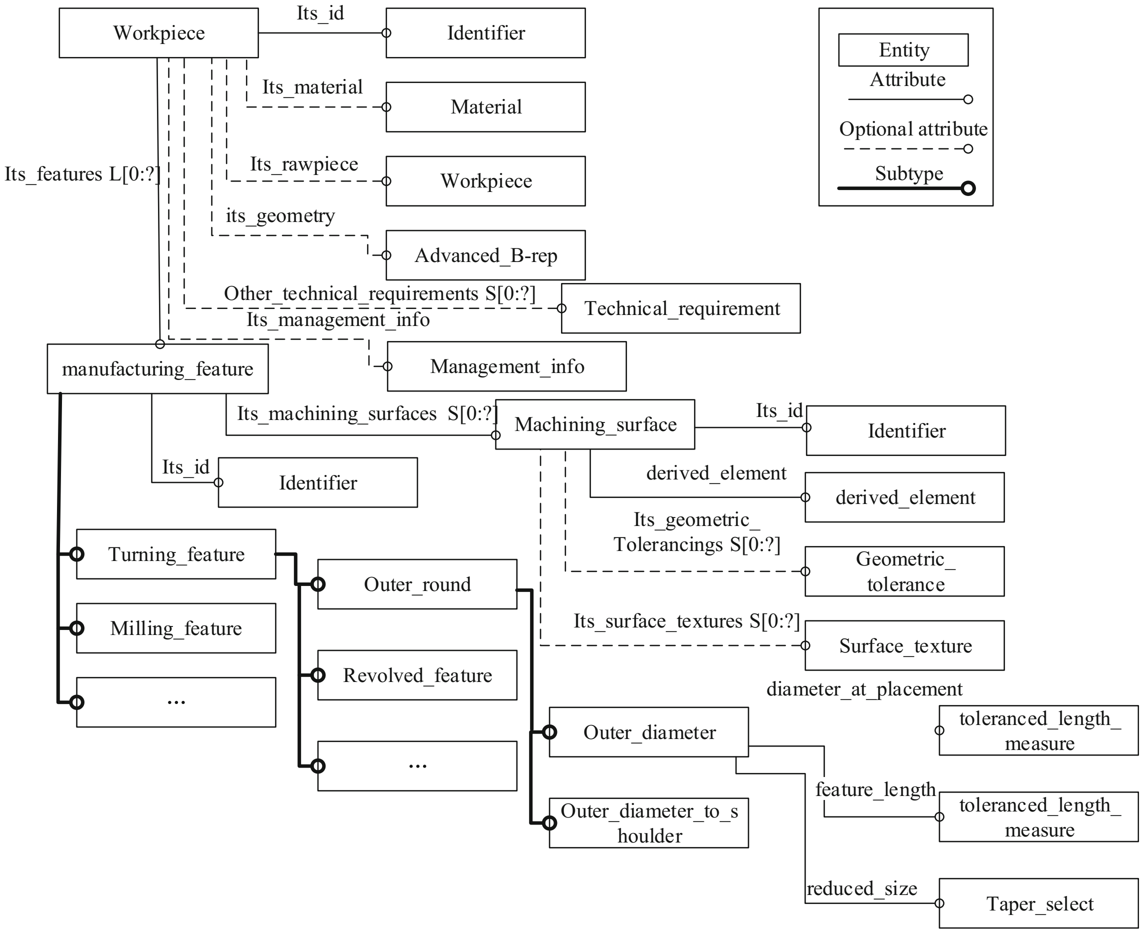


Fig. 4 EXPRESS-G representation of overall schema of the machining data model

information into shape and structure with specific functions and meanings, bridging underlying information and entire product. Besides manufacturing feature is applied as carrier of non-geometric information to express other technical information.

In this paper, commonly used manufacturing features (outer round, planar face, etc.) in STEP-NC are expanded to contain machining surfaces attribute in order to represent machining requirements like geometric tolerance and surface texture. These requirements are closely related to surfaces and difficult to represent through manufacturing features. The main part of the machining data model is workpiece described via a set of manufacturing features.

In Fig. 5, classification and representation of manufacturing features in EXPRESS-G are indicated. Classification and most of the representation of manufacturing_feature in STEP-NC [35] are used. A modification in bold type is that an attribute named its_machining_surfaces is added to supertype manufacturing_feature for all the subtypes can represent geometric tolerance and surface texture through this attribute. Following statements shows the definition of manufacturing_feature in EXPRESS. User-defined features can be created in a similar way.

```
ENTITY manufacturing_feature
ABSTRACT SUPERTYPE OF (ONE OF
(turning_feature, milling_feature));
   feature_placement: axis2_placement_3d;
   its_machining_surfaces: SET [1:?] OF
   machining_surface;
END_ENTITY;

ENTITY turning_feature
ABSTRACT SUPERTYPE OF (ONE OF
(outer_diameter, revolved_feature))
SUBTYPE OF (manufacturing_feature);
END_ENTITY;
```

4.3 Geometric tolerance

Geometric tolerance consists of two parts: form tolerance and position tolerance. As important processing accuracy information, it is one of the basis of process planning and have a great influence on product performance. Therefore, it is necessary to include geometric tolerance information in the machining data model according to the standards.

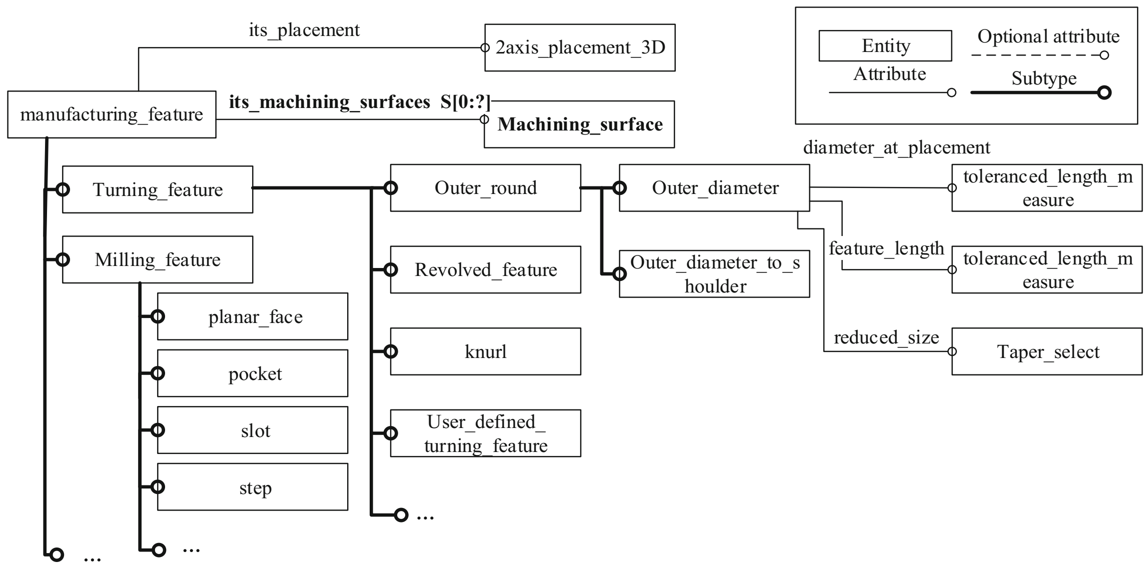


Fig. 5 EXPRESS-G representation of manufacturing feature

Geometric tolerance information contains measured feature, type of tolerance, tolerance value, datum reference frame and material conditions modifier. As show in Fig. 6, a proper structure is designed to represent inheritance and attributes of entity geometric_tolerance.

Geometric tolerance's measured feature, which is specified in attribute of_shape, can be divided into machining surface and derived element such as central axis which is derived from cylinder surface or cone surface. Therefore, entity shape_aspect is introduced, which has two subtypes, machining_surface and derived_element.

According to whether or not to refer to the datum, measured feature of geometric tolerance can be divided into two types: single feature and related feature. They have obvious difference in expression. For some of the form tolerances such as straightness, flatness, roundness, and cylindricity, they have single measured feature that is given to geometric tolerance according to itself, and the tolerance type and tolerance value can be directly specified. However, position tolerances like parallelism, coaxially, which have related measured features, not only tolerance type and tolerance value need to be specified, but also an attribute named it_datum which describes related measured features should be specified.

To represent datum, concepts of machining surface and its derived element are also applied. The datum of a related measured feature could be a machining surface, a derived element of a machining surface, or a datum system consisted of a set of machining surfaces or derived elements. An entity named datum_system is defined, which has three attributes, primary_datum, secondary_datum and tertiary_datum. These attributes are of type datum_select defined in following EXPRESS statement, which means the datum can be a single datum consist of single shape_aspect or a union datum consist of two or three shape_aspects.

```
TYPE datum_select=SELECT (single_datum,
union_datum);
END_TYPE;

ENTITY geometric_tolerance
ABSTRACT SUPERTYPE OF (form_tolerance,
position_tolerance);
   its_id: identifier;
   of_shape: shape_aspect;
   its_value: OPTIONAL geometric_tolerance_measure;
   its_modifier: OPTIONAL material_conditions_modifier;
WHERE
   Wr1: SELF IN of_shape. its_geometric_tolerances;
END_ENTITY;
```

4.4 Machining surface

As the carrier of information of geometric tolerance and surface texture, machining surface need to be identified, therefore entity named machining_surface is defined in Fig. 7. Express statements is as follows. Attribute of_feature shows to which manufacturing feature the machining face belongs. Its_geometry is an optional attribute to describe the geometric information using B-rep when a manufacturing feature have several machining surfaces. Its_geometric_tolerances and its_surface_texture represent a set of requirements about geometric tolerance and surface texture of the machining surface.

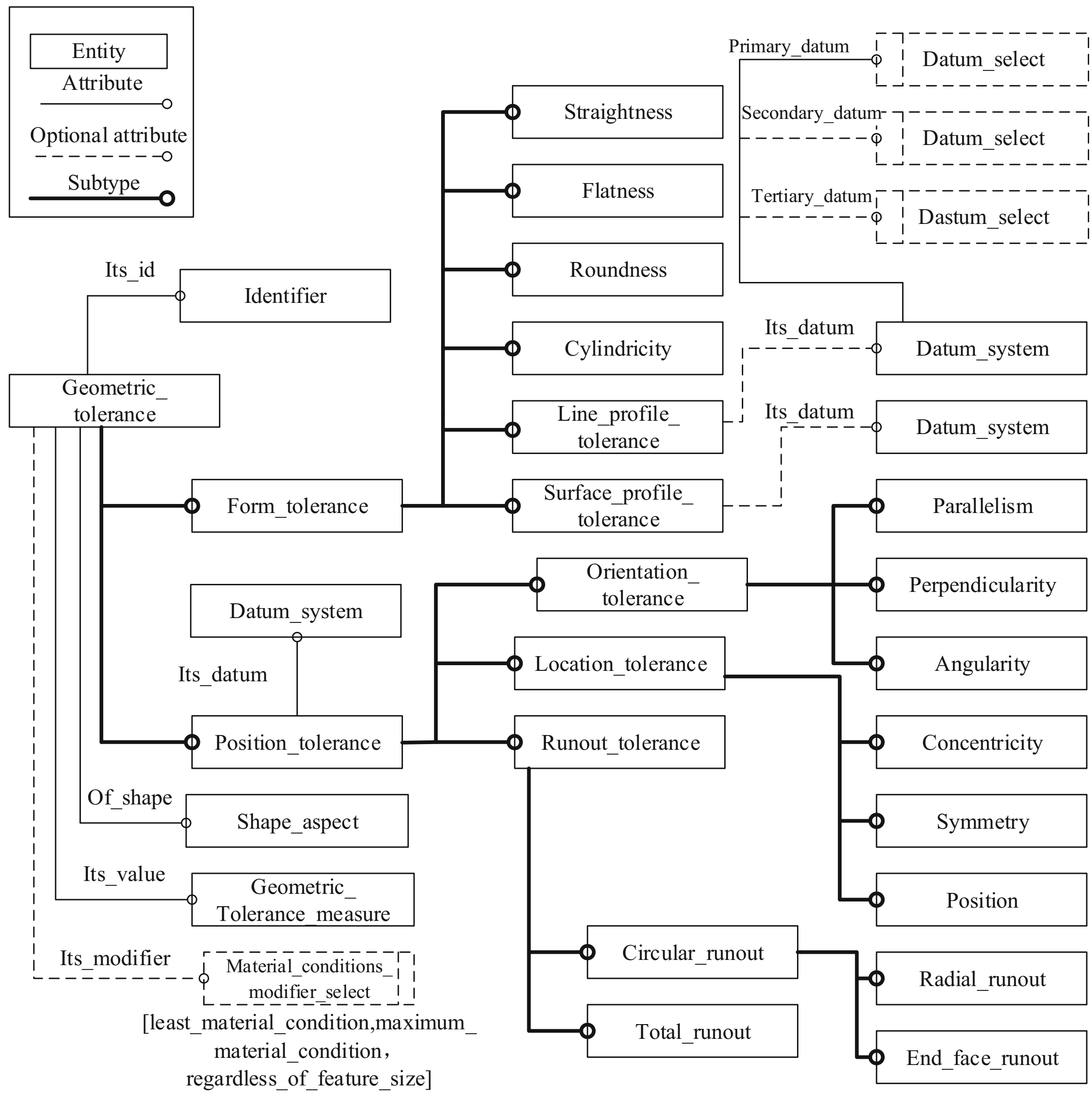


Fig. 6 EXPRESS-G representation of geometric tolerance

Derived element of machining surface such as axis of cylindrical and conical surface are important datum feature; thus, entity named derived_element is defined as an optional attribute of machining surface, which can be used as datum for geometric tolerance representation and also represent the geometric tolerance requirements of derived features. Following EXPRESS statements are the definition of derived_element, in which a domain rule is applied to ensure dependent existence of derived features. A similar rule is used to guarantee the consistency of manufacturing feature and its machining face.

```
ENTITY machining_surface;
   its_id: identifier;
   its_geometry: OPTIONAL advanced_face;
   of_feature: manufacturing_feature;
   derived_element: OPTIONAL derived_element;
   its_geometric_tolerances: OPTIONAL SET [0:?] OF
   geometric_tolerance;
   its_surface_textures: OPTIONAL SET [0:?] OF
   surface_texture;
END_ENTITY;

ENTITY derived_element
ABSTRACT SUPERTYPE OF (ONE OF (central_axis,
central_plane));
   of_shape: machining_surface;
   its_geometric_tolerances: OPTIONAL SET [0:?]
   geometric_tolerance;
WHERE
WR1: SELF: =:of_shape.derived_element;
END_ENTITY;
```

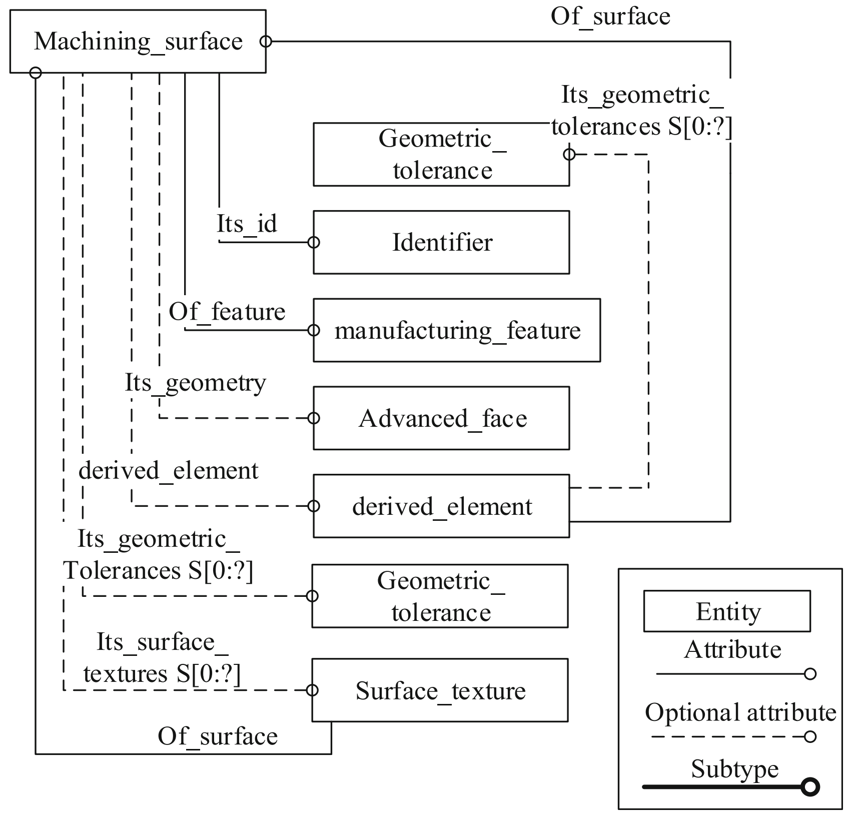


Fig. 7 EXPRESS-G representation of machining surface

4.5 Surface texture

Surface texture describes the macroscopic and microscopic geometrical characteristics of surface, has great influence on part performance in aspects of friction, wear, fit function, and fatigue resistance. Therefore, it is necessary to consider requirements of surface texture while machining a workpiece. Lay, which represents the direction of predominant surface pattern, is one of the important characteristics of surface texture. Another characteristic is surface profile, which can be divided into primary profile, roughness profile, and waviness profile, by the profile filter which specify the transmission band of profile. Each of these profiles have several parameters to control the surface texture. Therefore, entity surface_texture is divided into two subtypes: lay_pattern and surface_profile, as shown in Fig. 8.

According to the direction of predominant surface pattern, Lay_pattern is classified into six subtypes: parallel, radial, cross-hatched, circular, multi_direction, and particulate. Surface_profile has three subtypes: primary_profile, waviness_profile, and roughness_profile. They are classified through attribute its_fliters. Its_sampling_length and its_evalation_length separately specify the sampling length and escalation length of surface profile. Attribute its_parameter gives the requirement value of evaluation parameter of surface profile.

The representation and storage of profile parameter can be achieved in two ways, one is to store the profile parameter data as plain text using user-defined parameters, and the disadvantage of this approach is that meaning of each position must be clear when the text is submitted. The other way is to extend the data model to the definition of profile parameter, in this way user can clearly understand the meaning once the schema is referenced.

In this paper, the second approach is applied. For the commonly used surface texture parameter, such as max height of profile, arithmetical mean deviation of profile, and mean width of profile, the machining data model is extended to include its definition. Following EXPRESS statements clearly defines surface_texture, surface_profile, and profile_parameter.

```
ENTITY surface_texture
ABSTRACT SUPERTYPE OF (ONE OF
(surface_profile, lay_pattern));
   its_id: identifier;
   its_surface: machining_surface;
END_ENTITY;

ENTITY surface_profile
ABSTRACT SUPERTYPE OF (ONE OF
(primary_profile, waviness_profile, roughness_profile))
   its_sampling_length: OPTIONAL length_measure;
   its_evalation_length: OPTIONAL length_meausre;
   its_fliters: OPTIONAL SET [1:2] profile_filter;
   its_parameters: SET [1:?] OF profile_parameter;
END_ENTITY;
```

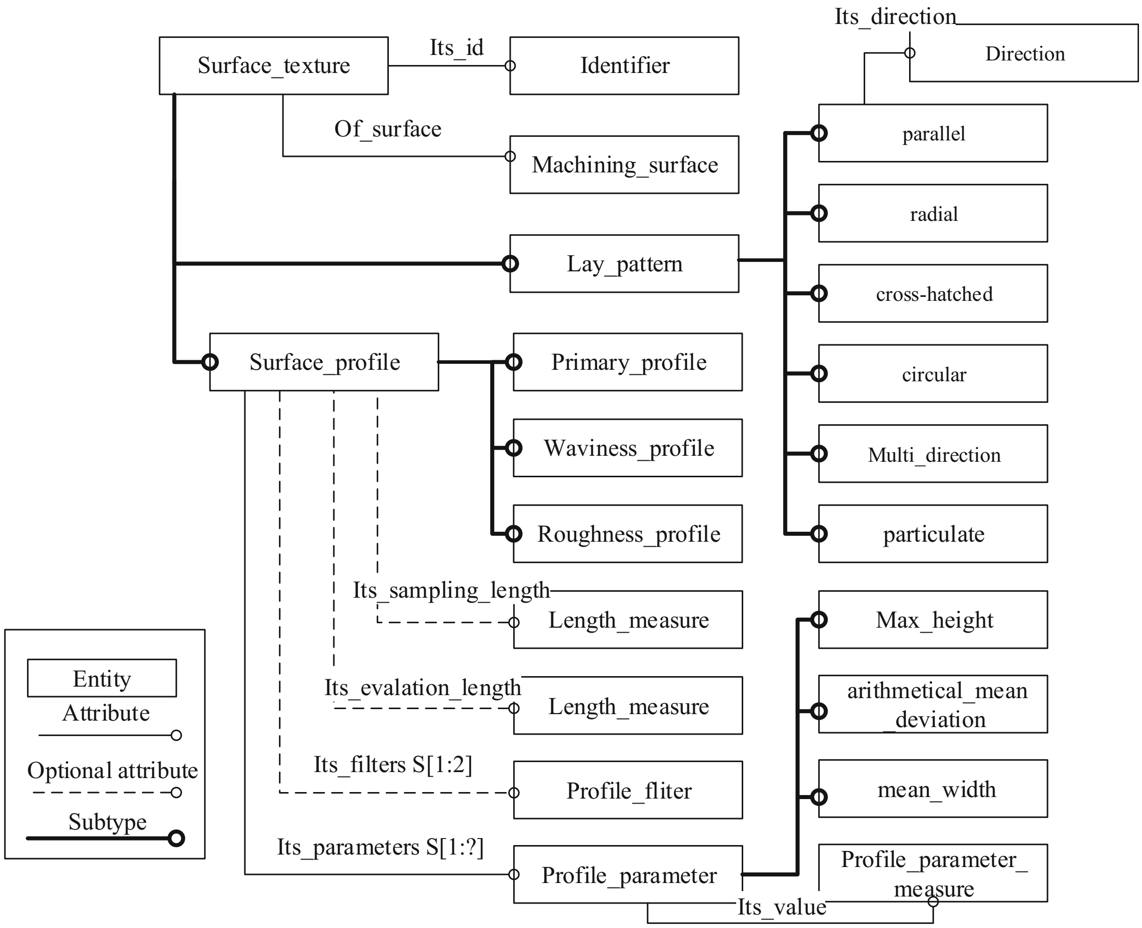


Fig. 8 EXPRESS-G representation of surface texture

ENTITY profile_parameter
ABSTRACT SUPERTYPE OF (ONE OF (max_height, arithmetical_mean_deviation, mean_width))
its_value: profile_parameter_measure;
END_ENTITY;

Through the above method, the EXPRESS machining data model for intelligent CNC controller is established. However, the EXPRESS model is a concept information model; information exchange depends on underlying implementing method, which is explained in the next section.

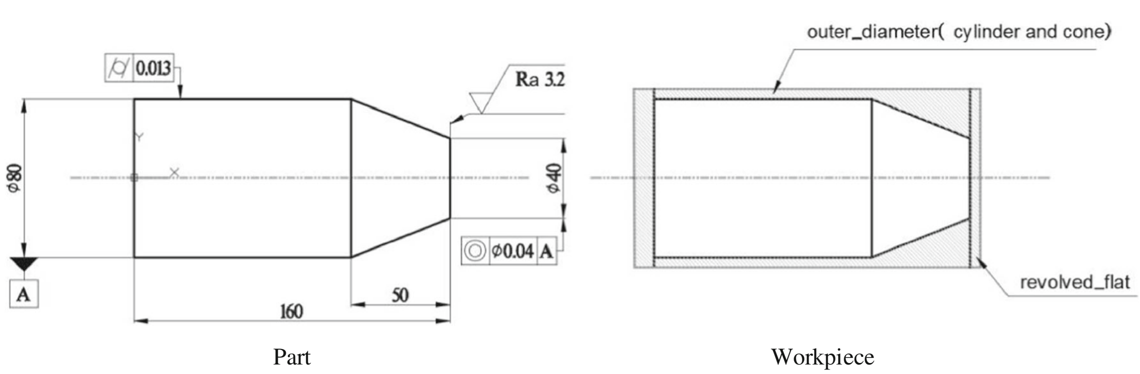


Fig. 9 Designed part and its workpiece

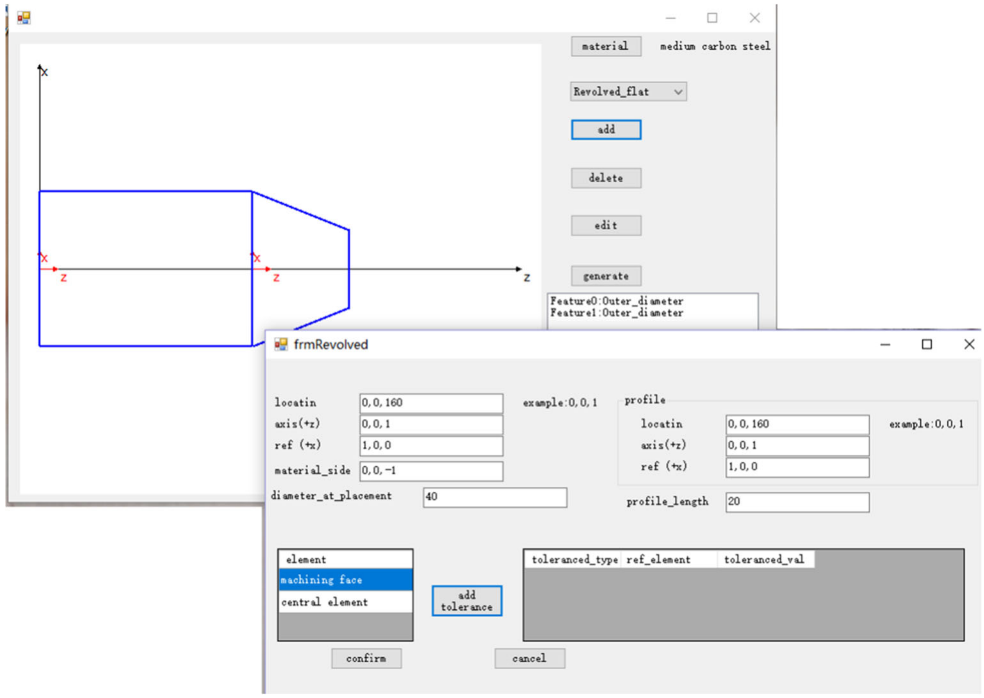


Fig. 10 User interface of data generator

5 Case study

In order to verify the feasibility of this data model, generation method of machining task complied with this data model and process plan generation based on the machining task have been put forward through a case. The workpiece, as shown in Fig. 9, is consisted of three manufacturing features with roughness, dimensional tolerances, and geometric tolerances including both self-reference and cross-reference.

Fig. 11 Description in machining task file

```
HEADER;
FILE_DESCRIPTION(('ISO14649','SIMPLE EXAMPLE'),'1');
FILE_NAME('EXAMPLE.STP','2017-9-20',('ZHU WEN DAN'));
FILE_SCHEMA(('MACHINING_DATA_MODEL'));
ENDSEC;
DATA;
......
/*manufaturing features*/
#5=OUTDIAMETER('Feature0:Outer_diameter',#0,#7,(#2),80,80,#10,$);
#15=OUTDIAMETER('Feature1:Outer_diameter',#0,#17,(#11),80,40,#20,$);
#24=REVOLEVED_FLAT('Feature2:Revoleved_flat',#0,#26,(#21),#29,40);
/*machining surfaces*/
#2=MACHINING_SURFACEFACE('Feature0:Outer_diameter:machining face',$,#5,#3,$,(#4));
#11=MACHINING_SURFACEFACE('Feature1:Outer_diameter:machining face',$,#15,#12,$,(#13));
#21=MACHINING_SURFACEFACE('Feature2:Revolved_flat:machining face',$,#24,#22,$,(#23));
/*derived elements*/
#3=CENTRAL_AXIS('Feature0:Outer_diameter:axis',#2,$);
#12=CENTRAL_AXIS('Feature1:Outer_diameter:axis',#11,(#14));
#22=CENTRAL_AXIS('Feature2:Revolved_flat:axis',#21,$);
/*geometric tolerance*/
#14=CONCENTRICITY('Feature1:Outer_diameter:axis:concentricity',#12,0.04,$,#3);
/*surface texture*/
#4=ROUGHNESS_PROFILE('ROUGHNESS_PROFILE0',#2,$,$,$,#35);
#13=ROUGHNESS_PROFILE('ROUGHNESS_PROFILE1',#11,$,$,$,#36);
#23=ROUGHNESS_PROFILE('ROUGHNESS_PROFILE2',#21,$,$,$,#37);
#35=ARITHMETICAL_MEAN_DEVIATION(12.5);
#36=ARITHMETICAL_MEAN_DEVIATION(12.5);
#37=ARITHMETICAL_MEAN_DEVIATION(3.2);
......
ENDSEC;
END-ISO-10303-21;
```

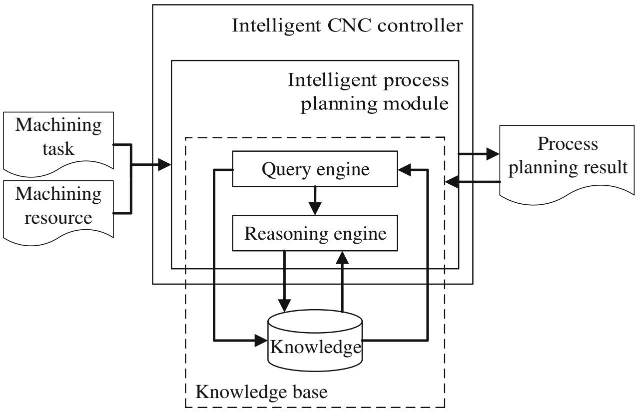


Fig. 12 Workflow of the intelligent CNC controller

5.1 Data generation

The implementation method of EXPRESS schema defines what type of exchange behavior is required to this data model. STEP file, an exchange structure named STEP format specified in ISO 10303 Part 21 is adopted because of its sufficient syntax, which never repeats same information, therefore avoiding contradictions.

In STEP file, the structure is complex due to nested and referred entities, which means feasibility of manual writing is low. As an information description language, EXPRESS cannot be used for programming and its implementation depends on the combination with other complier languages. In this case, data types of EXPRESS are mapped into C# data types. For example, entity in EXPRESS is mapped into a new class of C#, the attributes of entity are mapped into data members of the class, and constraint rules are mapped into member methods.

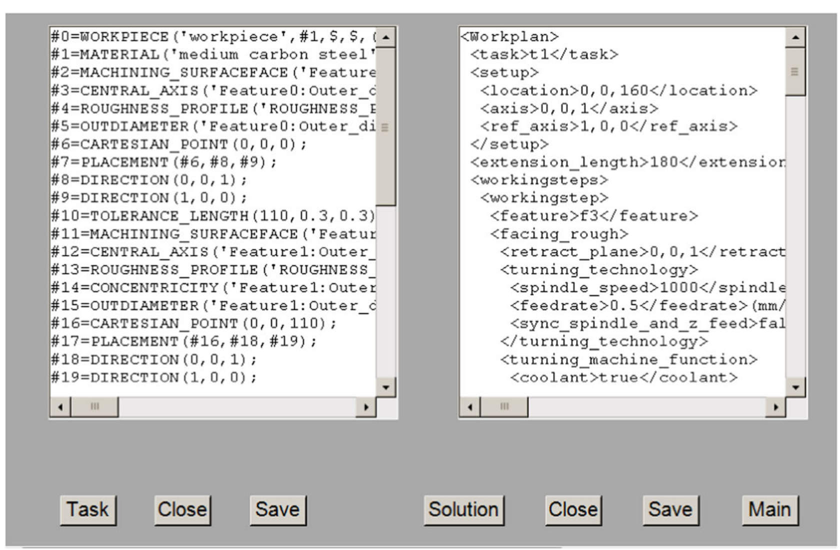
With the method above, a data generator is developed which gets part information by means of man-machine interfaces (as shown in Fig. 10), implements data model defined in EXPRESS using STEP format and finally generates machining data complied with the proposed data model.

After generator received input product information, a STEP file in Part 21 format is created. In this file, description of manufacturing features, machining surfaces, and their requirements are shown in Fig. 11. Once a physical STEP file of this machining dada model is generated, intelligent CNC controller can proceed with process planning according to machining task in this file and resource description. This will be illustrated in following section.

5.2 Using machining data model in intelligent CNC controller

In previous work of our group, an intelligent CNC controller was designed to verify the autonomous process planning ability with the help of process knowledge base [5]. This controller is adopted to test the feasibility of the proposed data model. The workflow of the controller, which use machining data model as the machining task for process planning, is shown in Fig. 12. After the machining task (as shown in Fig. 11) is generated and delivered to intelligent CNC controller, another file that contains resource description is also submitted to the controller. These two files are converted to required format and then sent to knowledge base by process planning module of intelligent CNC controller. After a series of query and reasoning, knowledge base generates a processing plan result, also called a solution, and then delivers it to process planning module, as shown in Fig. 13. After the solution is derived, the controller controls machining according to the process planning result, as shown in Fig. 14.

Fig. 13 Solution obtaining interface of the intelligent CNC controller



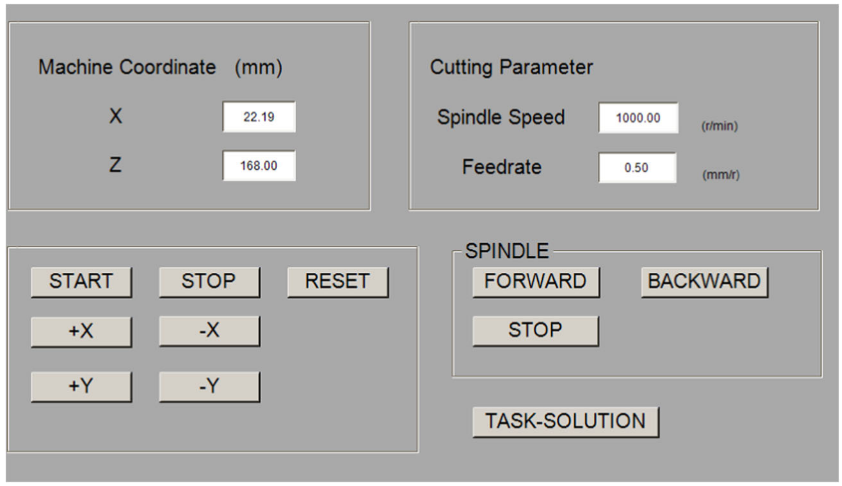


Fig. 14 Machining control interface of the intelligent CNC controller

In this case, the machining task which complied with the proposed data model provides sufficient information for intelligent process planning. Its capability to support intelligent CNC controller for autonomous process planning is proved. However, compound cases may be substantially more difficult to resolve, the data model used an object-oriented framework, with good expandability. When it comes to complex workpiece, the data model can be extended with user customized interface.

6 Conclusions

In this paper, a machining data model is designed as the machining task input which provides necessary workpiece information for autonomous process planning functions of intelligent CNC controller. This data model is defined in EXPRESS language and implemented in STEP format, which could provide support for realization of interoperability with CAD systems in the further. Through a case study, the feasibility of the proposed data model has been verified from two aspects: generation of machining task complied with this data model and process plan autonomous generation based on the machining task.

With this semantically rich data model, workpiece information and machining requirements can be clearly represented in machining task, a proper data structure is also designed for information expression. It provides support from machining data model aspect for intelligent CNC controller using knowledge base for process planning to understand the machining task and perform autonomous process planning according to machining requirements, which makes it possible to hand over the process planning right to intelligent CNC controller.

In the future, the interoperability can be realized by adding a plug-in to CAD system, in order to make easy generating of the proposed data model. Also, in order to support future intelligent manufacture mode, feedback information from machining stage can also be interpreted by such kind of plug-in of CAD system. Besides, online measurement-related information are not considered in our current research stage. In the future, corresponding support might be added to this data model. Perhaps other research can be done based on this data model to make it suitable for wider range of applications.

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