THE REPRESENTATION AND EXCHANGE OF MATERIAL AND OTHER ENGINEERING PROPERTIES

Norman Swindells

Ferroday Limited, 14 Mere Farm Road, UK-Birkenhead, CH43 9TT
Email: ns@ferroday.co.uk

ABSTRACT

The representation of information and its exchange in a communication requires the use of a common information model to define the semantics and syntax of the representation and a common dictionary to define the meaning of the data items. These fundamental concepts are the basis of the new standard ISO 10303-235: 'Engineering properties for product design and verification' for the computer representation and exchange of material and any other engineering properties of a product and to provide an audit trail for the derivation of the property value. A related dictionary conforming to ISO 13584 can define testing methods and their properties and enable the information model to be used for any property of any product.

Keywords: Materials properties, Data representation, Data exchange, Materials informatics, International standards

1   INTRODUCTION

Engineering properties are essential information for design and manufacturing processes and play an increasing role in the management of products throughout their life-cycle, including the end-of-life phase. For these reasons it is necessary to be able to communicate the information about the meaning of these properties and their values efficiently and without ambiguity among many different software programs and to retain this information for the lifetime of the product, independently from any proprietary software.

The fundamental requirement for the communication of information in a natural language is the combination of a common information model and a common dictionary. The information model for a natural language is the structure of the sentence and words are the data items that provide an instance of this model to represent the particular information that is to be communicated or exchanged. The structure of the information model is defined by the grammatical rules for a sentence that are particular to the natural language. The application of this model structure enables the recipient of a communication to correctly interpret the roles of the data items in the structure, and the dictionary can be used to extract the meaning of the information that the data stream represents. If the recipient uses a different dictionary or a different information model from that used by the sender, then the interpretation could either be different or fail. To achieve unambiguous communication, all the members in a communication chain must use the same information model and the same dictionary.

The intellectual achievement of the global project managed by Technical Committee 184/Sub-Committee 4 of the International Organization for Standardization (ISO TC184/SC4) has been to show that this combination of an information model and a dictionary is also fundamental for the representation of technical engineering information and for its communication among different computer software systems. This global project, with cooperation between all of the world's major manufacturing nations and most of its industrial sectors, has developed a collection of standards for the representation and communication of engineering product data with the generic title of *product data technology*. The standards produced by ISO TC184/SC4 are developed by a very rigorous, formal procedure, subject to extensive validity checks, quality control procedures, and approved by international ballots.

The subject of this paper is a solution to the representation and communication of material and other engineering property data by a new application of the combination of two of these standards:

- ISO 10303 Product data representation and exchange – a large collection of entity-relationship models for the representation of data from individual products and processes throughout the whole product life cycle and their archiving for data conservation (International Organization for Standardization, 1994).

- ISO 13584 Parts library – an information model for the classification of products and their properties (International Organization for Standardization, 2001).

ISO 10303 also includes the technology for product data representation and exchange that is also used by ISO 13584. All of these standards are written in EXPRESS (International Organization for Standardization, 2004; Schenk & Wilson, 1994). EXPRESS is an object oriented modelling language that is fully supported by both open-source and commercial software tools. EXPRESS model schemas can be converted into XML or referenced by modern web methods, and standard data access interfaces to existing software systems can be developed in Java, C++ and other languages. Instances of EXPRESS schemas can be exchanged as a data file with a format conforming to ISO 10303-21 Ed 2 (International Organization for Standardization, 2002) or archived for long term storage because the semantics and the syntax of the information are conserved in the standard.

Information models in the ISO 10303 family are of two main types:
- Integrated Generic Resources (IGR) - a single information model, but published in several parts, for the representation of basic concepts in engineering and manufacturing;
- Application Protocols (AP) - extensions of the generic resources model to meet the requirements of representation and exchange in specific industrial situations.

ISO 10303-45 Ed 2: Material and other engineering properties (International Organization for Standardization, 2008) is a part of the IGR that is a model for the representation for any property of a product and its value. ISO 10303-235: Engineering properties for product design and verification (International Organization for Standardization, 2009) is an Application Protocol that extends the IGR to represent the collection of processes by which a value of a product property is obtained.

2   QUANTITIES AND PROPERTIES

It is important to distinguish between quantities and properties. A quantity is an amount of something that can be expressed as a multiple of a unit amount, e.g. 1MPa x 35. A property indicates the behaviour or characteristic of something. The measure of the value of a property can be described quantitatively – by measuring a quantity, e.g. 35 MPa, or qualitatively – by a using a description, e.g. 'strong', or 'blue'.

The meaning or semantics of a property will be defined by the particular process required for its measurement, and a property may describe the behaviour of either a product or a process. A quantity can be defined independently, but a property cannot be independent since it is related to the process of its measurement and to the object that it describes.

There are two types of quantitative properties:
- simple – by making a comparison with a standard quantity (length, time, weight, voltage, etc) different measurement methods produce the same result;
- complex – where the meaning of the property is defined by the measurement method (e.g. hardness, fracture, creep strength) and different measurement methods create different properties.

In both types, the measure of the value of a property will depend on the conditions of the measurement process – the data environment. Communicating the value of a property without also specifying the data environment reduces the meaning of the measure value and its validity.

3   PROPERTIES OF A PRODUCT

ISO 10303-45 is the entity-relationship model that is the part of the IGR that defines a property representation explicitly as a property of a product. The representation of a property of a process is defined in ISO 10303-49 (International Organization for Standardization, 1998). The first edition of ISO 10303-45 was derived from experience of the testing of, so-called, 'materials' properties, and the terminology used in the standard reflects this experience. However, the information modelling of an engineering material, such as alloyed steel or high density polyethylene, is no different from the information modelling of a 'product'. The 'material' properties are therefore one of the characteristics of a product, just as its shape and other characteristics are. Therefore all 'materials' are products, and the information model in ISO 10303-45 can be used for any property of any product. The properties defined by ISO 10303-45 could be the aerodynamic properties of an aircraft wing, for example. The title of the second edition of ISO 10303-45 was therefore extended to include other engineering properties although the terminology in the body of the standard still refers to material properties for reasons of compatibility with implementations of the first edition. The first edition of ISO 10303-45 was reviewed in detail by Swindells (2000).

ISO 10303-45 consists of three schemas:

- material_property_definition_schema – defines a material property as a property of a product or a part of a product and specifies that an instance of a material property must have a data environment. The schema also provides entities for defining the chemical composition of the product and enables a materials designation to be described and linked to either a composition or a property.

- material_property_representation_schema – defines the representation of a material property and the conditions under which a property representation is valid (the data environment).

- qualified_measure_schema – allows representations of measure values to be further characterized as to their uncertainty and reliability and includes descriptive measures. The schema in the second edition of ISO 10303-45 provides the resources to describe the value of a measure by a mathematical expression and also to specify the uncertainty and reliability of this expression.

The partial information model from ISO 10303-45 for the representation of a material property and its relation to a product is illustrated in Figure 1. The model is presented in the graphical form of EXPRESS, defined in Annex D of ISO 10303-11. Engineering concepts are represented as information objects by entity data types and are identified with the name of the concept within a boundary of a solid line. Entities have attributes, and the values of some attributes will be a reference to another entity. References by attributes to other entities are shown as a thin line with a circle at the end of the line where the reference terminates. References to subtypes of entities are indicated with thick lines. Most entities have a name, a label, and a description, but only the names of the attributes that make reference to another entity are shown in this diagram. Constraints on the meaning of entities and attributes can be defined by formal rules, but these are not displayed in the graphical form of EXPRESS. Objects with boundaries of a broken line are select data types that allow for alternative entities to be referenced.
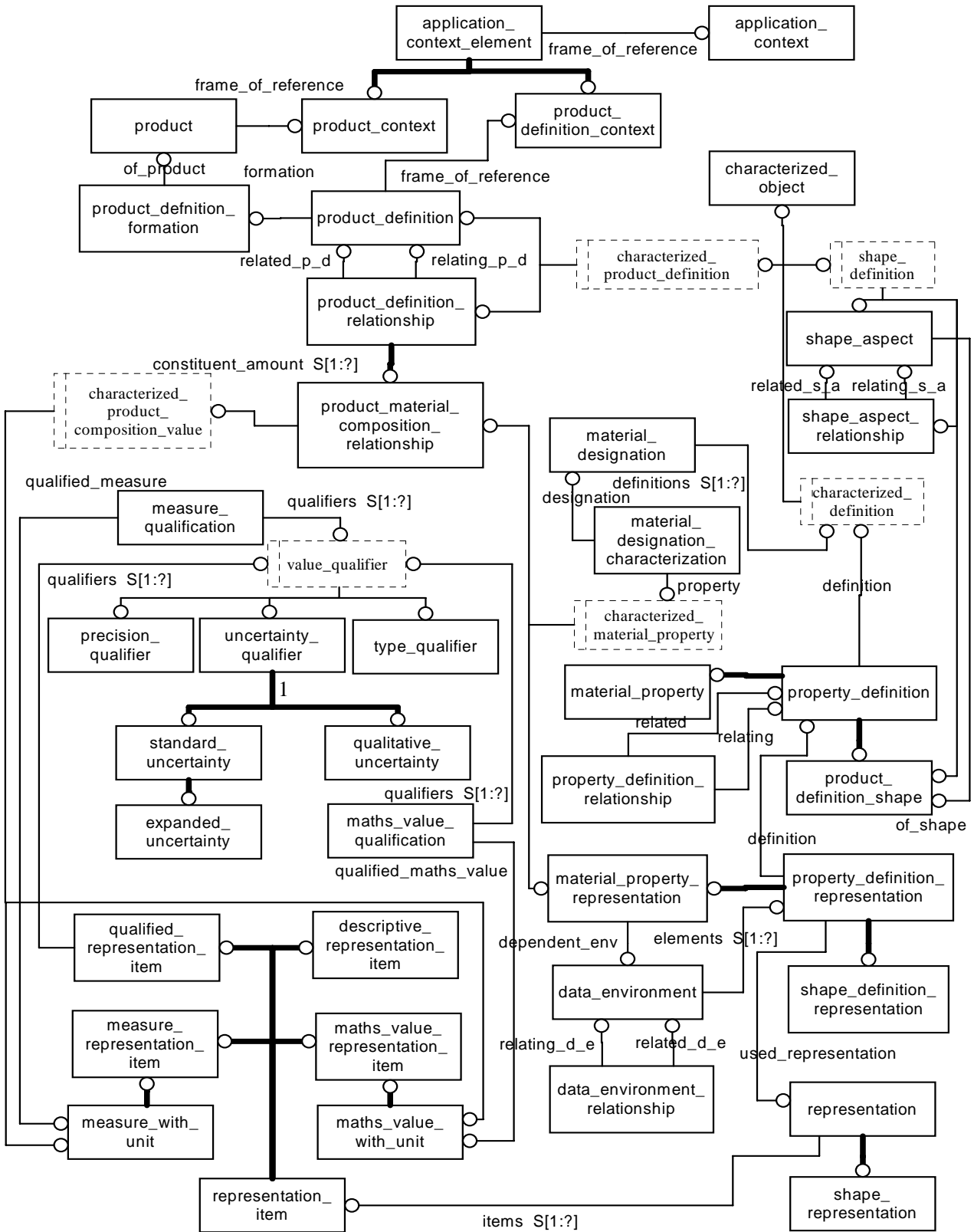
Figure 1. Graphical presentation of the information model for the representation of a property of a product

4   MEASUREMENT OF A PROPERTY VALUE

The determination of the value of an engineering property of a product is the result of a sequence of processes, and the representations of these processes, their supporting activities, and their results are standardised in ISO 10303-235: Engineering properties for product design and verification. The basis of ISO 10303-235 is the information model for a process that is illustrated in Figure 2.
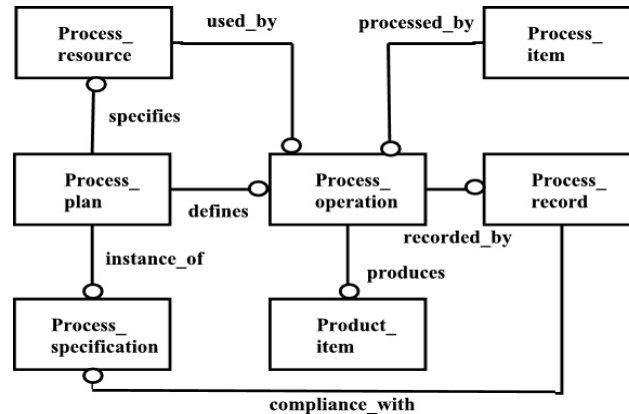

Figure 2. Information model for any process

The sequence of processes that are needed to determine an engineering property is shown in Table 1.

Table 1.   The sequence of processes to determine an engineering property of a product

Process	Input	Output
sampling	product for testing	sampled product
manufacture	sampled product	testable sample
testing method	testable sample	test result value
test evaluation	test result values	evaluated values
data reduction	evaluated values	reduced data value
test and data evaluation	reduced data value	approved data
test certification	approved data	test certificate for product

Manufactured products may not be in a convenient form for testing, and not all of the items in a batch of products will be tested for quality control and quality assurance. Therefore there needs to be a sampling process conforming to a specified procedure. A manufacturing process may be needed to transform the sample of the product into a specified shape for use in the testing method, such as a uni-axial tensile test. The outcome of the test should be evaluated to confirm that the test process was valid. The results of a series of tests may be processed to provide a reduced value, such as a mean and standard deviation, for reporting purposes. Testing procedures are usually specified by a quality manual, and therefore the whole sequence of processes should be evaluated to confirm that the requirements of the quality control process have been satisfied. The approved data resulting from this evaluation may be entered into a test certificate that would accompany the product for the assurance of the customer.

The scope of ISO 10303-235 is able to represent all of the processes in Table 1 and their outcomes and is briefly summarised in Table 2. The relationships of the objects along the rows and between the two columns are not significant, and this is not the complete scope.

Table 2. Partial summary of the scope of ISO 10303-235

Technical concepts	Administrative concepts
Product	Date, time, persons, organization, addresses
Property	Approvals, qualifications, certifications
Processes	Documents and files
Numerical values	External references
Mathematical values	Effectivity
Uncertainty and reliability	Language
Product Substance	Location
Substance Structure	Requirements
Tolerances, State	Resources

The entity-relationship model in ISO 10303-235 is sufficiently general to apply to any property of any product. There are thousands of names of properties and testing methods, and it is not possible to include all their possible names and definitions in the model. Therefore there is a benefit of having a computer-understandable dictionary of names of testing methods and properties that is accessible from the entity-relationship model. This approach means that there can be one software implementation of the entity-relationship model but many dictionaries for the different knowledge domains or industrial systems in which the model can be applied.

5   DICTIONARIES OF PROPERTIES

ISO 13584: Parts libraries (known as PLIB) were conceived as a standard for the representation of classifications of collections of products, as the name implies. PLIB uses an information model, defined in EXPRESS, which is specified in ISO 13584-42 (International Organization for Standardization, 1998). The most important consequence of using a standardized information model for the representation is that other classifications that conform to the same model can be combined. So concepts shared between two knowledge domains need only to be defined once in one classification and then can be referenced from the classification in the other domain. The capability to reference one classification from another was used successfully in ISO 13399: Cutting tool data representation and exchange (Nordström & Swindells, 2007).

The information model for ISO 13584 defines a classification of objects that is organised on the basis of their properties. Items in the classification can be super-classes of objects that have some properties in common, and the association with the common properties is defined at the level of the super-class. Objects can be classified as sub-parts (feature classes) of other objects in order to be able to specify the properties of the feature. For example, a thread is a feature of a bolt, and the thread has its own set of properties that are independent of the other properties (length, diameter, head shape, etc) of the bolt. However, a thread cannot exist in isolation from a bolt.

Because the model for the classification defines the names and definitions of types of objects and their properties, ISO 13584 also plays the role of a computer-understandable dictionary, and this is the important aspect that is needed for ISO 10303-235. Protocols for accessing such a dictionary from information models specified in ISO 10303 have therefore been agreed and standardised, and this capability has been incorporated in ISO 10303-235. In the earliest models developed for ISO 10303, the names and definitions of the data items – the dictionary – were built into the models.

The innovation in the use of ISO 13584 to provide the information model for a dictionary for ISO 10303-235 was to recognize that the types of objects in the classification could be measurement processes because, as argued in Section 2 above, types of properties are associated with the testing methods that simulate the behaviour which the property represents.

A dictionary of the names of testing methods and their properties therefore consists of a classification of measurement processes together with the properties that are associated with each class of method. Some methods, e.g. uniaxial tensile testing, generate several properties from each application of the method. Each class of measurement method in the dictionary has: a name, a short name, a definition, and up to three alias names. Each record of a process in the classification is identified with a unique identifier code, a version number,

and a revision number. The source of the definition can be identified together with the dates of the original record and any subsequent revisions. The identification code can be made unique, and a dictionary can have variants in different natural languages.

Properties can be defined as visible properties at the highest level of the classification and are then made applicable to the appropriate process. Each property has a name, a short name, a definition, and a symbol. Up to three alias names and symbols can be specified. The units of the property value can be defined, and the property can be illustrated with a diagram. Each record of a property is identified with an identification code, a version number, and a revision number. The source of the definition can be identified together with the dates of the original record and any subsequent revisions. A property may be dependent on another property, and the dependence can be identified and can also be specified by a mathematical expression.

This concept of a dictionary of testing methods and their properties was demonstrated (Kafka, 2003) by creating a prototype dictionary of some of the testing methods and their properties described in Military Handbook 5 (MIL-HDBK-5H) (U.S. Department of Defense, 1998). A screen shot of this dictionary, which shows the definitions of a plane strain fracture test and one of its associated properties, is shown in Figure 3. The dictionary was developed by using public domain software (University of Poitiers, 2009). The left hand panel shows the classification of testing methods and operational conditions. The upper right hand panel shows the definition of the selected testing method, and the lower right-hand panel shows the definition of one of the properties associated with the method.
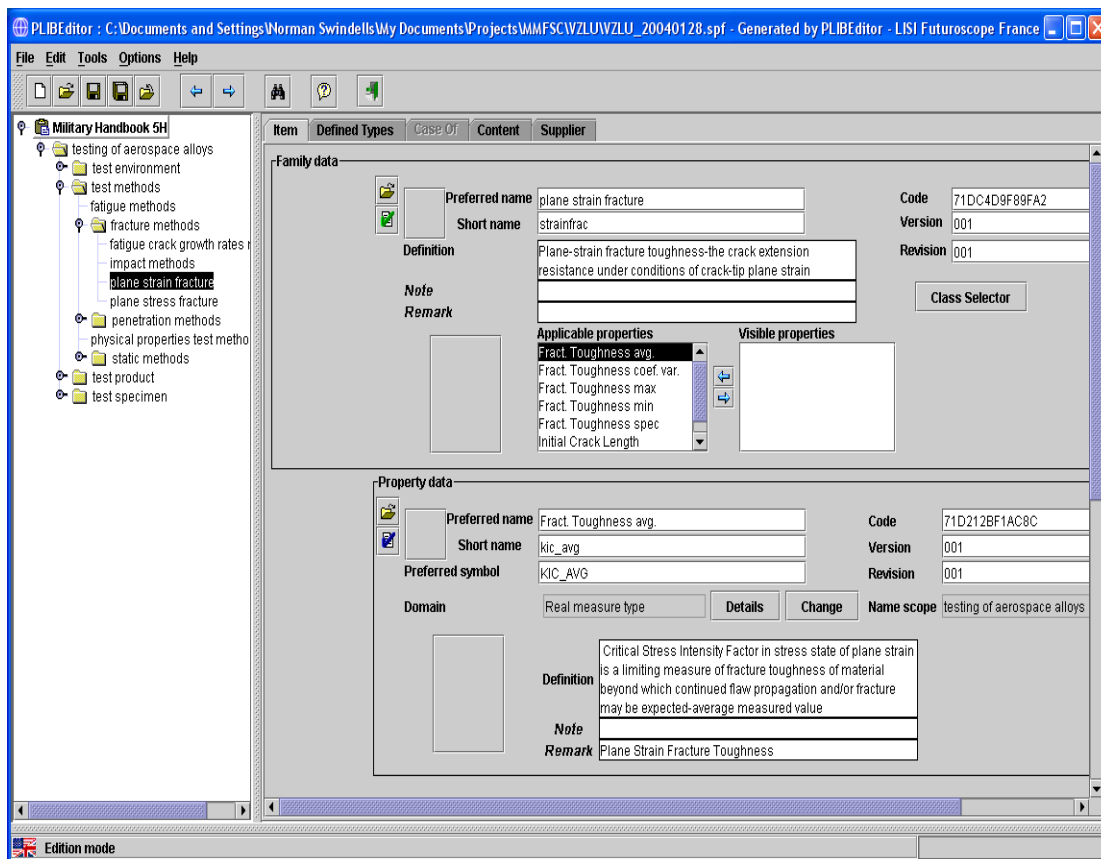

Figure 3. Screen shot of a prototype dictionary for mechanical testing methods conforming to ISO 13584

ISO 10303-235 therefore uses a combination of: an entity relationship model to represent the complexities of the measurement of product properties and a classification model used as a dictionary to define and name the measurement processes and the properties that they generate. This combination is necessary because of the importance of the details of the processes used to measure a property value, which needs an entity-relationship model, and the very large number of names and definitions of measurement processes and their properties – which requires a series of dictionaries. The names and definitions of properties will also be different in different national testing standards and in alternative languages.

6   RESULTS

The software to implement the complete information model for ISO 10303-235 is under development, but the internal approval procedures for ISO TC184/SC4 require that the validity of the standard to represent product data that is within its scope should be demonstrated before the draft standard is released for international ballot. Two of the examples provided for this approval process are described in the following subsections. Instantiation of key parts of the model was achieved by using the Instance Explorer software produced by PDTec GmbH (PDTec GmbH, 2009).

6.1   Example from Mil-Hndbk-5H

An example data set was derived from pages 2-38 of Military Handbook 5H (U.S. Department of Defense, 1998) by converting the data values to use SI units. The complete data set is shown in Table 3.

Table 3. Example data set derived from Mil-Hndbk-5H, 1998, pages 2-38

Product: Steel sheet
Dimension:
          thickness: 1.905 mm
Material designation: AISI 4130
Specified composition:

Element	Value wt %	Qualification
C	0.28	min
	0.33	max
Cr	0.80	min
	1.10	max
Mn	0.70	min
	0.90	max
Mo	0.15	min
	0.25	max
P	0.035	max
Si	0.15	min
	0.35	max
S	0.04	max

Product properties:
Maximum tensile strength: 1241 MPa
Yield tensile strength: 1200 MPa
Test temperature: 20 deg C

Test specimen:
Specimen orientation: longitudinal with respect to the length of the sheet.
Dimensions   Gross width: 57 mm
                 Net width: 38 mm
Notch dimensions:
depth: 19 mm   radius: 8 mm
Surface state: Electropolished

Testing process:
Axial tensile fatigue
Testing process properties:
          Frequency of load: 0.35 Hz min
                                     30 Hz max
          Temperature: 20 deg C
          Atmosphere: Air
Number of samples: 19

Consolidated test results:
Equivalent stress equation:

$$\text{Log } N_f = 8.87 - 2.81 \log (S_{eq} - 41.5)$$
$$S_{eq} = S_{max} (1-R)^{0.46}$$
$$\text{Standard Error of Estimate} = 0.18$$
$$\text{Standard Deviation in Life} = 0.77$$
$$R^2 = 94\%$$

Where:
N_f is the number of cycles to failure;
S_{eq} is the equivalent stress;
S_{max} is the maximum stress;
R is the ratio of maximum stress to minimum stress.

All of the data shown is this table was represented by ISO 10303-235. In particular, the capability to represent measure values by a mathematical expression was used to represent the equivalent stress equation, including the representation of the standard error and the standard deviation for this expression.

6.2   Example of Life Cycle Impact Data

Data for the life cycle impact of products is an example of information that has to be collected from many sources and communicated between several different systems in the process of carrying out a life cycle assessment (LCA) of products and processes. The European Commission has established an authoritative source of examples of life cycle impact data, and the data set for hot rolled steel sections from this source was used to verify the application of ISO 10303-235 for this kind of information (European Commission, 2009). The results of the instantiation of ISO 10303-235 for this application are explained and can be viewed as a sequence of e-learning courses created as part of the DEPUIS project (Swindells, 2009).

7   DISCUSSION

The use of the standards developed by ISO TC184/SC4 for the representation of product data and its exchange among different software systems has been a global success. These standards are used by the world's largest companies and organisations in aerospace, automotive, defence, machine cutting tools, shipbuilding, offshore oil, and gas. The application of product data technology to such diverse situations emphasises the fundamental nature of this general solution to the representation of product data by the use of computer-processable information models with rigorous constraints. The extension of this methodology to the representation of material properties was achieved by realising that all materials are products and can therefore be represented by the generic product models, but it must be recognised that the property values have to be supported by appropriate metadata to ensure that the meaning and the validity of the property and its value are understood. This capability was realised with ISO 10303-45.

The second extension to the technology of ISO TC184/SC4 was to recognise that a material property, like most other engineering properties, is defined by the process that is used to derive it. This concept was demonstrated by the development of the dictionary illustrated in Figure 3.

These two extensions have now been brought together by the completion of ISO 10303-235: Engineering properties for product design and verification. This is a specialisation and extension of the Integrated Generic Resources of ISO 10303 and connects the descriptions of products, processes, and properties together into one computer-processable framework. Because there is the capability to reference ISO 13584 dictionaries from this information model, the standard can be used for the representation and exchange of any property and any measurement process applied to any product. The completeness of this model would enable an audit trail to be followed from a property value through to its origins in the sequence of measurement processes.

However, it has proved extremely difficult to involve the potential user community in the development of these standards, and user acceptance and widespread adoption of this technology has been very difficult to achieve. One possible reason is that the development and understanding of entity-relationship models requires a special skill, and the combination of this skill with expertise in a domain of engineering knowledge is rare. Developing a skill in information modelling by an engineering domain expert requires a degree of commitment that many will not want, or be able, to provide. There is therefore a problem to capture the domain knowledge of the engineer in an information model that will satisfy his professional requirements and convince him that the result will be beneficial and should be adopted.

 ISO 13399: Cutting tool data representation and exchange was one of the first applications of product data technology that was developed outside the scope of ISO TC184/SC4. ISO 13399 was developed by ISO TC29 and describes the assembly of a modern machine cutting tool by an entity-relationship model, using resources from ISO 10303, with a dictionary conforming to ISO 13584 that defines the names and properties of the components of a modern cutting tool. The experience during the development of this standard was that the domain experts did not want to be involved in the development of the entity-relationship model. However, they were enthusiastic contributors to the development of the dictionary because its structure and its purpose were easy to understand and they could see an outlet for their experience by the development of the dictionary as an industrial resource.

Capturing domain knowledge in a computer-processable form has often been a challenge for software development, for artificial intelligence, and now for product data technology. The successful developments of ISO 10303-235 and ISO 13399 show that the capturing of domain knowledge is made much easier if part of this knowledge is captured in a dictionary that is accessible from the entity-relationship model and that this also makes the model more widely applicable and acceptable. The relative ease with which an ISO 13584 dictionary can be developed, by using public domain software, also offers the possibility of increasing the number of stakeholders using and benefiting from product data technology. The dictionaries can also provide support for the use of the information model in different national industrial systems and alternative languages.

8   CONCLUSIONS

The combination of an entity-relationship information model with a dictionary for the representation and communication of engineering information conforms to the fundamental requirements for any unambiguous communication.

The development of a computer-processable dictionary to support the entity-relationship model is an effective way of capturing the knowledge of domain experts and should make it easier to gain acceptance of product data technology and increase its application.

ISO 10303-235: Engineering properties for product design and verification is an application of this combination with a standardised entity-relationship model that enables the unambiguous representation and communication of the properties of products together with the supporting information to verify that the result is valid. The compilation of domain knowledge and terminologies into a separate dictionary will enable the entity-relationship model to be used in many different application scenarios with the potential for an increase in the number of stakeholders in the use of this technology.

Separating the domain terminology from the entity relationship model in ISO 10303-235 enables the model to be used in many application areas where technical information has to be communicated among many different systems and in situations where the information has to be conserved for longer than the typical lifetime of computer software. Examples of these applications are in aerospace engineering, environmental impact measurement and environmental monitoring, nuclear engineering, nuclear monitoring, and decommissioning.

9   ACKNOWLEDGMENTS

10   REFERENCES

European Commission (2009) European Platform on Life Cycle Assessment. Retrieved January 12, 2009 from the World Wide Web: http://lca.jrc.ec.europa.eu/lcainfohub/dataset2.vm?id=23

International Organization for Standardization (1994) ISO 10303-1, Industrial automation systems and integration –Product data representation and exchange – Part 1: Overview and fundamental principles.

International Organization for Standardization (1998) ISO 10303-49, Industrial automation systems and integration – Product data representation and exchange – Part 49: Integrated generic resources – Process structure and properties.

International Organization for Standardization (1998) ISO 13584-42, Industrial automation systems and integration – Parts library – Part 42: Description methodology – Methodology for structuring parts families.

International Organization for Standardization (2001) ISO 13584-1, Industrial automation systems and integration – Parts library – Part 1: Overview and fundamental principles.

International Organization for Standardization (2002) ISO 10303-21, Industrial automation systems and integration – Product data representation and exchange – Part 21 Ed 2: Implementation methods – Clear text encoding of the exchange structure.

International Organization for Standardization (2004) ISO 10303-11, Industrial automation systems and integration –Product data representation and exchange – Part 11 Ed 2: Description methods – The EXPRESS reference manual.

International Organization for Standardization (2008) ISO 10303-45, Industrial automation systems and integration –Product data representation and exchange – Part 45 Ed 2: Integrated generic resources – Material and other engineering properties.

International Organization for Standardization (2009) ISO 10303-235, Industrial automation systems and integration – Product data representation and exchange – Part 235: Application protocol – Engineering properties for product design and verification.

Kafka, V. (2003) Reference dictionaries for product properties, *Proc, Int. Conf. Metal Fabrication and Welding Technology*, Nottingham, U.K., 273-281.

Nordström, J. & Swindells, N., (2007) A New Era for Cutting Tools*, ISO Focus*, 4(12), 30-33.

PDTec GmbH (2009), *PDTec Instance Explorer software*. Retrieved January 12, 2009 from the World Wide Web: http://www.pdtec.de .

Schenk, D & Wilson, P (1994) *Information modelling the EXPRESS way*, New York, Oxford University Press.

Swindells, N. (2000) Communicating Materials Information – Product Data Technology for Materials, *Int. Materials Reviews*, 47(1), 31-45.

Swindells, N. (2009) *Design of Environmentally Friendly Products Using International Standards* (DEPUIS). Retrieved January 12, 2009 from the World Wide Web: http://www.depuis.enea.it/page.asp?page=Book

U.S. Department of Defense (1998), *Military Handbook 5H, Metallic Materials and Elements for Aerospace Vehicles*.

University of Poitiers (2009) *PLIB Editor software*, Retrieved January 12, 2009 from the World Wide Web: http://www.plib.ensma.fr/