An Ontology of Materials[‡‡]

Bernd Bachmann* Markus Steffens
German Research Center for AI (DFKI)
P.O. Box 2080
D–67608 Kaiserslautern
Germany

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Abstract

Knowledge about materials plays an important role in many engineering disciplines. We present a systematic account for structuring this domain according to the concepts that have already been developed in materials science. We focus specifically on polymers since they are important for our application scenario. The representation of our domain ontologies is performed by the use and in the sense of Ontolingua. We also show how already existing ontologies can be reused. With this basis our ultimate goal—structuring a knowledge base of composites—is further approached.

1 Introduction

We present an ontology of materials that has been developed in the context of the IMCOD (*I*ntelligent *M*anager for *C*omprehensive *D*esign) project [BBK+92]. IMCOD (cf. figure 1) is primarily concerned with the problems arising from multidisciplinary design. In our scenario each of the disciplines is realized by an already existing software system—the *local experts*—, e.g. expert systems, databases, simulation software, etc. The systems are consulted by the *design manager* (also realized as a knowledge–based system) in order to provide their limited expertise for the overall product design.

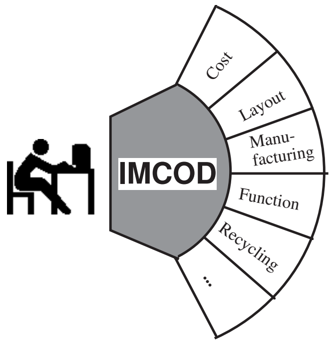

Figure 1: The IMCOD System

One of the issues we are tackling is the development of an integrated product model for the design manager that is capable of representing the product at an appropriate abstraction level, i.e. serving as a decision aid for controlling the design process, allowing the generation of partial views for each of the local experts, and mapping the advice of the local experts onto the product model. Especially the latter issue requires a mapping of the conceptualization of the local experts to the conceptualization of the integrated product model or the definition of a common conceptualization that is shared by all agents. We adopt the notion of *conceptualization* from [GN87]: the basic set of objects that exist in a domain and the relationships among them. Ideally, such a conceptualization would be shared among the local experts and can also serve as a basis for the integrated product model. Knowledge sharing is meant

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*e-mail: bachmann@dfki.uni-kl.de

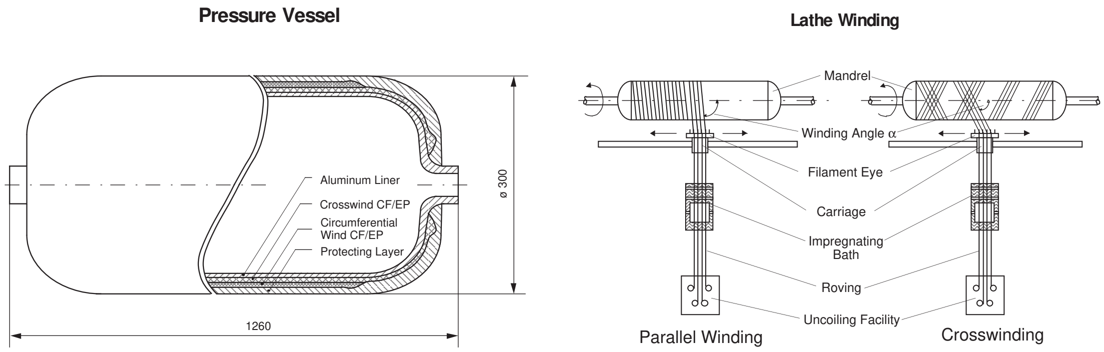

Figure 2: A composite pressure vessel and the winding process (source: IVW, GmbH)

in the sense of the Knowledge Sharing Effort [NFF+91]: Based on a common syntax and semantics of a representation language we define the common conceptualization explicitly.

The Application Scenario

Within IMCOD we chose the design of pressure vessels composed of composite materials as an application scenario [Ste94] (cf. figure 2). It turns out that materials play a crucial role for the following design issues in this domain:

liner A mandrel whose outer shape is equivalent to the inner shape of the vessel and on which the fiber rovings are wound. The liner remains part of the vessel as a barrier between the composite main vessel body and the stored medium. It may also have supporting structural tasks for the vessel.

fiber A single filament of typically 5 to 15μm, which is combined with some hundreds other filaments to a bundle (a so-called roving), with usually outstanding strength properties in fiber direction. It is used to reinforce other materials like polymers, forming a polymer composite.

matrix E.g. a polymer, in which fibers are embedded for its reinforcement. The matrix usually shows little strength but has ductile properties.

vessel attachment A fixing out of metal or another appropriate material to attach the vessel at its place of destination, e.g. a car's chassis.

vessel fittings Fittings like pressure flanges for a connection of the vessel to the pressure inlet and outlet and the installation of valves and measuring instruments.

Hence, some of the knowledge bases of the local experts, e.g. a database for material selection, a production cost analyzing system, etc., are (partially) based on an ontology of materials. Also the integrated product model requires such an ontology. However, the structure of ontology of materials science seems to be universally applicable to the domain, independent of any specific task. Therefore, we will present an exhaustive overview of materials science, especially plastics, in the following.

Materials Science and Composites

Materials in general can be subdivided into three different materials groups, which are *metals*, *ceramics* (defined as all inorganic non–metal materials) and *polymers*. A further group is often formed by the composite materials which are a combination of two or more materials deriving from one single or more materials groups mentioned above.

One should think that the group of *composites* does not necessarily need to be defined in more detail, as it is already completely explained by the definitions of the basic materials they consist of. On the one hand, this way of thinking could be accepted, when we consider the basic linear rule of mixture which in simple cases provides a mathematical formula for the calculation of mechanical composite materials properties by simply combining the single theoretical properties of the composite components. On the other hand, we also have to consider secondary effects, which take place at the interface, where the different materials meet each other. Furthermore, the different possibilities of appearance of one single material and the variety of methods how to combine them with others opens a wide range of aspects and suggests a treatment of the group of composite materials in its own right.

The aim of the combination of two or more materials forming a composite is the improvement either of the mechanical properties, such as fracture strength and elastic modulus (E– or YOUNG's modulus), or the fracture behavior or wear properties of the new created material. This – only in the ideal case – is reached by combining the components in a way that the positive properties of each material overcome the negative ones of the other. The final properties of the composite will always be set in the range between the maximum and the minimum properties of the single material components (figure 3, [Fri94]).

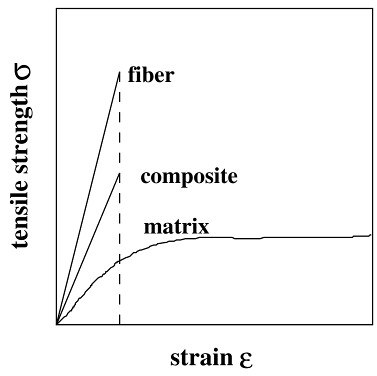

Figure 3: Stress–strain curve of reinforcing fibers, matrix and composite

There are several methods how the components can be combined with each other. One distinguishes in general between particle, fiber, layer and infiltration composites (figure 4, [Roe90]).

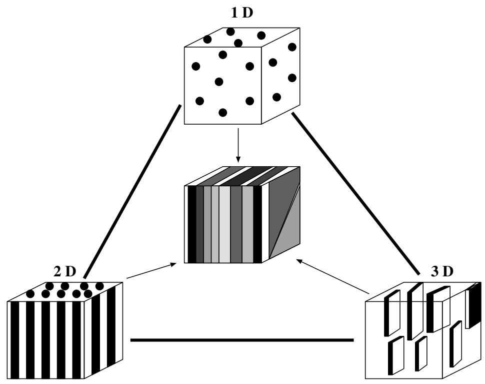

Figure 4: Classification of composites referring to material composition (1D) particle– (2D) fiber– (3D) layer– and infiltration–composite

As an example, a high reduction of the brittleness of mainly ceramics and also glass, bedded in a metal or polymer matrix with elastic and plastic properties, can be reached. In case of a ceramic–metal–combination this particle composite is called Cermet. Here, it is taken advantage of the high temperature resistance of the brittle ceramic and the outstanding elastic and plastic properties of the metal matrix, resulting in a pseudoplastic stress–strain curve.

The fiber reinforcement of comparably weak matrices has undoubtedly the highest importance of todays composites. Here again, unidirectional (UD–) and short fiber reinforced (SFR–) composites are distinguished. The mechanism of fiber reinforcement is based on the immense strength of typically glass– (GF) carbon– and aramide fibers (AF) with typical diameters of 8 to 15μm. Within these tiny dimensions, the probability of a defect of the microscopic fibrous structure is highly reduced and especially with glass fibers their almost perfect surface, showing a minimum of cracks, leads to an improvement of the mechanical properties. Thus, the measured mechanical properties of the fibers almost reach the theoretical values they should have when there is no defect in the microstructure at all.

Especially fiber reinforced plastics (FRP) are becoming more and more popular these days. Their relatively reasonable manufacturing costs, easy handling, their – with thermoplastics – welding option and their excellent weight to strength ratio are responsible for this development.

FRP with a thermoplastic matrix were furthermore gaining importance from then on, when the recycling of thermoset composites led to almost non–solvable problems after their use. In contrast to thermoset polymers, thermoplastic composites allow to melt open the matrix again in order to separate it from the reinforcement. The so recycled raw materials can now be reused in a new manufacturing process.

Processing problems of thermoplastics were mainly responsible for their only rare use as matrix materials in the past for advanced composites although they show excellent material properties like high fracture toughness and excellent chemical resistance. Difficulties in processing are on the one hand based on the low temperature resistance of common engineering thermoplastics and on the other hand on their relatively high viscosity of 500 to 5000Pa·s even at levels close to polymer decomposition temperature in comparison to thermosets with viscosities of only about 100Pa·s. This complicates a good impregnation of the fibers with the thermoplastic polymer, whereas a high degree of impregnation is one of the basic requirements for a sufficient fiber–matrix–adhesion, leading finally to acceptable mechanical properties of the composite.

Much effort has been spent in the last years to improve the manufacturing behavior of thermoplastics such as coupling agents on the fiber surface and further on simply higher processing temperatures, pressures and holding times; in the meantime also new high temperature thermoplastics like Polyetheretherketone (PEEK) or Polyamideimide (e.g. Torlon) had been developed. Another reasonable possibility is the choice of non– conventional fiber–matrix intermediate material forms at the beginning of processing which already show an intermingling of fiber and matrix in the not impregnated state.

2 Ontology of materials

Within the scope of the project, investigations were focused on UD-wound polymer composites, as they are used e.g. with the manufacturing of pressure vessels. Apart from starting to develop an ontology for the pressure vessel structure, a materials sub-ontology was created, mainly concentrating on materials common in the fiber winding technology. Others were only mentioned for a later completion. Generally, a subdivision of the materials into the two main groups *metals* and *non-metals* and the latter group again into the two groups *ceramics* and *polymers* was chosen in line with classical materials science.

Whenever a materials group contained materials, dominant in composite technology, they were subdivided more precisely, e.g. the groups glasses and polymers. Especially the latter group turned out to be of high complexity and thus was examined more detailed as described in the next chapter.

Any material can be characterized by use of its properties, always related to defined conditions. One distinguishes

- thermal (coefficient of thermal expansion α $[1/K]$; thermal conductivity λ $[W/(m^2 \cdot K)]$),
- electrical,
- magnetic,
- optical and
- mechanical (tensile strength σ [MPa]; elastic modulus E [MPa])

properties which are either qualitative or quantitative. Qualitative properties are expressed with boolean (True or False) or by help of a range of discrete values [vdVM91]. Furthermore, certain properties are characteristic for a materials group, some are valid for all groups. A tensile strength for instance is defined for any kind of material, a decomposition temperature in contrast is only senseful for polymers. As a material is given an extension in one dominant direction (e.g.

fibrous materials), its properties often become anisotropical, which results in various properties in different directions. Therefore fibers are always characterized by orthotropical properties, in and perpendicular to fiber direction.

The resulting ontology for materials is sketched in figures 5 and 6. This partition reveals that the two materials groups *metals* and *non–metals* represent disjunctive groups substances which, according to their principle macromolecular organization, have different values for the properties. Therefore, the classification along the values of the properties mentioned above together with some principle behavior (e.g. isotropic vs. orthotropic) leads to this hierarchy. The leaves of the hierarchy (drawn as ellipses) represent actual materials that have a fixed chemical composition and fixed properties.

For the purpose of representing the ontology in Ontolingua [Gru92] we adopted and enhanced[1] an ontology for engineering mathematics [GO94][2] that is already predefined and represented in Ontolingua. Additionally, we introduced a new relation In–Interval that is used to define intervals of physical quantities such that the intervals of more specific materials groups are enclosed in the intervals of the more general ones. We took into account the four properties (thermal expansion, thermal conductivity, tensile strength, and elastic modulus) as mentioned above. Also we defined two additional ontologies for Mechanical Quantities and Thermal Quantities. Those extensions can be found in appendix A. The representation of the materials ontology itself is shown in appendix B.

3 The ontology of polymers

Almost no industry branch has developed as quickly as the polymer industry in the last decades. Many properties of new developed polymers showed to be ideal for the tasks of the matrix in polymer composites. Thus, progress in composite technology was mainly linked to improvements in polymer chemistry. The main target was the development of new high temperature plastics—especially thermoplastics—with outstanding chemical and mechanical properties.

Polymers can be classified under four different aspects, like:

1. Manufacturing process

   polymerisation The chemical conversion of one or several chemically different and active low–molecular connections (monomers) to a linear branched, meshed or cyclic polymer. The most common polymerisation is the radical polymerisation.

   polycondensation Chemical reaction where bi- or higher functional low-molecular connections (monomers) are converted to linear or meshed macromolecular substances (polycondensates) by proceeeding condensation reactions. This is always combined with a separation (condensation) of low-molecular products, like water, ammonia, hydrochlorgas and methanol.

   copolymerisation (polyaddition) With copolymerisation, monomers are directly added to the basic structure, in contrast to a polycondensation, where low-molecular parts are separated.

2. Origin of raw materials

   modified natural materials Materials which originate from a natural material and have been modified for an industrial use.

   synthetic materials Materials which do not originate from a natural material and have been produced artficially.

[1] Thanks to Stefan Huwer!

[2] As it was available on May 1, 1994 on WWW as http://www-ksl.stanford.edu/knowledge-sharing/ontologies/html/...

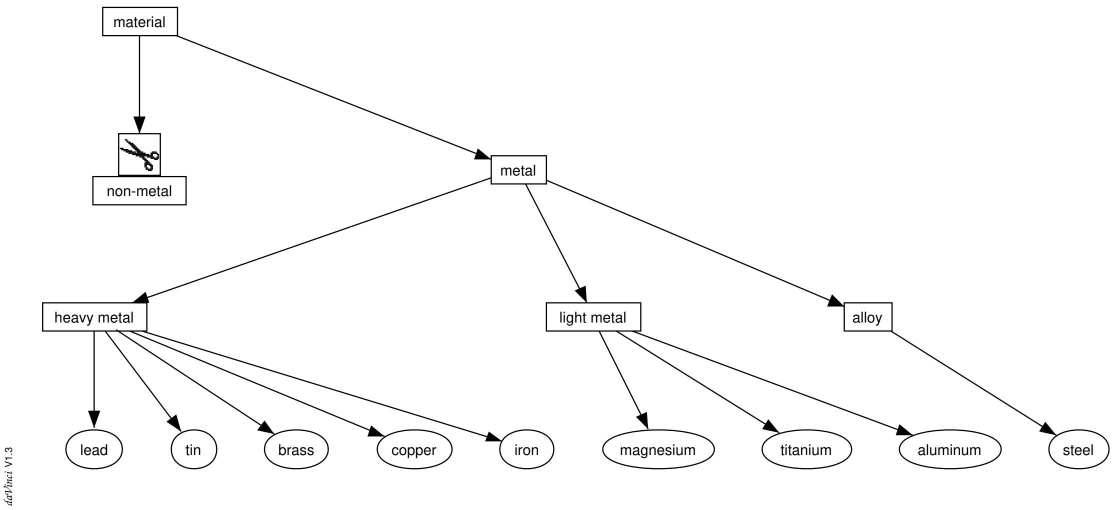

Figure 5: The materials ontology: metals

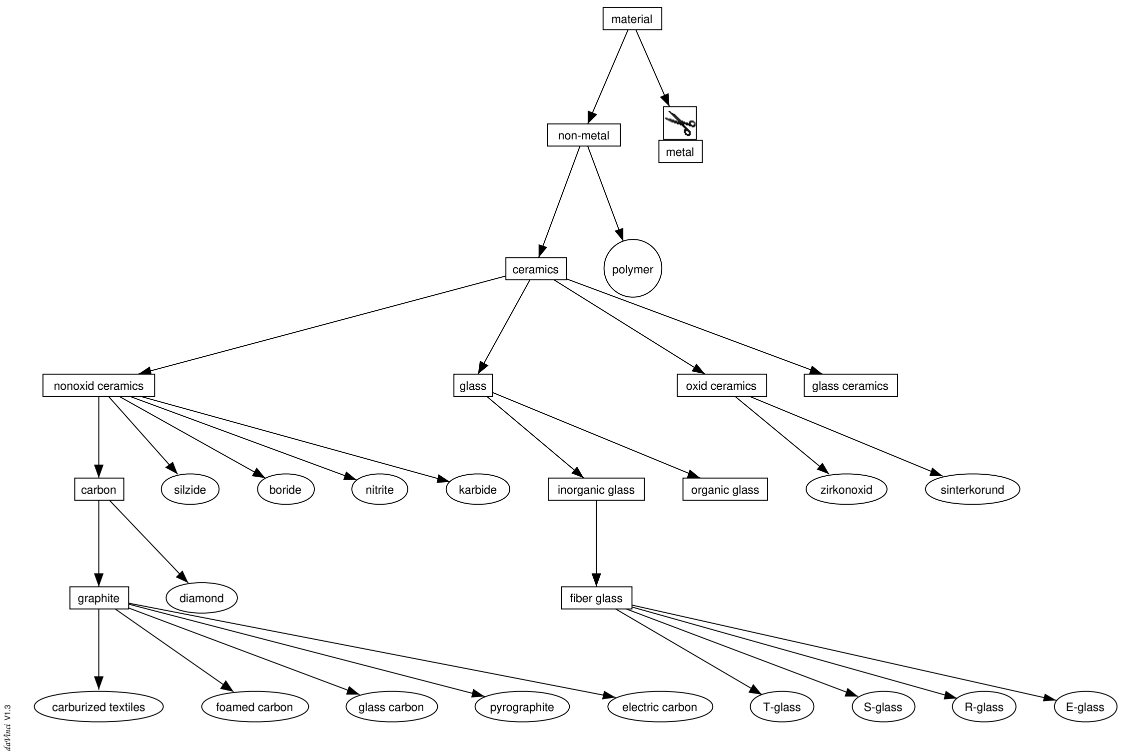

Figure 6: The materials ontology: non-metals

3. Composition of the macromolecules

amorphous structure Macromolecular design of a material, which only shows a short range

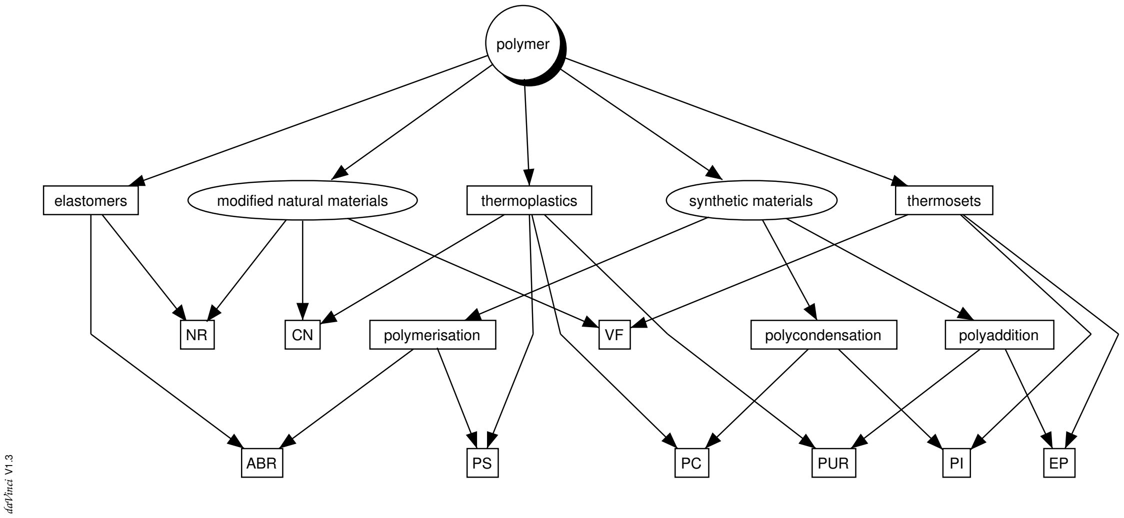

Figure 7: The plastics ontology

order of the atoms (e.g. glass) in contrast to a wide range order of cristalline structures.

semi-cristalline structure Materials with a partial wide range order of atoms but also a coexisting irregular, amorphous structure.

liquid-cristalline structure An intermediate state between the amorphous and cristalline state of high-molecular polymers, which are liquid but nevertheless have a regular, cristalline molecular structure.

4. Processing technology and polymer properties

thermoplastics Polymers with a loose connection of the molecule chains to each other. They can be melt open again by heat.

thermosets Polymers with a fixed meshed net of polymer chains to one big molecule which cannot be separated again after the meshing reaction (curing).

elastomers Polymers with irregular orientated molecule chains, which in contrast to thermoplastics and thermosets are able to move slightly against each other. After a deformation they automatically return to their initial position.

In contrast to the general subdivision of materials, the above main criteria are not unequivocal, i.e. a polymer is not belonging to only one single group but needs to be classified by all of them. The resulting ontology is sketched in figure 7. The (9) leaves of the hierarchy do by no way represent the complete set of existing polymers with fixed properties and chemical composition[3]. However, each of them may be regarded as a representative of the possible combination of the characteristics 1, 2, and 4 as mentioned above. Hence, we omitted characteristic 3 since it would complicate the layout of the hierarchy and it is not important for our application. The pure definition of the classes without properties can be found in appendix C.

[3] Till now we have taken into account 44.

4 Design Considerations

Before we will have a closer look for some of the decisions we made for the presented ontology we should emphasize that the ontology is not supposed to be a complete set of definitions for axiomatizing the domain of materials. First, the materials groups and single materials were chosen according to our specific application. Secondly, we represented only a small part of it in Ontolingua (cf. appendix A,B, and C) since Ontolingua will not be our final representation language [Bac93]. However, for the benefit of reusing existing ontologies and for comparing it with others we choose to represent a small subset of it in Ontolingua. Finally, we have not decided yet how to represent the composites (see below).

We regard our ontology of materials also as a test of how already existing ontologies can be used. For that purpose we adopted the ontology of ENGINEERING MATHEMATICS [GO94]. We enhanced the ontology STANDARD UNITS AND DIMENSIONS to capture our specific dimensions. Additionally, we added the possibility to define the physical properties of a materials group via an interval of values. Also mechanical and thermal quantities were defined, representing a small subset of imaginable ones, that might be important for classifying materials. The two ontologies THERMAL QUANTITIES and MECHANICAL QUANTITIES on top of the previously defined ontologies SCALAR QUANTITIES and VECTOR QUANTITIES capture them. It turned out that the preexisting ontologies are powerful enough to provide a basis for our needs. The result is shown in appendix A.

Vice versa the presented ontology will also serve as a testbed of how it can support the structuring of already existing knowledge–bases on materials that are tailored for a specific application in the sense of [Mar93]. For that purpose we are currently investigating the already existing knowledge base of the VEGA project [BBK94]. This knowledge base covers knowledge about the recyclability of glass fiber reinforced plastics with a thermoplastic matrix.

Science vs Logic

It turned out that the ontology that is used in materials science is not logically consistent for historical reasons. The class CERAMICS is defined as "all non–metallic, inorganic materials". However, if we look at the hierarchy in figure 5 we find the class ORGANIC GLASS as a specific ceramics whose materials definitely consist of organic elements. This situations happens since organic glasses were developed rather late and show the physical behavior of glass rather than that of polymers. In order to be consistent with standard textbooks in this field and to develop a structure that is acceptable for engineers we adopted the classical domain classification. This is uncritical since we do not use a relation that defines chemical composition as in [vdVM91]. Otherwise, either the usage of default definitions or a more elaborated, logical sound classification has to be considered. This leads directly to the question of an appropriate expressive power of a representation language for ontologies.

Artificial Classes and Instances

In the POLYMER ontology you can find some classes which do not have an associated formal definition, e.g. SYNTHETIC MATERIALS. The reason is that these classes do not contain any knowledge that is relevant for our application. However, they are used in standard textbooks [Dom88] for the classification of polymers. In order to design our ontology in a general way we have adopted them, too. Only the three classes THERMOPLASTICS, ELASTOMERS, and THERMOSETS play a crucial role. Their properties can be primarily described by the abstraction of the subsumed materials (instances and classes).

Furthermore, the POLYMER ontology contains a couple of instances which are the leaves in figure 7. However, we have only taken those materials as instance that have a fixed composition *and* properties. This is not the case for PC (Polycarbonat) that still shows an interval for the E–modulus quantity. In fact its actual properties depend on the manufacturer. Therefore, we have still defined this polymer as a class. The instances might be defined as a function of the manufacturer.

Implicit Assumptions

The physical quantities we present here are typically measured under standard conditions, e.g. room temperature, atmospheric pressure, etc. More precisely, these quantities are a function of e.g. temperature. Consequently, for a "correct" axiomatization of materials the properties have to be represented together with the explicit specification of the conditions under which they hold. However, in the worst case this would require the representation of arbitrary even uncontinuous functions.

Representation of Composites

Our final goal to represent an ontology of composite materials has not been discussed here. We currently use the ontology of the individual components to develop an axiomatization for composites. However, this cannot be performed by simply adding individual components presented here via a has–part relation, even if its semantics would be defined with a complex linear rule of mixture (cf p. 3). Beforehand, the properties of the components of the participating materials have to be defined for the case that the materials occur as fibers. In that case an isotropic material (E–modulus is equal in all directions) may show different E–modulus along and perpendicular to the fiber direction. We have already prepared the ontology for this requirement by introducing the E–modulus as a vector for all materials.

5 Outlook

In order to finally provide an ontology of materials especially composits we will continue to complete the knowledge that is presented here. Additionally, we have to have a closer look for the mixture rules that define the composition of several materials. These rules may also be defined in an independent ontology such that composites itself need not to be represented. Instead, the axiomatization for the various kinds of composition (cf. figure 4) and the specific knowledge about the single components (cf. figures 5, 6, and 7) may be sufficient to enable the sharing of knowledge about composites between agents.

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A Extensions to ENGINEERING MATHEMATICS

```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;; Extensions to standard-units-and-dimensions
;;     dimensions
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
(in-theory 'standard-units-and-dimensions)

(define-instance area-dimension (physical-dimension)
  "The physical dimension of an area is defined as length dimension squared."

  :axiom-def (= area-dimension
                (expt length-dimension 2)))

(define-instance pressure-dimension (physical-dimension)
  "the physical dimension of pressure is defined as force over area"

  :axiom-def (= pressure-dimension
                (* force-dimension
                   (expt area-dimension -1))))

(define-instance therm^-1-dimension (physical-dimension)
  :axiom-def (= therm^-1-dimension
                (expt thermodynamic-temperature-dimension -1)))

(define-instance work-dimension (physical-dimension)
  :axiom-def (= work-dimension
                (* force-dimension
                   length-dimension)))

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;; Extensions to standard-units-and-dimensions
;;     units
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

(in-theory 'standard-units-and-dimensions)

(define-instance megapascal (unit-of-measure)
  " 1 megapascal = 10^6 pascal "
  := (* pascal 1000000)
  :axiom-def (dimension megapascal pressure-dimension)  )

(define-instance watt (unit-of-measure)
  "unit of measure for measuring physical work"
  := (* newton meter)
  :axiom-def (dimension watt work-dimension)  )

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;; Extension to physical quantities by intervals
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

(in-theory 'physical-quantities)
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(define-relation in-interval (?x ?low ?up)
  "holds if :
                 (?x >= ?low) and
                 (?x <= ?up) and
if their dimensions are compatible"

  :iff-def (and (compatible-quantities ?x ?low)
            (compatible-quantities ?x ?up)
            (=< ?x ?up)
            (>= ?x ?low)))

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;; Mechanical Quantities
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

(define-theory mechanical-quantities (standard-units-and-dimensions
                                      scalar-quantities
                                      vector-quantities)

  "This theory is used to represent mechanical quantities such as
e-module, ... which are extensions to the quantities already
defined in the physical-quantities ontology"
  )

(in-theory 'mechanical-quantities)

(define-class e-module (?x)
  "e-module is a sub-class of vector-quantity of the dimension 3,
containing scalar quantities of the physical dimension pressure"

  :def (and (vector-quantity ?x)
            (vector.dimension ?x 3)
            (= (dimension ?x) pressure-dimension)
            )
  )

(define-instance e-module.basis (orthonormal-basis)
  "represents the unit-basis for the e-module class"
  :axiom-def (basis.dimension e-module.basis 3)
  )

(define-class tensile-strength (?x)
  "tensile-strength is a subclass of scalar-quantities associated
with the physical pressure-dimension"
  :def (and (scalar-quantity ?x)
            (dimension ?x pressure-dimension)
            )
  )

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;; Thermal Quantities
```

```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

(define-theory thermal-quantities (standard-units-and-dimensions
                                   scalar-quantities)

  "This theory is used to represent thermal quantities such as
thermal-expansion, ... which are extensions to
the quantities already defined in the physical-quantities ontology"
  )

(in-theory 'thermal-quantities)

(define-class thermal-expansion (?x)

  :def (and (scalar-quantity ?x)
            (dimension ?x therm^-1-dimension))
  )

(define-class thermal-conductivity (?x)
  :def (and (scalar-quantity ?x)
            (dimension ?x (* work-dimension
                             (expt area-dimension -1)
                             therm^-1-dimension)))
  )
```

B Ontology of materials

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;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;; Materials
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

(define-theory materials (mechanical-quantities
                          thermal-quantities)  )

(in-theory 'materials)

;;; Class Material

(define-class material (?mat)
  "A material has the properties
E-module and tensile-strength"
  :def (and (defined (material.e-module ?mat))
            (defined (material.tensile-strength ?mat))
            (defined (material.thermal-conductivity ?mat))
            (defined (material.thermal-expansion ?mat))
            ))

(define-function material.e-module (?mat) :-> ?emod
  "e-module is a vector-quantity of dimension 3 with
the pressure-dimension"
  :def (and (material ?mat)
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```
            (e-module ?emod)  )  )

(define-function material.tensile-strength (?mat) :-> ?x
  "tensile-strength is a scalar-quantity associated with the
pressure dimension"
  :def (and (material ?mat)
            (tensile-strength ?x)  )  )

(define-function material.thermal-conductivity (?mat) :-> ?x
  "thermal-conductivity is a scalar-quantity associated with the
dimension (work/(area*temperature))"
  :def (and (material ?mat)
            (thermal-conductivity ?x)  )  )

(define-function material.thermal-expansion (?mat) :-> ?x
  "tensile-strength is a scalar-quantity associated with the
therm^-1-dimension"
  :def (and (material ?mat)
            (thermal-expansion ?x)  )  )

;;; Class Metal
;;; subclass of Material
(define-class metal (?met)
  "A metal is a subclass of material. The material.e-module
value of metal consists of three equally valued components,
i.e. it is an isotropic material.
They must be bounded by 1600MPa and 415300 MPa "
  :def (and (material ?met)
            (= (vector-component (material.e-module ?met) 1 e-module.basis)
               (vector-component (material.e-module ?met) 2 e-module.basis))
            (= (vector-component (material.e-module ?met) 1 e-module.basis)
               (vector-component (material.e-module ?met) 3 e-module.basis))

            (in-interval (vector-component (material.e-module ?met)
                                           1
                                           e-module.basis)
                         (* 1600 megapascal)
                         (* 415300 megapascal)))
  )

;;; Class Non-Metal
;;; subclass of Material
(define-class non-metal (?nmet)
  :def (and (material ?nmet)
            (not (metal ?nmet)))
  )
```

C Ontology of plastics

```
(define-theory polymers (materials))
```

```
(in-theory 'polymers)

;;; Class Polymer
;;; subclass of Non-metal
(define-class polymer (?pol)
  ""
  :def (and (non-metal ?pol)))

;;; Class thermosets
;;; subclass of polymer
(define-class thermosets (?x)
    ""
  :def (and (polymer ?x))  )

;;; Class thermoplastics
;;; subclass of polymer
(define-class thermoplastics (?x)
    ""
  :def (and (polymer ?x))  )

;;; Class elastomers
;;; subclass of polymer
(define-class elastomers (?x)
    ""
  :def (and (polymer ?x))  )

;;; Class synthetic-materials
;;; subclass of polymer
(define-class synthetic-materials (?x)
    ""
  :def (and (polymer ?x))  )

;;; Class Modified-natural-materials
;;; subclass of polymer
(define-class modified-natural-materials (?x)
    ""
  :def (and (polymer ?x))  )

;;; Class polycondensation
;;; subclass of synthetic-materials
(define-class polycondensation (?x)
    ""
  :def (and (synthetic-materials ?x))  )

;;; Class polyaddition
;;; subclass of synthetic-materials
(define-class polyaddition (?x)
    ""
  :def (and (synthetic-materials ?x))  )

;;; Class polymerisation
;;; subclass of synthetic-materials
```

```
(define-class polymerisation (?x)    ""
  :def (and (synthetic-materials ?x))
  )

;;; Class PC
;;; subclass of polycondensation, thermoplastics
(define-class PC (?x)
    ""
    :def (and
          (polycondensation ?x)
          (thermoplastics ?x)
          (in-interval (vector-component (material.e-module ?x)
                                         1
                                         e-module.basis)
                       (* 2200 megapascal)
                       (* 2400 megapascal))        )  )

;;; Instance VF
;;; inherits from thermosets, modified-natural-materials
(define-instance VF (thermosets modified-natural-materials)
  "Vulkanfiber"  )

;;; Instance CN
;;; inherits from thermoplastics, modified-natural-materials
(define-instance CN (thermoplastics modified-natural-materials)
  "Cellulosenitrat"  )

;;; Instance NR
;;; inherits from modified-natural-materials, elastomers
(define-instance NR (modified-natural-materials elastomers)
    "Isoprenkautschuk"  )

;;; Instance PI
;;; inherits from thermosets, polycondensation
(define-instance PI (thermosets polycondensation)
    "Polyimid"
    :axiom-def (= (vector-component (material.e-module pi)
                                    1
                                    e-module.basis)
                  (* 3800 megapascal)))

;;; Instance EP
;;; inherits from thermosets, polyaddition
(define-instance EP (thermosets polyaddition)
    "Epoxid"  )

;;; Instance PUR
;;; inherits from polyaddition, thermoplastics
(define-instance PUR (polyaddition thermoplastics)
    "Polyurethan"  )

;;; Instance PS
```

```
;;; inherits from thermoplastics, polymerisation
(define-instance PS (thermoplastics polymerisation)
  "Polystyrol"
  :axiom-def (= (vector-component (material.e-module ps)
                                  1
                                  e-module.basis)
               (* 3200 megapascal)))

;;; Instance ABR
;;; inherits from polymerisation, elastomer
(define-instance abr (polymerisation elastomers)
    "Acrylat-Butadien-Kautschuk"  )
```