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DESIGNING MATERIAL STANDARDS

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1. Introduction

In the final stage of design the exact material in the component must be specified. If the product during its development has been verified with a material from a particular supplier, a straightforward way is to write the name, grade and supplier of that material on the drawing. However, this way of specifying is risky. The manufacturer will perhaps decide to stop manufacturing the particular grade or the price and availability may fluctuate. Here, material standards play an important role. By instead of a certain supplier, referencing to a material grade from a standard, the specification becomes less supplier dependent. It must be noted that in most cases new verifying tests must be made when changing supplier. Using a standard grade will facilitate finding a replacement supplier and material.
The structure of material standards vary depending on the type of material. All material standards contain different grades with minimum (or maximum) values of a number of material and other properties. If e.g. certain yield strength is needed, the designer refers to a grade with an accurate strength from the standard. In doing so the supplier is responsible for assuring that the strength requirement is met.
What differs between the standards is how these grades are certified and which properties that must be inspected. Certification means verifying that a material belongs to a certain material grade. Just testing the values of a number of properties is not sufficient in a complete material standard. Since the properties are affected by the way the material is treated in production or when the product is in service, additional specifications are needed. Examples include specifying that the chemical composition of the material must stay within certain ranges or that the microstructure of the material must be checked. The standard can e.g. state that the structure must be 90% martensitic for a particular grade.
One of the reasons for the diversity is that the material standards have, over a considerable length of time, been developed through building consensus at meetings in technical committees (TC). The standards are regularly revised by the organizations who issue them such as ISO or ASME. The resulting material standards are compromises of all the stakeholders' different interest. The material producers have one agenda, those how work in test and verification has another and so on.
However, the object of any material standard is to allow the designer to unambiguously specify the material in such way that the materials behaviour can be predicted in production as well as when the product is in service and when it is recycled. All other interest like e.g. minimizing the amount of testing is of secondary interest. In fact, the designer is the primary customer of the material standard.
Since the development of material standards is a matter of best fulfilling the customers' requirements under given constraints it is possible to treat it like any design problem. Taking on a design problem should start by clarifying the customer requirement, proceeding to finding concepts that fulfil these requirements. The concepts should be evaluated and the most promising should be detailed for further evaluation. Standard development is for historical reasons focused on the consensus building in national and international committees. The standards are finally adopted or rejected trough voting.

This gives little end user focus. The development of material standards can therefore gain from adopting methods from design. It is not obvious when studying different material standards how the customer requirements have been addressed.
This paper will attempt to find the customer requirements on material standards and then investigate how these requirements have been met in four different standards. It will not focus on a single type of material, but rather to find requirements that designers have regardless of the type of material. The result is that the standards match the requirements to a varying degree and none of the standard matches the requirements completely.

2. The structure of material standards

Material standards are mixes of performance and prescriptive elements. Performance elements are those that are directly aimed at the needs of the designers, such as the mechanical and physical properties of the material. Prescriptive elements are for checking the result. It can for instance involve checking if the microstructure of the material is correct. The terminology prescriptive and performance is mostly used in building and construction [Myers 1981], [Dehn 2010] It will in this paper also be used for other types of materials and components. All standards state the minimum requirement for properties such as the highest stress that the material must withstand. These properties must, to certify that a material belongs to a certain grade, be inspected using specified methods. These test methods are specified in referenced standards and describe how the testing procedures should be conducted, specifying the number of samples to test and so on. It can then be certified with a statistical certainty, that the property does not fall short of the minimum value. Properties that are mandatory to inspect are called normative. Some standards also include property values that do not have to be inspected. They are merely for indicating a likely result. These are called informative.

3. Customer requirements on a material standard

The customer requirements are based on the expected use of the standard. The first consideration of any material standard is to make a supplier independent specification of the material. A material from a certain grade must behave in a similar way regardless of supplier. When the materials are heat treated or subjected to various service conditions such as heat, cold or corrosive environments, the properties are affected. These effects depend on the chemical composition of the material. If the manufactures are allowed to decide the composition of the material freely, unexpected differences in behaviour between grades may occur. The addition or removal of a particular constituent would perhaps result in a different annealing temperature rending an unsatisfactory result or a component made from the material would start to behave differently in service. Either the material standard can specify the chemical composition or it has to be checked that the end result is the correct one by checking the microstructure. The first option is preferred since it gives the designer the possibility to predict other effects than just the materials reaction to heat treatment. Checking the microstructure can be done either by directly by microscope or by checking a property related to structure. The permitted ranges in the specification of the chemical composition must be carefully chosen to avoid sudden changes in material behaviour. The TC who designs the standards must therefore have knowledge on the expected use.
If the specification of the chemical composition is too firm there is little or no room for material development. It is better to have a standard that is oriented towards adding value for the consumers, i.e. providing better properties at the same or lower cost.
As new materials are being developed it is important to have an active and responsive TC. New grades should be added as needed for materials that cannot be accommodated in the existing ones. Further, an active TC is also helpful then problems with the existing grades occur such as when customers begin to use the materials in new ways. Countermeasures involving prescriptive actions such as checking the hardness to get a perception of the microstructure can be amended to the standards. The standard should exemplify and propose additional tests as commonly occurring pit-falls becomes known to the TC. If a reported problem cannot be solved directly at least the standard should report its existence. This can be communicated prior to making a new issue if the standard, preferably trough some type of website service.

It is important that the TC documents the reason for the changes, describing the nature of the problem and how the countermeasure is expected to solve the problems. If not properly documented, the standard will become hard to interpret. It is much easier for the customers to find confidence in the standards if the structure is readily understood. As revisions to the standard are made, descriptions of these should be published along with the standard.

In the early phases of design, the standard is presumably used for screening. The designer need to know what properties that can be expected from the material. It does not have to very precise, but provide enough information to make feasibility studies and compare to alternative materials and processes. The standard can give informative values for a large number of properties. Although material standards can be used for screening, it is less important than the specification task. For screening there are a lot of resources available on the web as well as dedicated software [Ashby et al. 2004]; [Ramalhete et al. 2010].

It is not known beforehand which properties that is important for the designer to specify to make the design successful. It all depends on what is expected from the design. Common elastic properties like tensile and ultimate strength are very often included. However, the designer will perhaps instead need to know the fatigue strength in rotating bending or the electrical conductivity. The properties that are important for the success of the design should be normative in that it gives the customer the possibility to hold the supplier accountable, should the material not fulfil the requirement.

However, the standard cannot possibly include verified minimum levels of all conceivable properties since the testing required would be too extensive. In order to get around this problem components with similar requirements can be identified, forming categories of components which need similar material properties to be sucessful. Precicely these properties should be mandatory to inspect in the standard. This will also provide assistance for the designer in the specification step - The important properties for a particular type of product will not accidently remain unspecified. Trying to predict the intended use of the materials is also important from the earlier mentioned specification of chemical composition. Knowing how the material will be processed and be used in service will be helpful when establishing which ranges to use.

There must also be acceptance that everything cannot be included in the standard. The designer will sometimes have to specify additional testing depending on the requirements. Broad scope classes need to be included such as “material for structural parts” with the notion that the designer can specify additional testing.

To summarise, the requirements that should be put on a good material standard are listed in the six points below in falling order of importance:

1. Materials belonging to the same grade should behave in similar ways regardless of supplier.
2. In must be possible to hold the supplier accountable, should the material not comply with the standard.
3. The structure of the standard should be motivated and the reasons for changes clarified.
4. The standard should support the designer in the making the specification.
5. The standard should allow improvements of the grades to increase customer value.
6. The standard should be useful in early stages of design (screening).

In addition, the expected deviation of the specified properties must be quantified. This is not included in the priority list since it is unconditional. The six other items can be fulfilled to a varying degree. The last point is an unconditional requirement. The Points 1-4 and 6 have been investigated for four different standards in this paper. It will give an insight in how well these requirements have been met. It is more difficult to find evaluation criteria for point 6. It has not yet been looked into. Further, allowing improvements and having similar behaviour of the grades are conflicting requirements. Similar behaviour requires strict specification, leaving little room for improvements. To design the perfect material standard, there must be a more thorough investigation on which of the two is most important. Alternatively, it is perhaps best solved by having two types of grades.

4. Investigated material standards

A standard for sintered materials ISO 5755:2001 [ISO 5755 2001] a standard for fasteners made of carbon steel and alloy steel ISO 898-1:2009 [ISO 898-1 2009], a standard for spheroidal graphite cast

irons ISO 1083:2004 [ISO 1083 2004] and a standard for cement ASTM C1157/C1157M – 10 [C1157/C1157M-10 2010] have been investigated. These standards are only a small selection of all the standards covering these fields. They encompass raw materials as well as ready components.
When evaluating the standards, differences emerge. The standards for cast iron and cement are to a high degree performance-based whereas the two other standards have a varying degree of prescriptive and performance elements. The evaluation starts with a brief description of each standard below.

4.1 Sintered materials

The standard ISO 5755 contains a number of tables structured according to the use of the material and the chemical composition. The materials are designated as grades e.g. F-05C2-300 is a copper carbon steel with 0.5% carbon and 2% copper and a minimum of 300MPa tensile yield strength (YS).
Of the 11 different tables, tables 1 and 2 are grades for use in bearings. Tables 3-10 are ferrous materials for structural parts and table 11 is non-ferrous materials for structural parts. The tables include both informative and normative properties. For all grades the chemical composition of the powder must be inspected. The percentage values of the constituents are specified with a large tolerance. Which properties that is informative and normative differs somewhat between the tables. For the grades used for bearings the radial crushing strength and the open porosity are normative. In addition informative values on a few other properties are given.
In the tables for structural parts, 3-11, the tensile yield strength (YS) or alternatively the ultimate tensile strength (UTS) are normative. Informative values are given for a number of different properties including hardness, elongation, and fatigue limit. The standard does not specify any maximum shrinkage after sintering.

4.2 Spheroidal graphite cast irons

In the same way as for sinter steels the spheroidal cast irons (ISO 1083) are structured into grades. An example of a grade is ISO 1083/JS/400-15/U. The letters JS stands for ausferritic spheroidal graphite cast iron. It has a UTS of minimum 400MPa and its minimum elongation to fracture is 15% as seen on the two figures 400 and 15 in the designation. The letter U tells that the sample is cast-on. The designations can be amended with letters RT and LT meaning that there is a requirement for a minimum impact resistance at low temperature (LT) or alternatively room at temperature (RT).
Notably, the standard does not have any requirement regarding the chemical composition of the iron. It is left completely to the discretion of the manufacturer although an example of a chemical composition is given. In order to certify a grade, the manufacturer just has to assure that the graphite is spheroidal and show compliance with the minimum mechanical properties.

4.3 Bolts, screws and studs

The designation system of metric bolts, screws and studs (ISO 898-1) is special. A screw is designated by the letter M (for metric) followed by its nominal dimension e.g. M8. The material properties of the screw is given by two numerals x.y where the first number x denotes the UTS of the material in hundreds of MPa and the second number y is what the factor to multiply it with to obtain the YS. This factor is multiplied by 10. Thus, the designation 10.9 means 1000Mpa UTS and 10*0.9=900MPa YS. Class 8.8 mean 800Mpa UTS and 640MPa YS.
The two tensile properties are only tested for some dimensions and classes. The chemical composition of the material with minimum and maximum values for the alloying elements is mandatory to inspect. There is also a requirement regarding the annealing temperature. The surface roughness of the thread and the hardness must be inspected for all screws. Depending on the class and dimension of the screw there are a number of other properties that are listed as mandatory, optional or impossible to inspect. Examples include UTS, elongation, and size of decarburised zone, proof load and several others. It is tabled which of them should be inspected for each dimension and class by stating “feasible” “non-feasible” or “optional”.
There is also a requirement on the microstructure of the material. It must be inspected that the structure is 90% martensitic for all screws in classes 8.y and higher. That requirement has been added to assure that the ductility is limited, so that YS is not reached too early compared to UTS.

4.4 Cement

The ASTM standard for hydraulic cement (C1157/C1157M-10) is predominantly a performance-based standard. It is divided into six different types: GU-general purpose, HE-high early strength, MS-moderate sulphate resistance, HS-high sulphate resistance, MH-moderate heat of hydration, LH-low heat of hydration. Only a single set of requirements apply to each type, i.e. unlike the other three standards it is not divided into several strength classes. The standard refers to methods of testing all requirements. For all six types the time of setting is tested and the compressive strength must exceed minimum values after 1, 3, 7 and 28 days. There are requirements also on the dimensional stability by specifying the maximum allowed shrinkage. There are specific requirements that apply to the type of cement (HE, MS and so on). The heat of hydration is for example maximised for the MH and LH types. In addition it is optional to specify low reactivity (option R) with a set of additional requirements. The standard also contains properties that must be measured, but no limit value exists. These properties are fineness i.e. the fraction retained in a 45µm sieve, air content and dry shrinkage.

5. Evaluation criteria

To assess how well the earlier identified customer requirements are met some criteria is needed. These criteria have been identified and are for each standard shown in table 1 below. To have a similar behaviour of the grades (requirement 1), the chemical composition is specified or alternatively the microstructure is somehow verified. Requirement 2 (accountability) is evaluated by the number of normative properties. Requirement 3 (deviation) is given for the normative properties in all standards. None of the standards gives an expected deviation for the informative properties. Requirement 4 (motivation) is divided into motivated structure and motivated changes.

Table 1. Evaluation of the standards

		Cast Iron (ISO1083)	Sinter (ISO5755)	Fasteners (ISO898-1)	Cement (C1157/C1157M-10)
1	Similarity				
	Chem. Composition	NO	YES	YES	NO
	Microstructure	YES (a)	NO	YES	NO
3	Number of normative properties	4	2(b)	10 (c)	12 (d,e)
4	Deviation specified	YES	YES	YES	YES
5	Motivation				
	Structure of the standard	NO	NO	NO	NO
	Changes specified	NO	NO	NO	YES (f)
6	Dedicated classes	NO	YES	YES	YES
7	Informative properties	YES	YES	NO	NO

(a) Spheroidal graphite specified. Informative section on dominating microstructure.
(b) Which two properties that are normative varies between the tables.
(c) The number depends on strength class - minimum 2, maximum 10
(d) Four of the 12 properties are optional.
(e) For three of the properties no limit value exist. Properties are measured and declared on the certificate.
(f) Description of changes from previous issue included.

6. Conclusions and future work

The reason why the chemical composition is specified for the sinter steel but not for the cast steel is possibly found in the traditional segmentation of the sinter steels where the simplest grades consists of iron, copper and carbon. More highly refined grades have additives of nickel, manganese, phosphorus and molybdenum. This provides a starting point for classifying the sinter steels. However, the exact chemical composition of the material is often not a primary consideration for the designers. The main

rule should be not to make any unnecessary specifications since it makes the continuous improvement of materials belonging to the existing grades more difficult. The chemical composition should only be specified in order to avoid foreseeable problems by e.g. maximizing or minimizing in the constituents.
The number of normative properties is smaller in the sinter standard than in the other standards. It is useful to have many normative properties since the supplier is responsible for that they are kept as well as keeping the deviation under control. Having a greater number of normative properties multiplies the amount of testing required to certify the grades. It would therefore be preferred if the TC: s started to identify typical component types with similar requirements. Only the properties that are important to the particular type of component would then have to be tested. The designers would be helped in making the specifications and the amount of testing would decrease without compromising the usefulness of the standard. For powder metallurgical components there have some classes defined [Stolt et al. 2010].
It is interesting to note that the American cement standard accounts for the changes made between different revisions of the standards directly in the new issue of the standard. It is useful for the designer to get a perception of the development of the standard. Apart from a brief synopsis, none of the standards gives an elaborate motivation for the structure. Accounting for the intent behind the different elements in recommended. This would increase the designer's confidence in the standard and their willingness to use it for specifying materials.
Informative properties are given in two of the standards. It has earlier been explained the necessity of doing so for screening purposes has decreased. It is instead the specification part of the standard that should be emphasized. Material suppliers can themselves inform on the performance of the standard grades through material databases. The standard should only feature guaranteed levels.
A universal structure, applicable for grading any material can probably not be found since different materials have different behaviour. Some materials are e.g. more sensitive to variation in the chemical composition than others, needing a stricter specification.
To summarize the recommendations to the standard organisations and the TC: s is:

- Specify chemical composition only when necessary to avoid foreseeable problems.
- Identify components with similar design requirements and structure the material grades accordingly. Relevant properties should be normative.
- Inform on the structure of the standard to make the designers more knowledgeable on the consequences of referring to material grades on drawings.
- Inform about on the changes in new issues of the standards.
- Inform about discovered problems between the issues of the standards.
- Remove the informative properties from the standards.

6.1 Future work

For individual types of materials it is perhaps possible to find a standard which best fulfil the needs of the designers. To find how such standard should be constituted, methods for assessing the requirements such as quality function for deployment (QFD) can be applied. The customer requirements will perhaps be found to be so diverse that the standard need to be divided into different section with dissimilar way of certifying the grades depending on the designer's needs.

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