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Evaluation Criteria for Comparing Domestic and Foreign Material Specifications

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Measurement Laboratory
Metallurgy Division
Washington, DC 20234

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ABSTRACT

Consistent decisions on the degree of equivalency between metal specifications of different national origins cannot be made only on the basis of chemical composition and direct comparison of mechanical property numbers. There are numerous additional factors, including metallurgical effects, product form effects, test acceptance criteria, and differences in specification philosophy which, if present, may influence the determination of equivalency because of their effect on property requirements. In order to remove the uncertainty in this decision-making process, these additional factors must be evaluated for each comparison.

Excerpts from actual comparisons have been used to illustrate the methodology based on the principles discussed in this report. The specific evaluation criteria identified are not meant to be totally inclusive, but rather represent those most often encountered. Some material specifications, especially application specifications, may include special requirements dictated by the application. Finally, material specifications are dynamic documents because revisions of test methods and test requirements are part of the specification writing process. Care must always be exercised to insure that the appropriate versions of specifications are being compared.

capped steel	A classification of steel based on the amount of gas evolved during solidification as a result of steelmaking deoxidation practice. In capped steels, the normal oxygen-carbon reaction during solidification is stopped at a particular point by placing a mechanical cap over the ingot mold. A capped steel will have the low carbon rim typical of rimmed steels but will have greater uniformity of composition and mechanical properties like a killed steel.
coupon	A piece of metal from which a test specimen can be prepared. Often an extra part of a casting or a forging.
ductility	The ability of a material to deform plastically without fracturing.
heat-affected zone (HAZ)	The portion of the base metal not melted during brazing or welding but whose microstructure and properties are changed by the heat from the molten metal. The region separates the unaffected base metal from the weld or molten metal zone.
killed steel	A classification of steel based on the amount of gas evolved during solidification as a result of steelmaking deoxidation practice. Killed steels are produced by adding deoxidation agents, e.g., silicon and aluminum, to the ladle before pouring into the ingot mold. This reduces the oxygen content to such a low level that there is little or no oxygen-carbon reaction during solidification. Killed steel ingots typically have a large shrinkage cavity and relatively uniform chemical composition and mechanical properties throughout the ingot.
martensite	In steel, a metastable phase of iron and carbon formed by the diffusionless transformation of a high temperature phase. A supersaturated solid solution of carbon in iron characterized by high strength and low ductility.
necking	Reducing the cross-sectional area of a tensile specimen in a localized area as a result of nonuniform deformation. Occurs after the attainment of maximum load during a tension test.
pearlite	In steel, a lamellar mixture of low carbon iron and iron carbide formed by a diffusion-controlled transformation of a high temperature phase.
rimmed steel	A classification of steel based on the amount of gas evolved during solidification as a result of the steelmaking deoxidation practice. Rimmed steels are poured into ingot molds without deoxidation by silicon or aluminum. Oxygen and carbon react continuously during solidification. This continuous reaction causes the region near the ingot surface to be lower in carbon, sulfur, and phosphorus than the average ingot composition. Rimmed steel ingots are less likely to have a large shrinkage cavity while chemical composition and mechanical properties vary widely throughout the ingot.
upper shelf or upper shelf energy level	The average value for all impact test specimens whose test temperature is above the upper end of the ductile-to-brittle temperature transition region.

INTRODUCTION

The Office of Merchant Marine Safety, United States Coast Guard, Department of Transportation, has primary responsibility for enforcing safety regulations applicable to all commercial shipping, both domestic and foreign, operating within United States territorial waters. For U.S. flag vessels manufactured in foreign countries or manufactured domestically with foreign produced materials, the Coast Guard is required (Title 46 Section 366 of the U.S. Code) to make a determination as to whether materials of construction produced under foreign specifications for specific components, such as pressure vessels, piping, fasteners, flanges, are acceptable substitutes for materials produced under approved United States specifications. Currently, Coast Guard rules are taken primarily from standards and specifications issued by United States standards writing organizations, e.g., American Society for Testing and Materials (ASTM) and American Society of Mechanical Engineers (ASME).

In recent years, a number of organizations have attempted to facilitate this process of comparing material specifications from different countries by using various approaches based primarily on matching chemical composition. As a result, a limited number of compilations of foreign and domestic material specifications have been developed. (1-5)* These lists of apparently equivalent specifications are of limited use, however, because of the emphasis on only chemistry and specific mechanical properties. The absence of a more comprehensive technical analysis of the equivalency or lack thereof between individual foreign and domestic specifications has often resulted in a case-by-case determination of equivalence or acceptability.

In the review of foreign material specifications, an inspector or approving official is responsible for evaluating the foreign materials and certifying that these materials can be substituted for U.S. approved materials. Materials produced under approved U.S. specifications have been proven suitable for their intended service, and since they also have been incorporated into various industry standards, any limitations or service restrictions on their use are known. Current procedures for evaluating the equivalence of foreign and U.S. approved materials are not always uniform and consistent because equivalency has taken on various meanings, depending upon the inspector or approving official. This often leads to uncertainty as to whether materials produced under foreign specifications will be accepted.

Some approving officials consider materials equivalent if only the chemical compositions are the same; thus a pipe specification could be considered equivalent to a forging specification if they had identical chemical requirements. Other approving officials consider both chemical and mechanical property requirements, while others take into account additional requirements, such as heat treatment, product form, and non-destructive tests. In addition to the different choices of requirements to be satisfied for equivalency, the weight given to specific requirements is not always the same. Some approving

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*The numbers in parentheses refer to references identified at the end of the report.

officials believe in absolute numerical equivalency without regard to end-use, and thus similar but not identical materials may be rejected or restrictions placed on the material to make it equivalent. Specification writers prefer to use whole numbers and thus rejection can occur even when minor differences in numerical values are not physically real but may be due to the conversion of numbers from one type of units to another, as between English and metric units. Other approving officials may take into account the end-use, e.g. a material used in an air line filter will not require the same degree of agreement between properties as would be required for pipe in a cargo piping system. In a similar manner, the design factor of safety for the component may be considered, that is, the greater the factor of safety, the less weight the approving official may give to small differences in the material specifications. Lastly, the amount of metallurgical knowledge and background possessed by the inspector or approving official will significantly affect the evaluation process.

In order to establish the level of equivalence between material specifications, comparisons must be based on a set of identified criteria characterizing the essential properties and behavior of the material. These criteria include specification writing philosophy, metallurgical and processing parameters, and quality control parameters. Systematic procedures or guidelines are necessary to achieve consistent and reproducible comparisons for determining the level of equivalence.

COMPARATIVE ASSESSMENT

To meet the short term problem of case-by-case determinations of the equivalence between material specifications, detailed metallurgical evaluations of selected specifications were carried out to develop a manual that specifies: (a) those foreign specifications or alloy grades within a specification that are acceptable substitutes or equivalent to domestic specifications; (b) those foreign specifications or alloy grades that are not acceptable substitutes; and (c) those foreign alloy grades that would be acceptable substitutes if certain additional criteria were satisfied. Approximately sixty material specifications, twenty domestic and forty foreign, were chosen representing the materials most widely specified for critical ships components. (see Table I) Comparisons were made between Japanese Industrial Standards (JIS), Deutsche Institut fur Normung (DIN) Standards, and American Society for Testing and Materials (ASTM) specifications. Each comparison was carried out between two specifications: the domestic ASTM document and the relevant JIS or DIN document, and an extensive report was prepared containing the metallurgical analyses and conclusions about the degree of equivalence for each pair of specifications. (6) In all cases, the ASTM specification was the Coast Guard approved benchmark to which the foreign specification was compared.

The process of determining whether one material specification is equivalent to another can be complex and is dependent on the evaluation of a variety of factors. Decisions must be made as to the relative importance of these factors. A finding that two material specifications are equivalent implies that these materials will be interchangeable in any application, that is, they will perform in a known and like manner even though the specification documents are not performance standards.

The process of comparing foreign specifications to domestic specifications is further complicated by differences in specification philosophy, not only for foreign versus domestic, but even among specifications of the same national origin. Some specifications are highly specific in listing typical applications or end-uses, i.e. application specifications, while others are highly specific in listing end-uses for which the specification does not apply either because of inappropriateness or because another specification covers the application. Other specifications are limited to product forms including plate, pipe, castings, etc., i.e. product specifications, while some are true material specifications not limited to product form or applications. Some specifications contain hints about the rationale for specific requirements or limits while others offer no guidance. Some specifications state the environment of the application, i.e., temperature and/or pressure conditions, without specifying properties for these conditions, while others specify additional requirements for these conditions. The final evaluation of specifications cannot be carried out without knowledge of the specific end-use of the material and its operating environment. Thus, there will be situations where the ultimate determination of equivalence between material specifications will depend on the actual application of the material in a component or structure and the design operating parameters for that structure.

Design engineers, however, still make material selection decisions based on specified material properties and these property requirements can be compared and a generalized determination of equivalence or suitability made on this basis. However, it is not sufficient to simply compare lists of numbers representing chemical and mechanical characteristics and conclude equivalence or lack thereof.

This report generalizes the approach followed in carrying out the specification comparisons. Evaluation criteria are identified and discussed in terms of their role in the determination of equivalence. These criteria are presented as a guideline for conducting comparisons of foreign and domestic material specifications. Portions of actual comparisons will be used to illustrate the methodology followed.

GUIDELINES AND EVALUATION CRITERIA

Consistent decisions on the degree of equivalency between metal specifications of different national origins cannot be made only on the basis of chemical composition and direct comparison of mechanical property numbers. There are additional factors which, if present, may influence the determination of equivalency because of their effect on property requirements. The factors may be broadly grouped in the following categories:

1) Specification Philosophy
2) Composition Effects
3) Metallurgical Effects
4) Product Form Effects
5) Test Acceptance Criteria

In order to remove the uncertainty in this decision-making process, the role of each category must be evaluated for each comparison.

The starting point is always to determine whether or not the two specifications being compared contain a common basis for comparison, i.e. are they describing the same subject? The determination is usually based on an examination of the section of each document which contains information about the specification philosophy being followed. (This is usually the "Scope section in U.S. specifications.) This step insures against comparing unrelated specifications, e.g. a casting specification against a forging specification. The philosophies illustrated by the foreign and domestic specifications reviewed for the Coast Guard are reviewed in this report with respect to their influence on the comparison and evaluation criteria.

Evaluation of chemical composition is the next step in comparing specifications. Such evaluations generally cannot stand alone, however, and must be interpreted along with other considerations such as: the methods of primary metal production and their effect on chemistry; subsequent thermo/mechanical processing and the interrelationship between chemistry, mechanical properties, fabrication requirements, corrosion resistance, and such qualitative requirements as weldability. In some specifications, chemical composition requirements are not directly controlling but are, in fact, determined from the desired mechanical property requirements and the allowed methods of primary metal production.

Mechanical properties such as strength and ductility are typically referred to directly in specifications and thus are major comparison criteria. Measured mechanical properties depend not only on such obvious factors as chemistry and thermo/mechanical processing, but can be strongly influenced by more subtle factors such as: location within the material from which test specimens are taken, changes in structure and properties due to cooling rate differences, or metallurgical effects; and the geometry (size and shape) of test specimens and its effect on measured parameters, the orientation of test specimens with respect to processing directions, or product form effects. In addition, there are situations where each specification may require the same qualitative test but use a different acceptance criterion to determine what constitutes passing the test. Thus, an evaluation of the acceptance criteria must be made to determine if the difference is significant. Caution must be exercised when direct comparisons are made between mechanical property numbers to insure that both numbers are a measure of the same phenomena normalized for differences in test conditions and test specimens.

Specification Philosophy

The general format and scope of the ASTM, JIS and DIN metals specifications reflect different characteristics that play a role in any comparison procedure. These differing characteristics can be used to classify specifications into broad categories or types. For metals, the classifying variables of composition, form or method of production, and use or application provide a basis for distinguishing between, respectively, material specifications, product specifications, and application specifications. Sometimes the specification does not fall neatly into one type but rather is a combination of two types. For example, in the United States, the dominant systems for identifying carbon and alloy steels are those developed by the American Iron and Steel Institute (AISI) and the Society of Automotive Engineers (SAE). These systems are based only on chemical composition and thus according to the approach outlined above, the published AISI/SAE designated alloys are true material specifications. ASTM, on the other hand, has developed a number of product/application specifications which frequently reference AISI/SAE alloys. For example, American Iron and Steel Institute (AISI) type 304 stainless steel with one set of chemical requirements is specified within 31 different ASTM specifications: 6 specifications are for fabricated products, e.g. nuts, bolts, flanges, for general, high or low temperature service; 16 specifications are for mill products for general service, e.g. plate, sheet, strip, pipe; and 9 specifications are for mill products for specific applications, e.g. boilers and other pressure vessels, sanitary tubing.

The typical ASTM metal specification is written as a product/application specification, that is, other than chemical limits, the mandatory test requirements are frequently tailored for a particular product and application. The JIS specifications are also usually product/application specifications, while the DIN documents are often substantially different in format and content than either the ASTM or JIS specifications. Some of the DIN specifications resemble material specifications, that is, they contain a large generic class of alloys, e.g. quenched and tempered steels, stainless steels, used in many diverse applications. These specifications, however, also contain detailed information on all product forms available, e.g. plate, sheet, bar, pipe, wire, forgings, the heat treatment conditions available, e.g. normalized annealed, quenched and tempered, and the specific properties guaranteed for particular products forms and heat treatment. A classification of foreign and domestic metals specifications by specification type is shown in Figure 1.

Often the ASTM document is organized into two parts. The first part is divided into sections which contain all of the descriptive and mandatory requirements for the specific alloys covered by the specification. These sections cover topics such as: scope; applicable documents and general requirements for delivery; basis for purchase or ordering information; manufacturing process, including heat treatment; chemical requirements; mechanical requirements, including test specimen and methods of test;

number of tests and retest rules; marking and packaging; and basis for rejection. The second part, not present in all metal specifications, contains supplementary or optional requirements which may be requested by the material purchaser and agreed to by the seller. Typically, these supplementary requirements include additional numbers of tests and/or different types of tests than the mandatory tests.

In some ASTM ferrous mill product specifications, the alloy will be described as representing a specific "quality." The term quality as used by the metals industry does not mean that the product is better or worse than other mill products but, rather that the product has characteristics that are particularly important for specific applications or subsequent fabrication processes. Over the years, a group of terms or "quality descriptors" have been developed by the metals industry to enhance communication between producers and users of metals products. Detailed descriptions of many of these terms can be found in the appropriate parts of the AISI Steel Products Manual. A few examples are given below with the accompanying descriptions located in Appendix A.

Carbon Steel Quality Descriptors

<u>Carbon Steel Plates</u>
- Regular Quality
- Structural Quality
- Forging Quality
- Pressure Vessel Quality
- etc.

<u>Hot Rolled Carbon Steel Bars</u>
- Merchant Quality
- Special Quality
- etc.

<u>Steel Specialty Tubular Products</u>
- Pressure Tubing (Quality)
- Mechanical Tubing (Quality)
- etc.

There are additional mandatory requirements for most of the ASTM alloy specifications that are not contained within the specific alloy document or its supplementary requirement section. These additional requirements are found in other specifications, often called general requirements for delivery. These general requirement specifications must also be satisfied unless otherwise stated in the individual document. Thus, the individual alloy specifications may contain those requirements that are different or not included in the general requirements for delivery.

The mechanical property requirements in ASTM specifications are almost always specified only for room temperature even for alloys designated for other than room temperature service. Data and other information on the typical or expected mechanical properties for the alloy at other temperatures are not provided in the specification, but are left to other standards or code writing organizations to specify.

The JIS metal specifications closely resemble the ASTM specifications, occasionally using almost identical language, as illustrated in Figure 2. The document format is somewhat different, however, because the JIS specifications do not contain a section on supplementary or optional requirements. Some of the ASTM supplementary requirements are mandatory in the JIS documents while others are omitted. Many JIS metal specifications also must satisfy requirements which are not found within the specification document. These requirements are found in specifications of general rules for inspection, somewhat analagous to the ASTM general requirements for delivery. However, the JIS general rules for inspection primarily contain requirements for the location of various types of test specimens as well as the number of tests to be carried out. Comparisons between individual ASTM and JIS specifications have shown that overall the same types of tests are required in both documents even though the test details, e.g. specimen type, location, and acceptable test value may be different. As in the case of the ASTM specifications, the JIS documents do not include elevated temperature requirements for the alloys specified for elevated temperature service. Only room temperaature properties are specified.

The DIN documents, both material specifications and product specifications, tend to be more complete because a larger number of property requirements are included, e.g. mandatory requirements on notched bar impact strength, steel hardenability behavior, magnetic properties. Further, those DIN specifications for alloys in elevated temperature service contain tensile strength requirements, typically yield strength, over the applicable temperature range. Often, reference or advisory data on such properties as creep-rupture strength and ultimate tensile strength, working pressures for piping, temperature dependence of modulus of elasticity, thermal expansion and thermal conductivity, and hot working temperatures are included to assist in materials selection for specific applications. When ASTM product specifications are compared to these DIN specifications, care must be exercised to insure the correct comparison.

Many of the DIN product specifications, e.g. for welded steel pipe, contain different sets of requirements for various quality levels associated with different end-use applications. These quality levels are usually identified by a particular code, e.g. Sheet 2 quality, Sheet 3 quality. Although the alloy grades common to more than one quality level have the same chemical composition limits and the same tensile property requirements, each quality level requires either different additional tests or different acceptable property values for the same test. Thus, only one of the DIN quality levels may satisfy the domestic requirements.

As an example, ASTM A312, Seamless and Welded Austenitic Stainless Steel Pipe, describes a mill product, pipe, in either the hot or cold finished condition and contains requirements for numerous grades of austenitic stainless steel pipe in standard nominal diameters for high temperature and general corrosion service. Further, a foreign specification comparable to ASTM A312 is assumed to be DIN 17440, Stainless Steels. The appropriate versions to be compared are the 1977 edition of A312, designated A312-77, and the 1972 edition of DIN 17440, designated DIN 17440-72.

Specification DIN 17440-72 resembles a material specification because it includes almost all alloy steel grades generically called stainless steels, including ferritic and martensitic grades in addition to the austenitic grades. Futher, DIN 17440-72 covers most of the mill products in the hot or cold finished conditions, except castings, including sheet, strip, bars, wire, seamless and welded tubes (pipes), and forgings. On the basis of the scope of each specification, it can be concluded that the mill product described in ASTM A312-77 is one part of DIN 17440-72, thus leading to the next level of comparison.

It is necessary to identify within DIN 17440 those requirements applicable to welded and seamless pipe, including chemistry, thermo/mechanical treatments, and mechanical properties. Since a material specification covers many types of mill products, not all of the specified characteristics and tests are applicable and each section must be reviewed to sort out only the requirements for the product form and/or application covered by the product or application specification. In this example, there is little ambiguity because: almost without exception the various product forms in DIN 17440 have identical chemical requirements; the DIN austenitic grades have heat treatment requirements independent of product; and the DIN mechanical property requirements are based only on alloy composition and heat treatment, again, independent of product. Obviously, mechanical property requirements and special tests applicable only to pipe, e.g. flattening, hydrostatic, must also be evaluated by additional criteria at a later stage in the comparison.

The content of some material specifications, however, is much more complicated because of the metallurgical behavior of the class of materials. Specification DIN 17200, Quenched and Tempered Steels, is an example of a material specification which includes almost all of the mill products except castings, including wire, bars, plate, sheet, strip, seamless tubes (pipe), and forgings, where the individual alloys are supplied according to the processing treatment received. As a result, DIN 17200 contains separate requirements for alloys in a number of thermo/mechanical conditions, including quenched and tempered, normalized, soft annealed, and heat treated for either specific strength or improved workability. Thus, in this example, only the properties and requirements of the appropriate thermo/mechanical condition can be used as the basis for comparison.

Composition Effects

Chemical composition requirements are the starting point for the technical comparison procedure because of the dominant role chemistry has in controlling metal properties, not only specified mechanical properties, but also such often unspecified properties as steel weldability or corrosion resistance. Chemical requirements can be expressed as maximum or minimum values, or as a range of acceptable values. Generally, a determination of chemical equivalence is straightforward since a direct absolute comparison of numbers can be carried out without ambiguity. Most chemical requirements are specified on the basis of ladle or heat analyses of molten samples taken from the refining furnace, representing the homogeneous alloy composition. If the product form covered by the specification is subject to a significant non-uniform distribution of alloying elements or chemical segregation e.g. resulting from steel deoxidation practice, then a product analysis may be permitted in which the product is sampled and wider chemical limits allowed to compensate for the segregation effect. The critical factor in making comparisons of chemical composition limits is to distinguish between differences in alloying element concentration that strongly affect properties, e.g. corrosion resistance and weldability, and those that do not. This evaluation becomes particularly difficult when the affected properties are not directly addressed by the specifications. Weldability requirements are typically not explicitly stated and it is necessary to evaluate the influence of the differing chemical composition limits between the two alloys based on some weldability criterion so that if the foreign material is less weldable, additional controls on the welding procedures may be necessary.

One widely used measure of weldability for ferrous materials is the carbon equivalent (CE) of the alloy; the lower the carbon equivalent the greater the ease of welding for a given material thickness. The CE is determined by the chemical composition and is equal to the sum of the contributions from the alloying elements; each alloying element has a different "weighting" factor in the sum. A number of empirical arithmetic relationships have been developed to fit the behavior of different classes of ferrous alloys.* For carbon and low alloy steels, the carbon equivalent can be represented by:

CE = % carbon + % manganese/6

For example, ASTM A105-77, Carbon Steel Forgings, has maximum carbon and manganese limits of 0.35% and 1.05%, respectively, while DIN 17200-69, Quenched and Tempered Steels, specifies maximum carbon and manganese limits of 0.39% and 0.8%, respectively, for Grade C35. The CE for these two alloys is the same, 0.52, and thus, based on this criterion, have the same level of weldability in spite of differences in chemical composition limits.

Metallurgical Effects

Most of the typically measured mechanical properties, e.g. ultimate tensile strength, yield strength, percent elongation, percent reduction-in-area, and impact resistance can be affected by metallurgical factors such as chemical segregation and microstructure, even for identical chemical compositions.

The thickness effect on properties in many wrought products is an important example of a metallurgical effect. As-cast steel ingots typically exhibit chemical segregation zones because of the very slow cooling rates from the molten state. The extent of the chemical segregation is strongly dependent on the deoxidation practice used and is least for fully deoxidized or killed steels and greatest for rimmed steels. (7) There is substantial variation in chemical composition in rimmed steel ingots compared to killed steel ingots, and this can result in a limitation in maximum thickness for certain rimmed steel products. The degree of segregation for a rimmed

*Examples of these relationships can be found in International Series on Materials Science and Technology, Volume 33, Pergamon Press, 1980.

carbon steel is schematically shown in Figure 3. In addition, steel ingots usually contain an undesirable columnar or coarse dendritic cast microstructure which often exhibits reduced strength and poor ductility. As the ingots are reduced in size by mechanical working, the cast microstructure is broken up, the grain structure refined, and the chemical heterogeneity reduced. If the ingot reduction is not sufficient, the influence of the non-uniform chemical composition and coarse grained cast microstructure may cause unacceptable variability in the mechanical properties of the end product. When high thickness reductions occur from ingot to final product, the microstructural and chemical variations found in the as-cast ingot are reduced. For example, ASTM A36-77a, Structural Steel, does not permit rimmed or capped steel for plates and bars over 13 mm (0.5 inch) thick because of the adverse effect of greater chemical heterogeneity in rimmed or capped steels on both mechanical properties and weldability. The DIN specification for structural steel, DIN 17100-66, however, permits six of its alloy grades to be produced as either rimmed or killed steels without restriction on thickness for plates and bars. Thus, additional limitations on steelmaking practice, must be applied to these DIN grades for thicknesses over 13 mm (0.5 inch) in order to satisfy the A36 requirement.

However, as shown in Figure 4, a killed carbon steel which has undergone substantial thickness reduction still exhibits a lamellar or banded microstructure at the mid-thickness originating from chemical segregation. (8) Thick products tend to retain more of the chemical and microstructural inhomogeneities from the ingot than thin products and thus can retain measurable property variations through the thickness of the product. When comparisons are made between specifications for products in a wide range of sizes, two common approaches can be followed. First, for products below a certain thickness, a specification may require full-thickness test specimens so that the effects of inhomogeneities are averaged out. Data should then be compared between full-thickness specimens. Second, where product thickness allows test specimens less than full-product thickness, the locations within the material from which specimens are taken may be specified to minimize the effects of chemical and structural inhomogeneities. In such cases, care must be exercised to ensure that numerical comparisons are made between specimens representative of a similar microstructure.

Product thickness also results in variations in cooling rate which affects mechanical properties independent of chemical composition effects. For example, thick hot-rolled steel products will typically exhibit lower strength and higher ductility than thin products because, after mechanical working, the differences in cooling rates through the transformation temperature produce different microstructures with different properties. (9) As shown in Figure 5, the change in pearlite spacing due to changes in cooling rate have a strong influence on strength properties. Specifications deal with this problem in a number of ways. In one approach, followed in DIN 17100, Structural Steel, and DIN 17155, Boiler Plates, the chemical composition limits of the major alloying elements are held reasonably constant and the mechanical property requirements adjusted based on product size or thickness to compensate for the cooling rate effect. In another method, used in ASTM A36, Structural Steel, and ASTM A515, Pressure Vessel Plates, the mechanical property requirements are held reasonably constant and the chemistry, primarily carbon and manganese levels for steels, adjusted to maintain the same mechanical properties as the size or thickness changes. One result of comparing specifications based on each approach, e.g. DIN 17100 vs ASTM A36 and DIN 17155 vs ASTM A515, is the observation that as the product thickness increases, a single DIN grade is less likely to satisfy the strength requirements of a single ASTM grade. Different thickness ranges for a DIN grade may satisfy the requirements of different ASTM grades, e.g. grade HIV plate from DIN 17155-59 satisfies ASTM A515-78 Grade 65 strength requirements up to 130 mm thick but satisfies ASTM A515-78 Grade 70 strength requirements only up to 95 mm thick.

A similar influence of cooling rate on microstructure is observed for both ferrous and nonferrous castings because the casting section thickness usually controls the resulting as-cast mechanical properties. Thick-section castings have a lower strength and lower ductility than thin-section castings. (10-12) The determination of mechanical properties of castings requires careful control over the preparation of the test specimen. The solidification behavior is very important because the cooling rate strongly affects the resultant casting grain size; the type and amount of the metallurgical phases present; and the extent and location of chemical segregation, shrinkage, and porosity. These factors dominate the final mechanical properties of the casting in the absence of further heat treatment. Not only are mechanical properties often dependent on the casting size or section thickness, but separately cast test bars can have markedly different mechanical properties than the component casting poured at the same time from the same heat of metal due to exaggerated differences in size, as shown in Figure 6. Typically in copper alloy castings, the permitted test bars or test coupons have essentially the same dimensions, independent of the casting section thickness.

In the case of gray cast iron, an attempt has been made to respond to this problem by adjusting, over a limited range, the test bar dimensions based on the controlling or critical section thickness of the casting. Most castings have critical areas where the resultant mechanical properties control the subsequent behavior of the component. ASTM A48 and JIS G5501 for gray cast iron provide for a series of separately cast test piece sizes allowing selection of a test piece which approximates the cooling rate in the critical section of the casting in an effort to reduce the effect of the cooling rate on mechanical properties. A48 recognizes as-cast specimen diameters of 22.4 mm (0.88 inch), 30.5 mm (1.20 inch), and 50.8 mm (2.00 inch) for a critical section thickness range of 6 mm (0.25 inch) to 50 mm (2 inch) while G5501 requires specimen diameters of 20 mm, 30 mm, and 45 mm for a critical section thickness range of 8 mm to 50 mm. Thus, these specimen diameters are almost the same or are within 10% while the critical thickness ranges for each test piece closely overlap and so the requirements based on these specimens can be directly compared.

For steel castings, test specimens may be taken from coupons cast as part of the casting, from separately cast coupons, or from specified areas of the casting itself. For example, DIN 17245-67, Ferritic Steel Castings, generally requires test specimens machined from coupons cast as part of the casting although separately cast test specimens are permitted when the former is not possible. ASTM A216, Carbon Steel Castings, (by reference to ASTM A703) also allows the test specimens to be taken from casting coupons or separately cast test specimens. Although the ASTM test bar, whether from a casting coupon or a separately cast piece, has an initial diameter of about 31 mm (1.25 inch) and a final diameter of about 13 mm (0.5 inch), the dimensions of the DIN test bars are not defined. Therefore, the DIN properties must be evaluated on the basis of a similarly sized test specimen. In all situations, however, mechanical property comparisons should be carried out on the basis of similarly sized test bars without regard to the correlation between test bar properties and casting properties.

Product Form Effects

The value of testing is measured by the degree to which the performance of a material in service can be predicted from information obtained from tests. Mechanical properties are not uniquely determined; rather, indications of these properties are obtained from samples of the material tested under certain sets of circumstances. A test is significant if: (a) it measures a sufficiently fundamental property such that test data can be used in design, or (b) it can discriminate between suitable and unsuitable materials based on experience in service. (13)

After fabrication, many wrought metal products exhibit mechanical properties that depend on the orientation of the test specimen within the product. This non-uniformity or anisotropy of properties (14) arises generally from one of two sources, crystallography or microstructural features. Athough the individual grains in a commercial alloy are anisotropic in strength properties because of their crystallographic nature, a reasonably random orientation of the grains will result in similar properties in all directions due to the averaging of the orientation anisotropy. Severe cold work, however, can produce a preferred or non-random orientation of the grains which causes anisotropic behavior in the commercial alloy similar to that observed in the individual grains. The yield strength of nonferrous alloys, for example, can be increased or decreased in the direction of the principal deformation depending on the type of preferred orientation which is produced.

Ferrous alloys are more likely to develop anisotropic mechanical properties due to the preferred alignment of microstructural features, e.g. inclusions, chemical segregation, in the principal deformation direction. This alignment is often observed in forgings and rolled products. This preferred alignment, or banding in the case of chemical segregation, relates to the three principal deformation directions in these products. The longitudinal direction is the principal direction of working and longitudinal specimens have their axes aligned parallel to this direction. The short-transverse direction is the direction of minimum product dimension, e.g. the plate thickness. Often, properties in this direction cannot easily be measured because of insufficient material for a specimen. The long-transverse direction (often just called transverse direction) is perpendicular to both the longitudinal and short-transverse directions. For plate products, longitudinal properties are typically specified, while for tubular products, transverse properties are also often specified.

a. Tensile Test

Although little difference between ultimate tensile strength and yield strength values of longitudinal and transverse specimens have been found for forgings and plate products, substantial variations in the tensile ductility parameters and notched impact toughness properties occur. Higher values for percent elongation and reduction-in-area of from 10% to 50%, respectively, have been observed in longitudinal specimens compared to transverse specimens. (15-17) For steel forgings, the anisotropy effect is illustrated in Figure 7. The strong decrease in transverse ductility is primarily a result of the drawing out of the non-metallic inclusions into long stringers. The relationship between impact toughness properties and test specimen orientation is more complex, however, because of the larger number of specimen configurations that can be specified (Figure 8a). The effect of specimen orientation on impact toughness as measured by energy absorption in an impact test is significant (Figure 8b), particularly in the region of the upper energy plateau or upper shelf. (18) For some applications, properties in certain directions assume special importance. For example, in piping and cylindrical pressure vessels which are internally pressurized, the transverse properties are important because the largest principal stress, or hoop stress, acts in the transverse direction. Generally, when specifications do not identify specimen orientation, the longitudinal orientation is assumed. In any event, requirements for the same orientation should be compared.

For over a century, investigators have reported size and shape effects on material strength properties. A recent review (19) of this phenomena reveals the considerable controversy in the literature on specimen size and shape effects on static strength and ductility properties. Although a comprehensive theory or model is lacking, a number of studies (20-24) have indicated that the size and shape of test specimens, including round and rectangular specimens, had no effect on either the measured ultimate tensile strength or yield strength. A tension test, therefore, can give strength properties that, when modified by a suitable factor of safety, can be used as allowable working stresses. Further, the results of these and other studies (25, 26) demonstrated that for round specimens, the tensile ductility parameter percent reduction-in-area is practically independent of specimen diameter as long as the ratio of gage length to diameter, L/D was greater than about 2, whereas a larger effect of size was observed for rectangular specimens. During the test, local nonuniform deformation occurs over a distance of about 2 to 3 times the diameter so that for L/D less than 2, the specimen shoulders act as a lateral restraint against necking and thus the reduction-in-area becomes geometry dependent. (13) Similarly, the interpretation of the rectangular specimen results focuses on the role of restraint by the specimen shoulders on the strain behavior in the reduced section. (26) However, the overall evidence supports the conclusion that the measured ultimate tensile strength, yield strength, and the ductility parameter percent reduction-in-area are relatively independent of specimen size and shape for limited ranges of geometry, assuming metallurgical factors like microstructure are size independent.

A different situation exists for the tensile ductility parameter, percent elongation. Numerous studies (19,20,22-26) have demonstrated the strong effect of specimen size and shape on percent elongation. Percent elongation has significance only when it can be correlated with the performance of the material during fabrication or in service. It is not a design parameter but rather a measure of the relative response of the material to plastic deformation. Historically, the total elongation measured in a tensile test has been divided into a uniform strain component proportional to the specimen gage length and a local nonuniform strain component (necking) that is proportional to the square root of the cross-sectional area. (27,28) A number of empirical relationships between percent elongation, specimen gage and specimen cross-sectional area have been formalized into the following widely used equation combining the uniform and nonuniform components of the total elongation: (29)

$$e = \sigma \left(\frac{\sqrt{A}}{L}\right)^{\alpha} \quad \ldots\ldots \qquad [1]$$

where e is percent elongation, L is the specimen gage length, A is the specimen cross-sectional area, and σ and α are the constants. For round specimens, $\sqrt{A}$ can be replaced by the specimen diamenter, D. For many types of carbon and alloy steels in several heat-treated conditions, the value $\alpha = 0.4$ has been found to give reasonable conversions between different specimen sizes and shapes while $\alpha = 0.127$ can be used for annealed austenitic stainless steels. (30) For copper and brass, a value of $\alpha = 0.2$ has been reported. (29)

This equation is used by ASTM to normalize percent elongation between retangular and round standard test specimens (30) for all wrought products except tubular products. The ASTM round specimen has a constant ratio of L/D of 4 or an equivalent $L/\sqrt{A}$ of 4.51 while the rectangular specimens have a variable $L/\sqrt{A}$ ratio because the specimen thickness is generally the full-thickness of the material. In a similar fashion, foreign standards-writing organization like Deutsches Institut fur Normung (DIN) and the Japanese Industrial Standards (JIS) Committee have identified standard test specimens. The DIN standard specimens for wrought products, whether round or rectangular, generally have a constant ratio of L/D of 5 or the equivalent value of 5.65 for $L/\sqrt{A}$. The JIS standard specimens for wrought products include types with $L/\sqrt{A}$ ratios of 4 to 9 (L/D ratios of 3.54 to 8) as well as specimens with variable $L/\sqrt{A}$ ratios. A summary of the specimen types is shown in Table II.

Elongation values can be converted between specimens of different sizes and shapes by re-writing equation [1] for specimens X and Y:

$$e_X = e_Y \left(\frac{\sqrt{A_X}\, L_Y}{\sqrt{A_Y}\, L_X}\right)^{\alpha} \quad \ldots\ldots \qquad [2]$$

Comparisons of elongation requirements from different specifications must be made on the basis of equivalent geometry. The approach discussed above can also be used for situations which involve more than test specimens with different fixed geometries. For example, ASTM A53-78, Steel Pipe, and DIN 1626-65, Welded Steel Pipe, contain differing approaches to tensile ductility as measured by percent elongation. ASTM A53 calculates the minimum percent elongation for a 50 mm (2 inch) gage length from the ultimate tensile strength and the specimen cross-sectional area. Thus, the $L/\sqrt{A}$ ratio varies for each specimen and the minimum percent elongation for each grade of pipe is different and depends on the type of test specimen and pipe wall thickness. In DIN 1626, a minimum percent elongation is specified for each grade of pipe based on ultimate tensile strength but independent of pipe wall thickness and specimen cross-sectional area, or a constant $L/\sqrt{A}$ ratio of 5.65 for all specimens. Thus, a direct comparison between the elongation requirements between A53 and DIN 1626 cannot easily be made. However, since for all DIN specimens, $L/\sqrt{A}$ is 5.65, it is possible using Table X7 from ASTM A53-78 to calculate the specimen area for constant L = 50 mm at the same $L/\sqrt{A}$ and then compare for any ASTM specimen the resulting expected percent elongation. Assuming the correlation between gage length and specimen area does not change over the range of pipe wall thicknesses in ASTM A53, then the conclusion can be drawn that if requirements of both specifications are satisfied at the same $L/\sqrt{A}$ ratio, then the requirements will be satisfied as the specimen dimensions change.

b. Bend Test

Bend tests are a simple, widely used means of obtaining an index of the materials ductility. For flat products, e.g. plates and flats, the test establishes a measure of a materials ability to undergo plastic deformation without cracking, and thus represents a qualitative forming limit. In the case of welded products, e.g. pipe, bend tests can characterize the overall weld ductility by assessing the behavior of the weld, the fusion line, the heat-affected zone (HAZ), and the base metal for various directions of stressing. Bend tests can also be used as a screening test to monitor the bending ductility for particular types of service or to detect a loss of ductility as a result of processing or other thermo/mechanical treatments. For example, transverse bend tests on electric-resistance welded pipe can detect the undesirable, brittle martensitic structure that sometimes develops in some steel alloys as a result of this high cooling rate welding technique.

Typically, the bend test is a go/no go type of test in which a prepared specimen is bent about a radius of curvature. The material passes the test if a crack does not develop on the specimen tensile surface after being bent through a specified angle, and fails if a crack or cracks develop. In some cases, the tensile surface elongation is measured and used as a ductility index. Generally, the elongation of the tensile surface is directly proportional to the specimen thickness and inversely proportional to the radius of curvature. (See Appendix B) Thus, in order to maintain approximately the same levels of tensile surface strain, specimens of different thickness are bent around different radii of curvature. This analysis only approximates the actual test because it does not account for the observation that the actual maximum tensile strain experienced in bending tests substantially exceeds the calculated value. (31) This observation is not relevant to this report because the bend test criteria normally do not contain any quantitative requirements based on the analysis given in Appendix B. The test itself, however, is considerably more complex than the go/no go criterion indicates because of the strong role that specimen dimensions have on the severity of the test.

In simple bending of a rectangular specimen, shown in Figure 9a, the strain tangent to the bend radius, ε_C, or circumferential strain is assumed to vary only in the thickness direction of the specimen and has its maximum tensile value at the outer specimen surface. The actual circumferential strain distribution across the specimen width is fairly uniform except at the edges, where it is somewhat higher. However, the strain distribution in the specimen width direction, ε_T, is very nonuniform, with a maximum compressive strain at the specimen edges that decreases with distance from the edges, and has a greater effect as the specimen width decreases. Thus, both the specimen width and thickness affect the in-plane or biaxial strain distribution within the specimen. The ability of the bend specimen to undergo plastic deformation, defined as its ductility, is a function of the stress state in the outer tensile surface of the specimen. A biaxial tensile stress state reduces the ductility of the material and so specimens with a low width to thickness ratio (w/t) require a high bending strain to produce fracture because the transverse strain is compressive and must be overcome before a tensile biaxial stress state can be produced. As the width to thickness ratio increases, the effect of the transverse compressive strain decreases and therefore the strain to produce fracture decreases until it reaches its saturation or minimum value at about $w/t = 8$, as illustrated in Figure 9b. For specimens with a $w/t < 8$, the specimen dimensions strongly affect the minimum bend radius below which the material will crack on the outer tensile surface. In evaluating the relative severity of bend test requirements from different specifications, the specimen geometry must be considered in addition to the bending radius. For example, both ASTM A285-78, Pressure Vessel

Plates, and DIN 17155-59, Boiler Plates, require bend tests on transverse-oriented specimens. Each test requires the specimen to be bent 180° around a mandrel of fixed diameter without developing a crack on the tensile surface. The ASTM specification reduces the mandrel diameter/specimen thickness ratio as the specimen thickness increases in order to maintain similar degrees of test severity while DIN 17155 sets a constant ratio independent of thickness for each grade of steel. These requirements are illustrated as follows:

$$\frac{\text{Mandrel Diameter}}{\text{Specimen Thickness}}$$

Specimen Thickness	ASTM A-285-78 (ASTM A20-78)	DIN 17155-59 Grade HI	Grade HII	Grade HIII
$\leq$ 25 mm	1-1/2	1/2	2	2-1/2
>25 to $\leq$ 38 mm	2-1/2	1/2	2	2-1/2
>38 mm to 50 mm	3	1/2	2	2-1/2
Specimen Width	32 - 41 mm	30 - 50 mm		

The somewhat wider specimen allowed by DIN 17155 means that for a given specimen thickness, the DIN test is generally more severe than the ASTM test. Based on the the mandrel diameter/thickness ratio: the DIN test for grade HI is more severe than the ASTM test for all specimen thicknesses; the DIN test for grade HII is less severe than the ASTM test for all specimens 25 mm (1 inch) or less in thickness and more severe than the ASTM test for specimens greater than 25 mm (1 inch) thick; the DIN test for grade H III is less severe than the ASTM test for specimens 25 mm (1 inch) or less in thickness, of equal severity to the ASTM test for specimens greater than 25 mm (1 inch) thick and 38 mm (1-1/2 inch) or less thick, and more severe than the ASTM test for specimens greater than 38 mm (1-1/2 inch) thick and 50 mm (2 inch) or less thick.

c. Impact Test

Historically, the tendency for normally ductile steels to catastrophically fail in a brittle manner under certain conditions led to the increased usage of notched-bar impact tests to evaluate the susceptibility of a material to brittle fracture. The notched-bar impact test satisfies the important criteria contributing to brittle fracture, namely, a triaxial stress state and a high strain rate. The notch provides a localized stress concentration and limits local deformation, while impact loading creates the high strain rate resulting in the impact energy being absorbed in a localized volume at the root of the notch. The notch contributes the triaxial stress state in the same way that the specimen width contributes a biaxial stress state in a bend specimen. Static tests, e.g. tension tests, are not sensitive to this type of brittle behavior. Materials that exhibit similar ductility in tension tests or even unnotched impact tests can have large differences in notch sensitivity.

Notched-bar impact tests measure the amount of energy absorbed during the fracture of small standardized specimens. The test results do not directly predict the ductile-brittle behavior of a component in a structure and thus the test values cannot be used in design. The test results have significance only when they are correlated with the behavior of the material in service. In some service environments, the probability of failure greatly increases when the energy absorption values fall below a given value and so the test can be used to screen out materials unsuitable for specific applications.

Although a number of different notched-bar test specimens have been employed in investigating the ductile-to-brittle behavior in metals, two broad types of specimens have been standardized: center notched Charpy-type specimen supported as a beam in 3-point loading and the asymetrical notched Izod-type specimen clamped at one end. The Charpy-type specimen has become dominant in the United States and is now widely used throughout the world. Standard sized specimens must be used because the relative magnitudes of the three principal stresses at the notch root depend critically on the test bar dimensions and the notch configuration. Reducing the width or depth dimensions has two effects. First, it decreases the volume of metal and so tends to lower the energy necessary to break the specimen. However, reducing the size can increase the energy necessary to fracture the specimen because the restraint at the notch root is decreased, reducing the chance of brittle fracture. (32) Although the energy absorbed by the specimen is not strongly influenced by the notch angle unless it exceeds 60 degrees, the sharpness of the notch root definitely affects the energy absorbed in breaking the specimen, especially for less ductile materials. The fracture energy decreases as the root radius decreases because of an increase in the stress concentration. (33) Finally, there are two options for reporting the energy absorption values measured by the notched-bar impact test. Generally, domestic specifications specify the minimum energy absorption directly in energy units, foot-pounds or joules, because there is only one standard Charpy-type specimen. In many foreign specifications, additional standard specimens are permitted in which the notch depth or specimen dimensions are different and so the minimum energy absorption is specified in energy per unit area units, J/cm^2. Comparisons of notched-bar impact test requirements must be made on the basis of geometry, size, specimen type, and equivalent energy absorption units. However, it is not correct to directly compare results from different size specimens on the basis of normalized absorbed energy, i.e. energy absorbed/unit area, because the strong effect of notch restraint on the specimen fracture mode.

d. Wedge Tension Test

The wedge tension test is a widely used test applied to bolting materials for the quantitative determination of ultimate tensile strength and the qualitative measure of bolt head ductility. This test together with hardness measurements are used as an acceptable alternative to the standard tension test, especially for bolts too short to be made into tensile specimens. The bolt head is subjected to eccentric loading through use of a wedge to simulate misalignment of the bolt in service. The test requires fracture of the bolt to occur in the body or threaded section, and thus does not allow brittle fracture at the head-body junction. The angle of the wedge determines the severity of the eccentric loading or bending: the larger the angle the more severe the test. The general ASTM test requirement for wedge angle is based on yield strength, with heat-treated high yield strength bolts tested with a smaller wedge angle than lower strength bolts because of the normally reduced ductility of the higher strength material. Other specifications, e.g. DIN, specify wedge angles based on bolt diameter, bolt length, and the percent elongation requirement. Bolts with the lowest expected ductility are tested with the smallest wedge angles, as in the case of the ASTM test. When comparing wedge tension test requirements, the wedge angle specified in the foreign test should be equal to or greater than the domestic requirement to insure at least an equally severe ductility test.

e. Flare Test

Expansion, flare, or drift tests of tubes, both seamless and welded tubes, provide qualitative information about the tube ductility and, when applicable, the weld strength. These tests are widely used for tubes with a wall thickness that is too thin for standard tension test specimens. In the test itself, a solid cone of fixed included angle slowly expands the end of the tube to a predetermined change in diameter without rupturing or developing cracks. If the tube is welded, the tube may be expanded until rupture occurs. If failure occurs outside the weld zone, then the weld possesses sufficient strength and ductility. (34) There are two major test variables that affect the severity of the test: the amount or percent of diameter expansion and the included angle of the cone. When comparing test requirements based on diameter expansion only, a larger required diameter expansion means a more severe test for a constant cone angle. When comparing test requirements based only on cone angle, a larger cone angle means a more severe test, even for the same diameter expansion, because the strain developed in the transition between the deformed and undeformed portions of the tube is greater. A cone with a 60 degree included angle.results in about a 10 percent increase in the angle between the deformed and undeformed portions of the tube than a cone with a 45 degree angle. Comparisons between two specifications must account for any differences in both the required percent diameter expansion and the included angle of the cone.

Test Acceptance Criteria

There are some required tests common to specifications of different national origins that, although identical, contain different specific values for parameters which determine acceptable or unacceptable behavior. The hydrostatic test and flattening test, often required in ferrous and nonferrous specifications for both seamless and welded tubular products, are examples of such tests.

a. Flattening Test

This test is used as a qualitative measure of the transverse ductility of the pipe including weld and base metal. In particular, the test is used to identify external and internal defects, e.g. lap seams, cracks, laminations which can affect the integrity of the pipe. The transverse ductility is particularly important in piping because the hoop stress or transverse stress in the pipe wall of an internally pressurized pipe is substantially greater than the longitudinal or axial wall stress. Most ASTM, JIS, and DIN ferrous specifications for seamless and centrifugally cast pipe and some welded pipe specifications require the pipe specimen to be flattened without cracking to a height that is a function of the geometry of the pipe and a constant parameter whose value depends on the particular ferrous alloy type. The relationship used in these specifications is as follows:

$$h = \frac{(1 + e)t}{(e + t/D)} \quad [3]$$

where H = distance between flattening plates
D = pipe outside diameter
t = pipe wall thickness
e = constant for a given grade

This analysis only approximates the actual test because it does not account for the experimental observation that the actual maximum tensile strain experienced in pipe flattening substantially exceeds the calculated value, similarly to that observed in the bend test. This effect does not affect the comparisons because all three national standards groups base their acceptance criterion on equation [3]. In ASTM specifications, the constant "e" is defined as deformation per unit length. In JIS and DIN specifications, "e" is defined only as a constant that varies according to the grade of pipe. The actual value of this constant for a particular alloy type, however, is not always the same in the ASTM, JIS, and DIN specifications. In order to evaluate the significance of different values of this constant, it is necessary to have some physical understanding of the constant. Based on the work of Thomas et al. (35), equation [3] can be developed from a simple curved beam bending equation, shown in Appendix C. This analysis defines the constant "e" used in these specifications as the maximum tensile circumferential strain in the pipe. Thus, as the value of "e" increases, the pipe must sustain a greater circumferential strain without cracking in order to pass the test. In both ASTM A53-78, Steel Pipe, and JIS G3454, Carbon Steel Pipe, each alloy grade must undergo a flattening test based on fixed values of the maximum tensile circumferential strain, "e." The maximum strain required is identical (e = 0.07) for A53 Grade B and JIS G3454 class 3 pipe. However, for Grade A, A53 requires a maximum surface strain of 0.09 compared to 0.08 required for JIS G3454 class 2. The JIS test, therefore, permits the class 2 pipe to experience about 12% less strain (less flattening) than A53 Grade A pipe and thus the JIS requirement for class 2 pipe is less severe than the ASTM requirement. Although the JIS acceptance criterion in this example is less severe, this criterion could be adequate for specific service applications. However, any further analysis of the difference in acceptance criterion must include both the designed service environment and a determination that some important aspect of component behavior in service is measured by this test.

b. Hydrostatic Test

The hydrostatic test as applied to welded and seamless pipe and tubing is typically used as either a mill quality control or inspection test, especially for welded pipe, or as a proof test to indicate the ability of the pipe to operate at design pressures without leaking. As a quality control test, the test pressures are not intended as a basis of design requirements and may not be related to the intended operating pressures. As a proof test, the test pressure will exceed the specified operating pressure by some minimum amount. The analysis used in all specifications, however, is based on the same equation for the hoop or circumferential stress in an internally pressurized, thin-walled cylinder:

$$P = \frac{2St}{D} \quad . . . [4]$$

where P = internal pressure
S = hoop stress
D = outside diameter
t = thickness

Most specifications set the internal pressure by requiring the hoop stress, S, to be some fraction of the minimum material yield strength and upper limit on the test pressure. Occasionally, a specification may fix the internal pressure at a constant value for a variety of pipe diameters and wall thicknesses thus causing the hoop stress to be a variable function of the minimum material yield strength. Therefore, comparisons must be made based on equivalent values on the hoop stress rather than internal pressure test values.

SUMMARY

Consistent decisions on the degree of equivalency between metal specifications of different national origins cannot be made only on the basis of chemical composition and direct comparison of mechanical property numbers. There are numerous additional factors, including metallurgical effects, product form effects, test acceptance criteria, and differences in specification philosophy which, if present, may influence the determination of equivalency because of their effect on property requirements. In order to remove the uncertainty in this decision-making process, these additional factors must be evaluated for each comparison.

Excerpts from actual comparisons have been used to illustrate the methodology to be followed based on the principles discussed in this report. The specific evaluation criteria identified are not meant to be totally inclusive, but rather represent those most often encountered. Some material specifications, especially application specifications, may include special requirements dictated by the application. A checklist of typical requirements and tests found in product and application specifications has been compiled to aid in making comparisons between foreign and domestic material specifications. This list (Appendix D) is based on the results of the metallurgical evaluation of a selected group of domestic materials specifications. (6) No attempt has been made to evaluate the appropriateness of specific tests and requirements for specific applications or end-uses. Finally, material specifications are dynamic documents because revisions of test methods and test requirements are part of the specification writing process. Care must always be exercised to insure that the appropriate versions of specifications are being compared.

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Appendix A

A summary of selected quality descriptors as defined in appropriate parts of the American Iron and Steel Institute Steel Products Manual.

CARBON STEEL PLATE QUALITIES[a]

Regular Quality

A common designation for carbon steel plates having a maximum of 0.33 per cent carbon by ladle analysis. Plates of this quality do not have the high degree of uniformity in chemical composition, internal soundness or freedom from nonmetallic inclusions and surface imperfections that are associated with other plate steel qualities. Plates of this quality are not customarily produced to mechanical property, cold bend, or ductility requirements. Such plates are not intended for deep drawing, severe cold forming or for pressure vessels or any applications requiring specified minimum mechanical properties. Tension and bend tests are not appropriate for such plates.

Structural Quality

Plates are intended for application in structures such as bridges, buildings, structural steel for locomotives, railroad cars and other mobile equipment. Two longitudinal tension and two longitudinal bend tests taken at random are commonly required from each heat.

Forging Quality

Plates are intended for forging, heat treating or similar purposes or when uniformity of commposition and freedom from injurious defects are essential. Plates of this quality are produced by a killed steel practice and rolled from slabs or ingots conditioned to eliminate injurious surface defects. Forging quality is ordinarily furnished with the phosphorus content up to 0.035 per cent and the sulphur content up to 0.040 per cent by ladle analysis. Plates of this quality can be produced to chemical ranges and limits and mechanical properties. When mechanical properties are specified, two tension and two bend tests from each heat are made. Where the steel from one heat differs 3/8 in. or more in thickness, one tension and one bend test are made from the thickest and thinnest plate rolled, regardless of the weight represented. All test specimens are taken in a longitudinal directions.

(a) Steel Products Manual "Plates and Rolled Floor Plates," American Iron and Steel Institute, January 1979.

CARBON STEEL PLATE QUALITIES (CONT)

Pressure Vessel Quality

Steel plates are intended for application in pressure vessels. Except for quenched and tempered plates, a minimum of one transverse tension and one transverse bend test representing each plate as-rolled are required as described in ASTM A 20. For quenched and tempered plates ordered to ASTM or ASME specifications, two transverse tension and one transverse bend test are required from each plate as heat treated. Plates of this quality may be supplied to ultrasonic testing requirements.

HOT ROLLED CARBON STEEL BARS[(b)]

Merchant Quality

Merchant quality is the lowest quality for carbon steel bars. Merchant quality bars are produced to specified sizes, with appropriate control of the chemical limits or mechanical properties for non-critical uses. Bars of this quality are usually rolled from unconditioned billets. The size ranges are limited and the type of steel applied is at the producers option, i.e., rimmed, capped, semi-kiled or killed steel. Merchant quality steel bars are produced for a wide range of uses, such as structual and similar miscellaneous aplications involving mild cold bending, mild hot forming, punching and welding as used in the production of non-critical parts of bridges, buildings, ships, agricultural implements, road building equipment, railway equipment and general machinery. Mild cold bending refers to bending using a generous bend radius with the axis of the bend at right angles to the direction of rolling. This quality is not suitable for applications which involve forging, heat treating, cold drawing, or other operations where internal soundness or relative freedom from detrimental surface imperfections is of prime importance. Merchant quality steel bars should be free from visible pipe; however, they may contain pronounced chemical segregation and for this reason product analysis tolerances are not appropriate. Internal porosity, surface seams, and other surface irregularities may be present and are generally to be expected in this quality. Steel bars of this quality are commonly produced to chemical composition (cast or heat analysis only), within the limits of 0.50 percent maximum carbon, 0.60 per cent maximum manganese, and 0.04 per cent maximum phosphorus. This quality is produced in nonresulphurized steels only within the limit of 0.05 per cent maximum. Merchant quality steel bars are not produced to any specified silicon content, grain size, or other

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(b) Steel Products Manual, "Alloy, Carbon and High Strength Low Alloy Steels," American Iron and Steel Institute, August 1977.

Merchant Quality (Cont)

requirements which would dictate the type of steel produced. Merchant quality steel bars do not require the chemical ranges typical of standard steels. They are produced to wider carbon and manganese ranges and are designated by the prefix, "M". Merchant quality bars are also produced to compatible mechanical properties as previously described in this Part.

Special Quality

The basic or standard quality for carbon steel bars. Special quality steel bars can be produced using a rimmed, capped, semi-killed or killed type of deoxidation practice. The appropriate type is dependent upon chemical composition, quality and customer's specification. Killed steels can be produced to coarse or fine austenitic grain size. Steel bars of this quality are produced to be free from visible pipe and excessive chemical segregation. Also, they are rolled from billets which have been inspected and conditioned, as necessary, to minimize surface imperfections. The frequency and degree of surface imperfections are influenced by the type of steel, chemical composition and bar size. Resulphurized grades, certain low carbon killed steels and boron treated steels are most susceptible to surface imperfections. Special quality steel bars can be produced to chemical requirements. Bars of this quality are produced to tolerances for product analysis. Also, they can be produced to mechanical property requirements. Special quality steel bars are used when the application, method of fabrication or subsequent processing treatment requires quality characteristics not available in merchant quality. Typical applications involve hot forging, heat treating, cold drawing, machining and many structural applications.

STEEL SPECIALTY TUBULAR PRODUCTS[c]

Pressure Tubing

Pressure tubes, as distinguished from pressure piping, are used to convey fluids at elevated temperatures or pressures or both and are suitable to be subjected to heat application. Pressure tubes are also used at low temperatures. Pressure tubes are produced to actual outside diameter and minimum or average wall thickness (as specified by the purchases) and may be hot finished or cold finished, as specified. Wall thickness is commonly specified in decimal parts of an inch rather than by gage numbers. Specifications for

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(c) Steel Products Manual, "Steel Specialty Tubular Products," American Iron and Steel Institute, October 1980.

Pressure Tubing (Cont)

pressure tubes are written by such bodies as American Society for Testing and Materials and American Society of Mechanical Engineers. These specifications should be consulted for the grades and chemical compositions involved.

Mechanical Tubing

Mechanical tubing derives its name from its end use. It is employed for a variety of mechanical purposes and is generally produced to meet specific end use requirements. Mechanical tubing can be produced to a wide variety of finishes and mechanical properties. It is made in sizes up to and including 12-3/4 inches in outside diameter. Tubing produced by hot rolling processes has surfaces similar to the surface regularly produced on hot rolled steel and, in general, the dimensional tolerances cannot be held so closely as in the case of tubing produced by cold finishing. Cold finished mechanical tubing can be produced by cold working or by means of surface removal. By cold working is meant the cold reducing to effect changes in cross-sectional dimensions. Surface removal includes turning, polishing, grinding or machining. Cold working can also be used to produce tubes having cross-sectional shapes other than round. Requirements involving additional testing are sometimes specified, such as restrictions in chemical compositions, mechanical properties, qualifications for macroetch, fracture, hardenability, and nonmetallic ratings. Mechanical tubing is commonly specified to outside diameter and wall thickness. If inside diameter is the more important dimension, cold worked tubing is specified to inside diameter and wall thickness or outside diameter and inside diameter.

Strain analysis in bending test

General Strain Equation

$$e_y = \left[\frac{1}{r_2} - \frac{1}{r_1}\right]\frac{r_1 y}{r_1 + y}$$

where: e_y is strain parallel to the neutral axis (N.A.) at a distance y from the N.A.

r_1 radius of curvature at N.A. before bending

r_2 radius of curvature at N.A. after bending

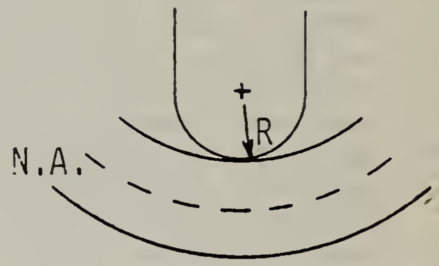
y distance from N.A.

Assume:

(a) N.A. does not move during bending

(b) N.A. lies midway between specimen surfaces

BEFORE



AFTER

$$r_1 = \infty \quad ; \quad r_2 = R + \frac{t}{2} \quad ; \quad y = \frac{t}{2}$$

substituting for r_2 and y in the general strain equation,

$$e_y = \left[\frac{2}{2R+t} - \frac{1}{r_1}\right]\left[\frac{1}{\frac{2}{t} + \frac{1}{r_1}}\right]$$

then,

substituting for r_1

$$e_y = \frac{1}{\frac{2R}{t} + 1}$$

APPENDIX C

Strain analysis in pipe flattening test

General Strain Equation for Curved Section

$$e_y = \left[\frac{1}{r_2} - \frac{1}{r_1}\right] \frac{r_1 y}{r_1 + y}$$

where: e_y is strain parallel to the neutral axis (N.A.) at a distance y from the N.A.

r_1 radius of curvature at N.A. before bending

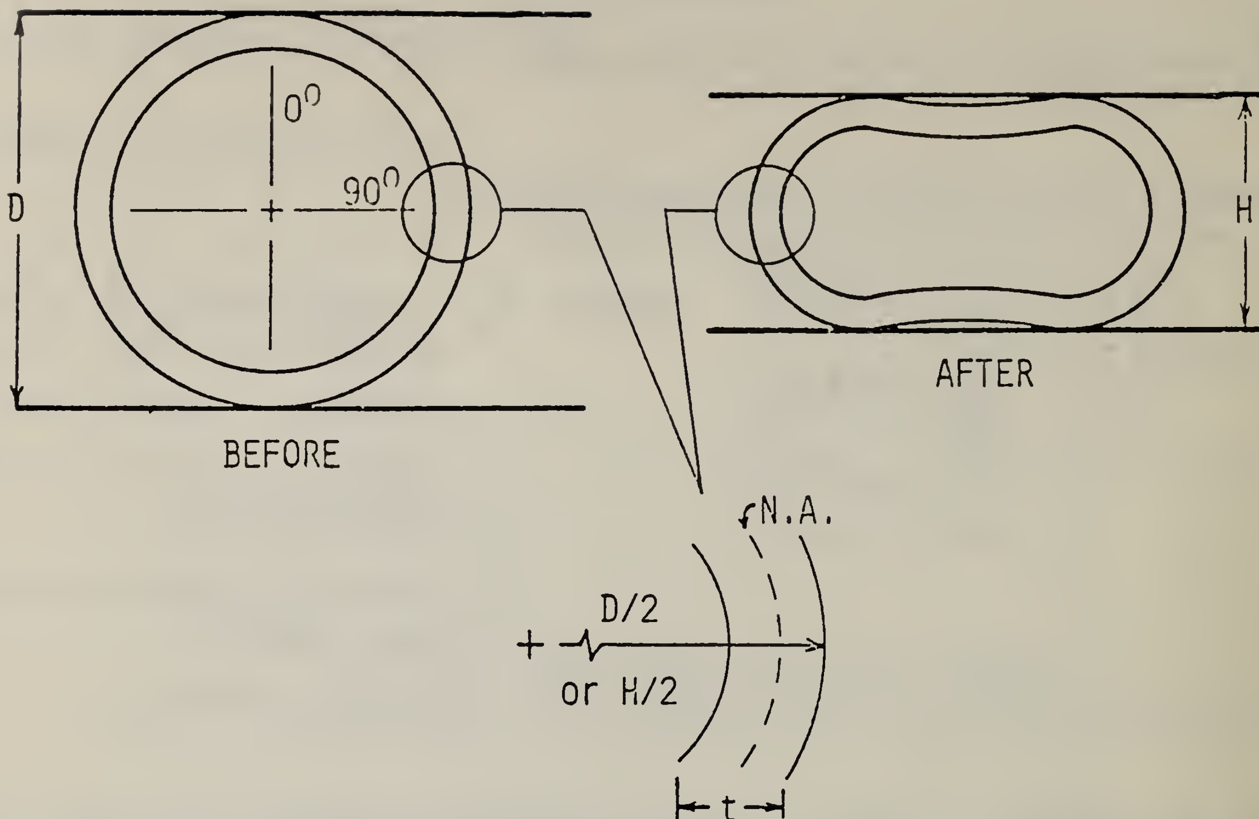
r_2 radius of curvature at N.A. after bending

y distance from N.A.

For the case of a pipe of original outside diameter D flattened to a distance H, the maximum circumferential tensile strain at the 90^0 position occurs at the outer surface fiber parallel to the N.A. and is determined as follows:

Assume:

(a) N.A. does not move during bending
(b) N.A. lies midway between pipe surfaces
(c) Semi-circular pipe shape at 90^0 position is maintained during bending



$$r_1 = \frac{D}{2} - \frac{t}{2} \quad ; \quad r_2 = \frac{H}{2} - \frac{t}{2} \quad ; \quad y = \frac{t}{2}$$

substituting into the general strain equation,

$$e_y = \frac{1 - \frac{H}{D}}{\frac{H}{D} \cdot \frac{D}{t} - 1} \qquad \text{or rearranging,}$$

$$H = \frac{(1 + e)t}{e + \frac{t}{D}}$$

where $e \equiv e_y =$ maximum circumferential strain at surface

Appendix D

Checklist of typical tests and requirements found in a selected group of domestic material product and application specifications.

<u>Structural Products</u> (including plate, strip, shapes, rods, bars)

<u>Typical Requirements</u>
- Chemistry
- Ultimate Tensile Strength and Yield Strength
- Percent Elongation

<u>Supplemental Requirements</u>
- Bend Tests
- Impact Tests
- Nondestructive Evaluation (NDE) Tests

<u>Wrought Tubular Products</u> (including pipe and tubes)

<u>Typical Requirements</u>
- Chemistry
- Ultimate Tensile Strength and Yield Strength
- Percent Elongation
- Bend Tests
- Flattening Tests
- Hydrostatic Tests
- Flare Tests (Nonferrous alloys)
- Corrosion Tests (Nonferrous alloys)
- NDE Tests
- Hardness

<u>Cast Products</u>

<u>Typical Requirements</u>
- Chemistry
- Ultimate Tensile Strength and Yield Strength
- Percent Elongation
- Percent Reduction-in-Area

<u>Supplement Requirements</u>
- Bend Tests
- NDE Tests

<u>Bolting and Fastener Products</u>

<u>Typical Requirements</u>
- Chemistry
- Ultimate Tensile Strength and Yield Strength
- Percent Elongation
- Wedge Tension Test
- Hardness

Supplemental Requirements

- Impact Tests
- NDE Tests

Forging Products

Typical Requirements

- Chemistry
- Ultimate Tensile Strength and Yield Strength
- Percent Elongation
- Percent Reduction-in-Area
- Hardness

Supplemental Requirements

- NDE Tests

TABLE I. LIST OF MATERIAL SPECIFICATIONS COMPARED

ASTM STANDARD	DESCRIPTION	JIS STANDARD	DIN STANDARD
A36	STRUCTURAL STEEL	G3101	17100
A53	BLACK & GALVANIZED STEEL PIPE	G3454	1626
A106	SEAMLESS STEEL PIPE FOR HIGH TEMPERATURE	G3456	-----
A312	AUSTENITIC STAINLESS STEEL PIPE	G3459	17440
A426	FERRITIC ALLOY STEEL PIPE FOR HIGH TEMPERATURE	G5202	-----
A576	SPECIAL QUALITY CARBON STEEL BARS	G4051	17200, 17210
A307	CARBON STEEL FASTENERS	G3101	267, 17200, 17240
A193	ALLOY & STAINLESS STEEL BOLTING MATERIAL	G4107	17240, 17440
A105	CARBON STEEL FORGINGS FOR PIPING COMPONENTS	G3201	17200
A285	PRESSURE VESSEL STEEL PLATES	G3103	17155
A515	PRESSURE VESSEL STEEL PLATES, HIGHER TEMPERATURE	G3101	17155
A216	CARBON STEEL CASTINGS FOR HIGH TEMPERATURE	G5151	17245
A217	ALLOY & STAINLESS STEEL CASTINGS	G5151	17245
A48	GRAY IRON CASTINGS	G5501	17245
B584	COPPER ALLOY SAND CASTINGS	H5111	1705
B124	COPPER & COPPER ALLOY FORGING ROD, BAR, & SHAPES	H3250	-----
B88	COPPER WATER TUBES	H3300	17671
B111	COPPER & COPPER ALLOY CONDENSER TUBES	H3632	1785
B62	BRONZE CASTINGS	H5111	1705
B43	SEAMLESS BRASS PIPE	-----	17671

TABLE II. STANDARD TENSILE TEST SPECIMENS
WROUGHT PRODUCTS (EXCEPT TUBULAR)

ASTM TYPE	ASTM GAGE LENGTH MM	ASTM WIDTH OR DIAMETER MM	ASTM THICK-NESS MM	ASTM $L/\sqrt{A}$	JIS TYPE	JIS GAGE LENGTH MM	JIS WIDTH OR DIAMETER MM	JIS THICK-NESS MM	JIS $L/\sqrt{A}$	DIN TYPE	DIN GAGE LENGTH MM	DIN WIDTH OR DIAMETER MM	DIN THICK-NESS MM	DIN $L/\sqrt{A}$
RECT	200	40	VAR.	VAR.	RECT	200	40	VAR.	VAR.					
					RECT	200	25	VAR.	VAR.					
RECT	25	6.25	VAR.	VAR.										
					RECT	80	20	VAR.	VAR.	RECT	80	20	VAR.	VAR.
RECT	50	12.5	VAR.	VAR.	RECT	50	12.5	VAR.	VAR.	RECT	50	12.5	VAR.	VAR.
					RECT	$8\sqrt{A}$	15	VAR.	8					
										RECT	5D	VAR.	VAR.	5.65
					RECT	$4\sqrt{A}$	VAR.	VAR.	4					
										RECT	$5.65\sqrt{A}$	20	VAR.	5.65
					ROUN	8D	≤ 25	---	9					
										RECT	$5.65\sqrt{A}$	12.5	VAR.	5.65
					ROUN	4D	>25	---	4.51					
ROUN	4D	VAR.	---	4.51										
					ROUN	50	12.5	---	4.51					
					ROUN	5D	VAR.	---	5.65	ROUN	5D	VAR.	---	5.65

RECT = RECTANGULAR CROSS-SECTION
ROUN = ROUND CROSS-SECTION
VAR. = VARIABLE
A = CROSS-SECTIONAL AREA
D = DIAMETER

FIGURE 1. Classification of Metals Specifications

NATIONAL STANDARD	AISI SAE ↓ DIN ↓	ASTM JIS ↓	
SPECIFICATION TYPE	MATERIAL	PRODUCT	APPLICATION
CLASSIFYING VARIABLE	COMPOSITION	FORM & METHOD OF PRODUCTION	USE - TEMPERATURE, PRESSURE, ENVIRONMENT
EXAMPLES:	STAINLESS STEEL TOOL STEEL COPPER ALLOYS	PLATE SHEET TUBULAR CASTINGS	TUBING MECHANICAL PRESSURE SANITARY PLATE STRUCTURAL PRESSURE VESSEL

FIGURE 2. EXAMPLE OF TEXT SIMILARITY BETWEEN ASTM AND JIS SPECIFICATIONS

ASTM A515 CARBON STEEL PRESSURE VESSEL PLATES

SECTION 5.1 "PLATES 2 IN. (50.8 MM) AND UNDER IN THICKNESS ARE NORMALLY SUPPLIED IN THE AS-ROLLED CONDITION."

SECTION 5.2 "PLATES OVER 2 IN. IN THICKNESS SHALL BE NORMALIZED."

JIS G3103

SECTION 3.1.1 "THE STEEL PLATE OF 50 MM AND UNDER IN THICKNESS . . . SHALL BE AS-ROLLED."

SECTION 3.1.2 "THE STEEL PLATE OVER 50 MM IN THICKNESS . . . SHALL BE NORMALIZED."

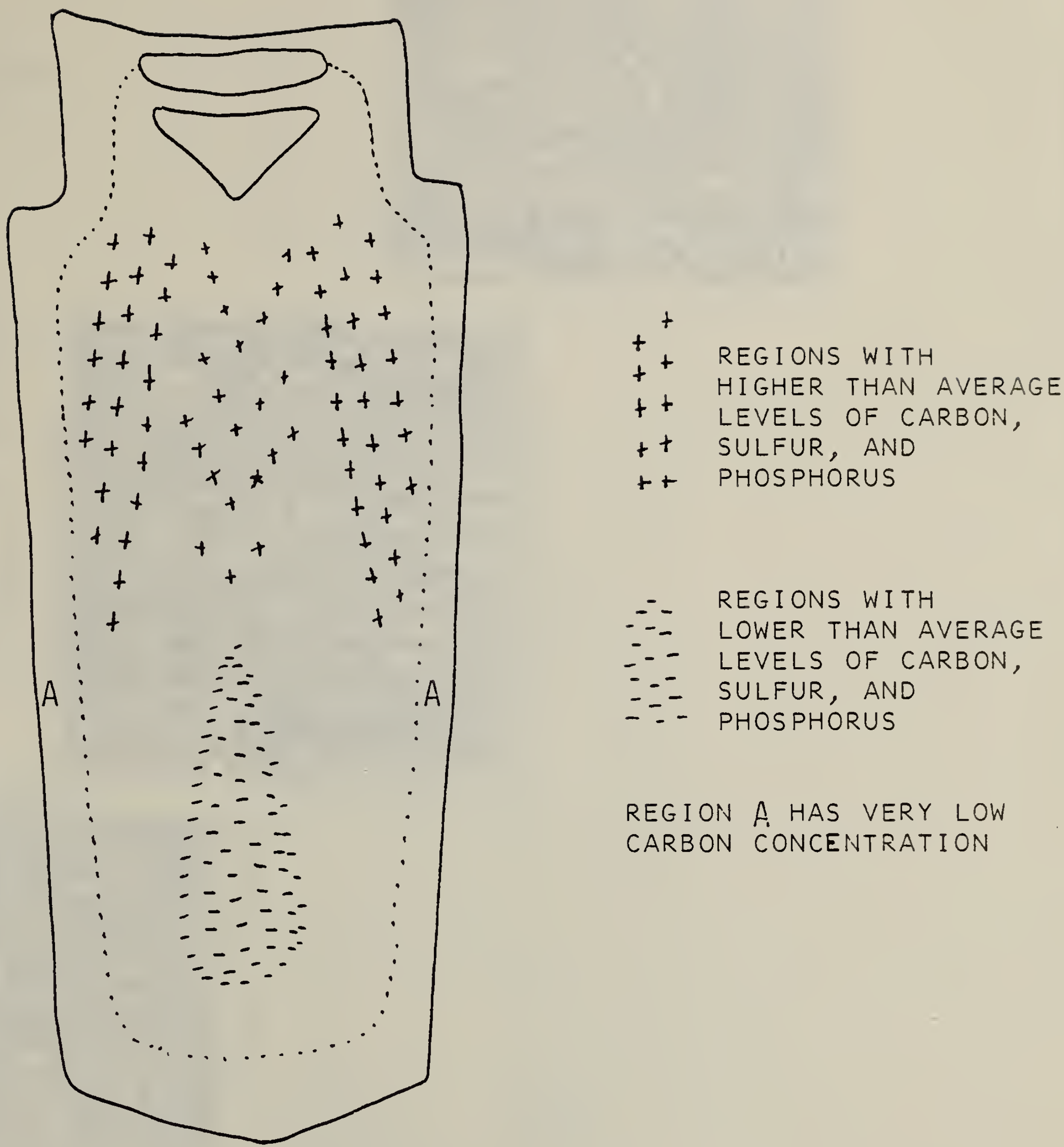


FIGURE 3. SCHEMATIC OF RIMMED STEEL INGOT SHOWING SEGREGATION REGIONS (7)

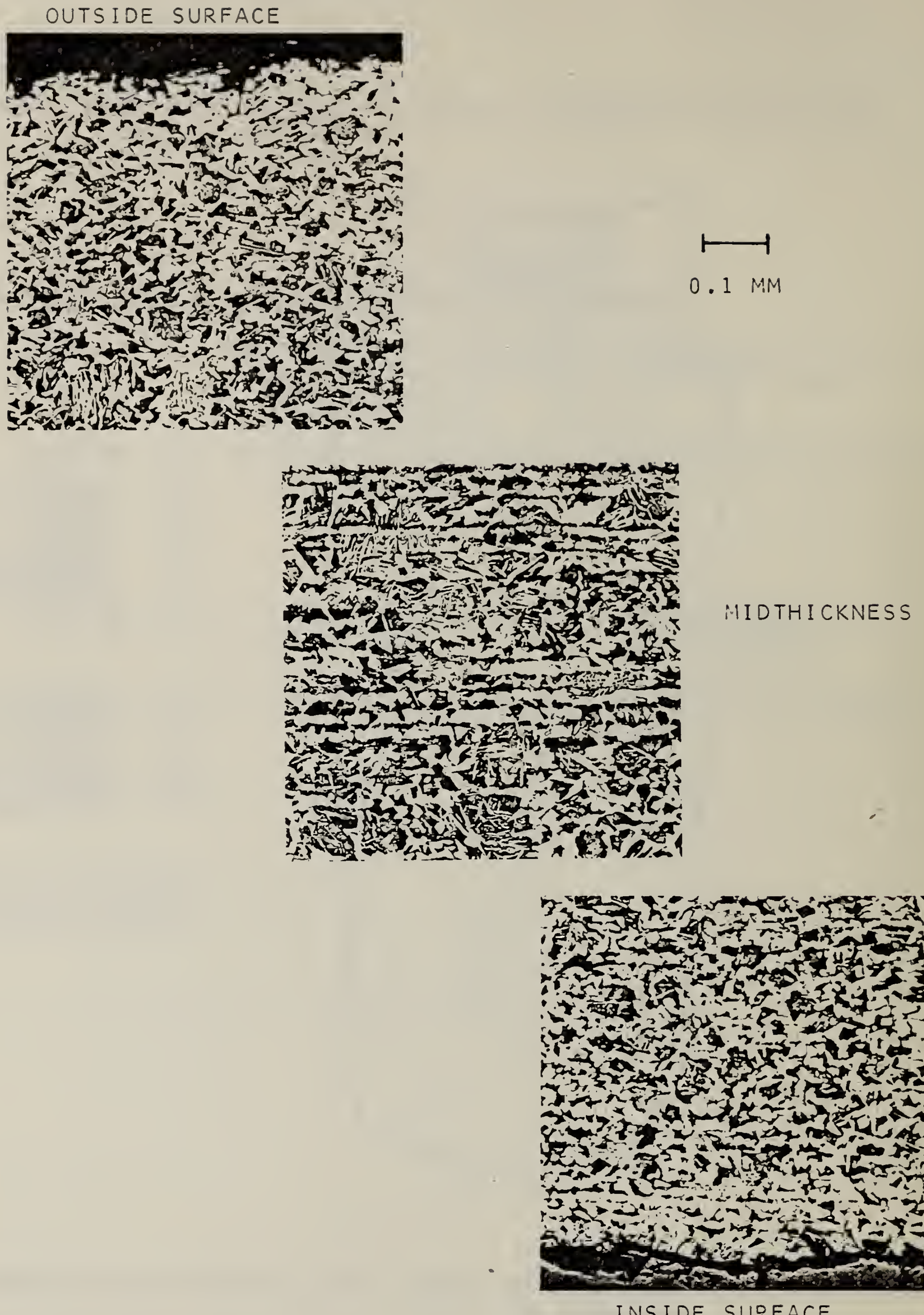


FIGURE 4. REPRESENTATIVE MICROSTRUCTURE OF A HOT-ROLLED CARBON-MANGANESE STEEL PLATE (8)

FIGURE 5. EFFECT OF COOLING RATE ON MECHANICAL PROPERTIES OF EUTECTOID STEEL (9)

COOLING RATE	PEARLITE SPACING 10^{-5} MM	ULTIMATE TENSILE STRENGTH		YIELD STRENGTH		HARDNESS R_C
		MPa	10^3 PSI	MPa	10^3 PSI	
SLOW	63	830	120	340	50	19
↓	25	1070	155	660	95	30
FAST	10	1310	190	930	135	40

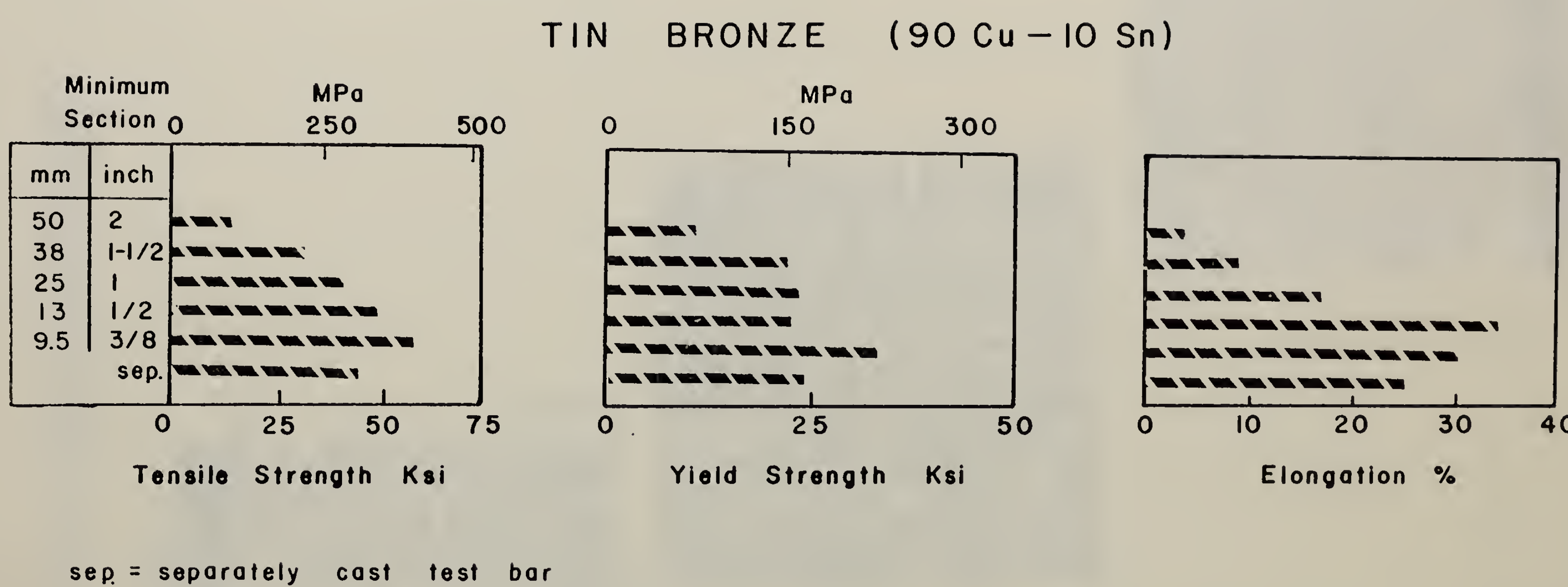


FIGURE 6. EFFECT OF CASTING SIZE ON TENSILE PROPERTIES (10)

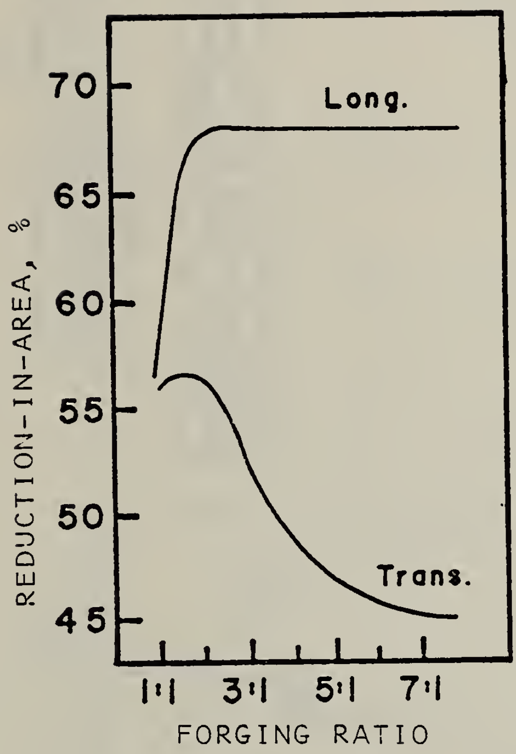
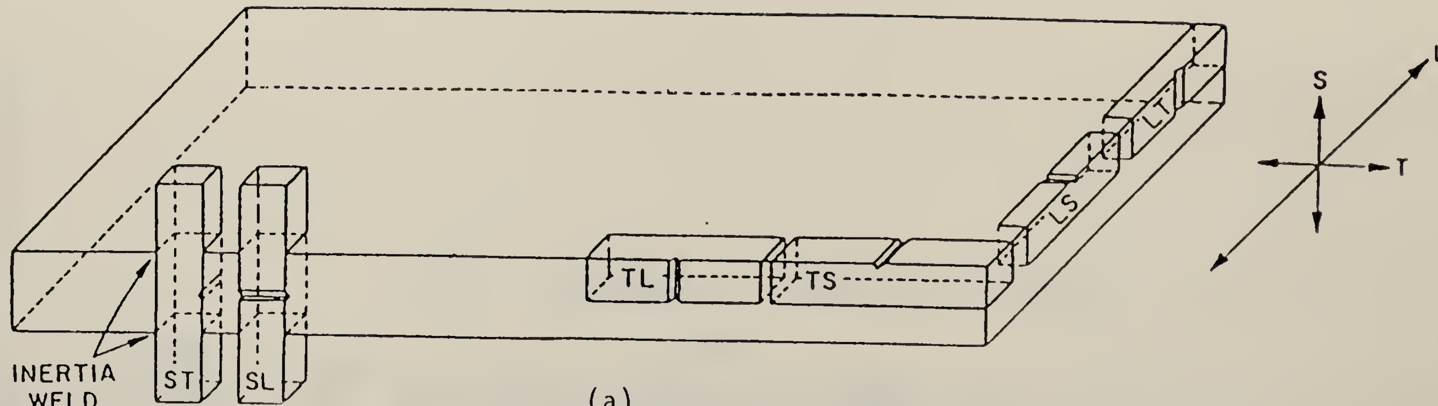


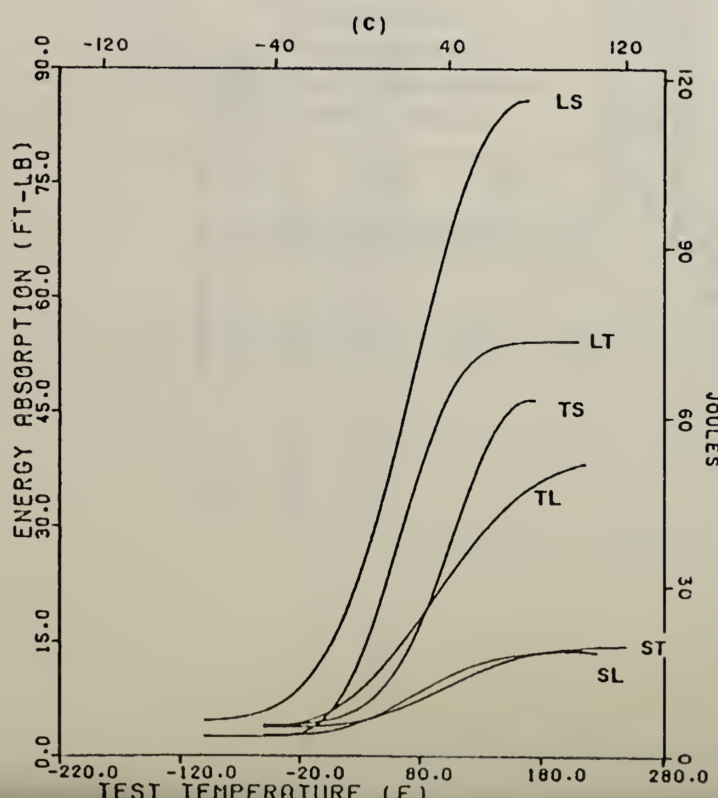
FIGURE 7. EFFECT OF MECHANICAL WORKING ON TENSILE DUCTILITY ANISOTROPY (15)

FORGING RATIO = RATIO OF AREA BEFORE & AFTER FORGING

Long. = longitudinal specimens
Trans. = transverse specimens



(a)



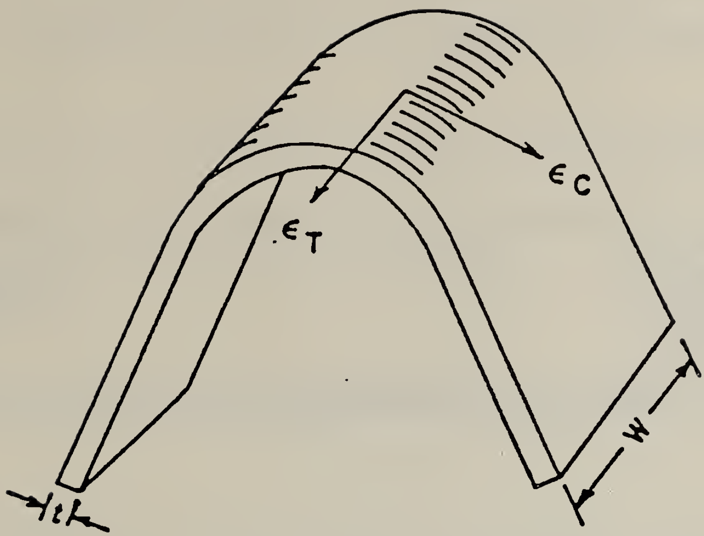
Specimen Orientation Code: The two letter code gives direction of the long axis of the specimen (L, T, or S) followed by the direction of crack propagation (L, T, or S). The letters L, T, and S refer to the three orthogonal plate directions, as defined below:

L Longitudinal or rolling direction of plate.

T Transverse direction: perpendicular to rolling direction but in the plane of the plate.

S Short-transverse direction: perpendicular to L and T.

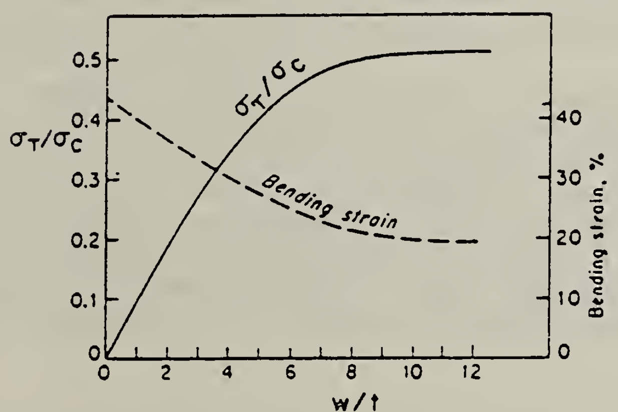
FIGURE 8. TEST SPECIMEN ORIENTATION IN ROLLED PRODUCTS (18)



ϵ_C = CIRCUMFERENTIAL STRAIN, NORMAL TO RADIUS OF CURVATURE

ϵ_T = TRANSVERSE STRAIN

(a)



σ_C = CIRCUMFERENTIAL STRESS

σ_T = TRANSVERSE STRESS

(b)

FIGURE 9. STRAIN ANALYSIS OF BEND TEST SPECIMEN (31)

NBS-114A (REV. 2-8C)

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11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Consistent decisions on the degree of equivalency between metal specifications of different national origins cannot be made only on the basis of chemical composition and direct comparison of mechanical property numbers. There are numerous additional factors, including metallurgical effects, product form effects, test acceptance criteria, and differences in specification philosophy, which if present, may influence the determination of equivalency because of their effect on property requirements. In order to remove the uncertainty in this decision-making process, these additional factors must be evaluated for each comparison.

Excerpts from actual comparisons have been used to illustrate the methodology followed which is based on the principles discussed in this report. The specific evaluation criteria identified are not meant to be totally inclusive, but rather represent those most often encountered. Some material specifications, especially application specifications, may include special requirements dictated by the application. Finally, material specifications are dynamic documents because revisions of test methods and test requirements are part of the specification writing process. Care must always be exercised to insure that the appropriate versions of specifications are being compared.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

ASTM, comparison methodology, DIN, foreign specifications, JIS, metal specifications, tests

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