Mechanical Properties –Test Coupons and Heavy Section Steel Products

Raymond Monroe, SFSA

Unimagined a generation ago is how much we now live in a virtual world. Video games are the preferred entertainment. Exercise is done with an action virtual game. We can play tennis, golf, box and dance in a virtual world. In the engineering, solid modeling, computer solidification simulation, finite element analysis, etc.; allow us to make and test our new designs in a virtual world. In virtual space, materials have uniform properties everywhere regardless of processing, direction or size.

In past generations, complex critical components were designed and produced by craftsman that knew the characteristics and limitations of their materials in the real world. A carpenter knew to take into account knots and grain direction in making furniture. A blacksmith knew how to shape and bend steel to make a part in the direction of working to get the highest strength. A foundryman knew how to use riser and chills and draft and radiuses to get a functional, beautiful and lasting casting.

During the industrial revolution, craftsman were well aware that all their materials had non-uniform properties and that they needed to accommodate the capabilities of the material through clever design and expert manufacturing. Today, design engineers may have a limited experience with actual materials and their properties and expect homogenous materials with uniform properties in all directions. This is a naïve understanding. This problem is exacerbated by our current educational taxonomy where mechanical engineer designers use elegant mathematical models to design complex geometries using the assumption of uniform properties in the materials. Materials strive to eliminate “defects” which often are not mistakes made in production but natural occurrences in the manufacturing process that may limit the performance of the steel components made from the material. All materials in the real world have non-uniform properties. Understanding the limits of process and material performance is especially important in the use of heavy section steel products.

Heavy section steel products are becoming increasingly common as economic efficiency in capital equipment leads to the requirement for larger, more capable equipment. Making heavy section, high performance steel components raises technical and production problems that are challenging to the designer and producer. One challenge is to understand the capacity of heavy section components to achieve the demanding performance required. Assurance that a steel component will perform adequately requires understanding the properties achieved in the component manufacture. Often this is done through the specification of heavy section test coupons for test samples. This approach can be useful in qualifying critical components but often is misunderstood.

Heavy Section Steel Properties

There are two issues in understanding the properties of heavy section steel products, geometrical and metallurgical effects (R. Monroe, 1982). Geometric effects are due to the size and shape of the part. Metallurgical effects are due to the section size and shape limiting the cooling rates.

Large components of complex geometry often have constrained smaller cross sections that are the failure path when a component is overloaded. This does not allow significant plastic deformation and gives the appearance of a brittle fracture. The constraint on the path of fracture because of the size and geometry of the component when loaded to failure can lead to a plane strain condition. Fracture toughness is a measure of the performance capacity of a steel component when loaded in a plane strain condition.

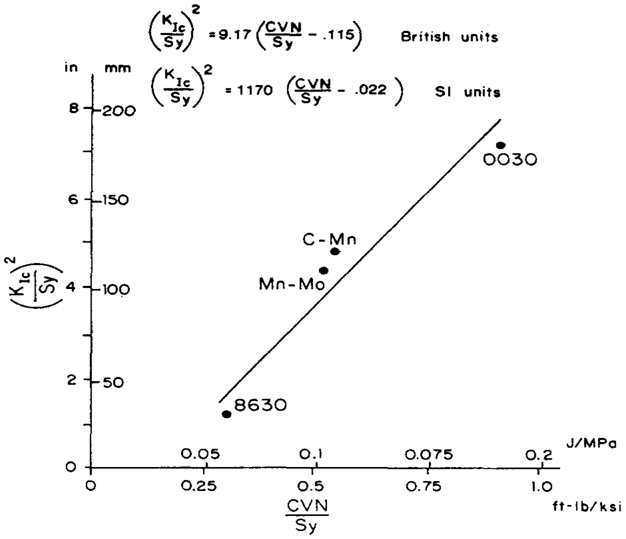

Figure 1 Relationship of Fracture Toughness, Yield Strength and Charpy for common Steel Casting Grades (Stephens, 1982)

For most steel grades, fracture toughness is difficult to measure since the steel is able to plastically deform. The thickness where fracture toughness dominates can be calculated from the ratio of the fracture toughness to the yield strength squared. This squared ratio gives a characteristic length of a failure initiation. The thickness where failure will be dominated by fracture toughness is this ratio times 2.5. Figure 1 shows the squared ratio with values for a typical carbon steel (SAE 0030) up to a common alloy steel (AISI 8630). The ratio is from 1.5 to 7 inches and the thickness where fracture toughness dominates is 3.5 to 18 inches. This characteristic thickness (B) is one way of defining a heavy section. Higher strength materials allow the use of smaller components but these higher strength grades have typically lower toughness and fracture toughness. Fracture toughness can be related to toughness measured by the Charpy test but the correlation is limited and normally can only be used for interpolation within a steel grade. (Stephens, 1982)

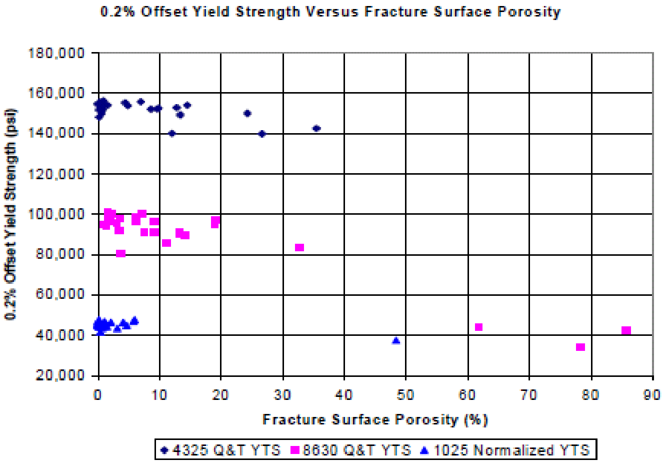

Figure 2 The Effect of Porosity on Steel Casting Yield Strength for Three Grades (Griffin, 2004)

The strength of a steel grade will depend not only on the material capacity to carry a load but also on the constraint that prevents plastic deformation. This can be seen in earlier work where porosity is present in tensile test. This means that the failure can occur at or above yield strengths measured in standard tests.

This can be seen in three typical grades in the Figure 2 showing that at less than 10% porosity in the fracture, the yield strength appears unaffected. The test will have lower plastic deformation as measured by elongation or reduction of area. Figure 3 shows that compared to the strength, the measured plastic behavior or ductility is dramatically reduced even at modest porosity levels. (Griffin, 2004) This suggests that the localization of the stress due to a notch effect leads to a significant reduction in gross and measurable ductility. This is true even though the material continues to exhibit ductility when examined at the micro-level. This suggests that fracture toughness in large components can be a useful way of characterizing the design requirement. It also means that brittle appearing fractures in large components are not necessarily an indication of poor material properties.

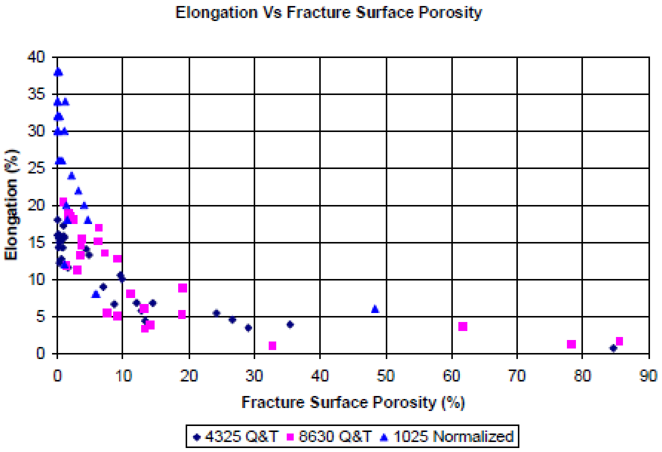

Figure 3 The effect of Porosity on the Elongation of Three Steel Casting Grades (Griffin, 2004)

The notch effect is true in any steel product. If a steel bar with 40% elongation and reduction in area is notched, the yield strength and ultimate strength will only be reduced, if at all, by the reduction of cross-section. The ductility as measured by elongation or reduction in area will fall dramatically. The steel is not less ductile as a material but the geometry including a notch or constrained cross-section will be unable to plastically deform.

In addition to the stress intensity and notch effect, the smallest cross section in a large casting is still large compared to other smaller steel sections and results in a larger volume of steel being subject to the load. There is a higher probability of some weak feature in the steel to be in this larger volume leading to a lower load at failure. This is not a casting issue but a large steel part problem. These geometric problems cannot be resolved with any test coupon if standard size specimens are used to do standard mechanical tests. The metallurgical effects of larger section sizes can be measured with standard tests from larger test coupons. The metallurgical effects include microstructure, grain size, inclusion size, segregation, and porosity.

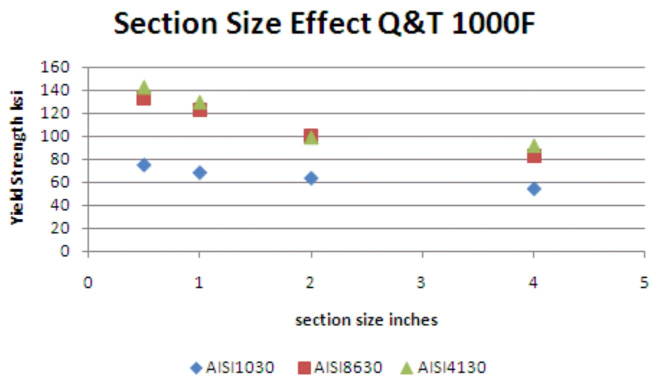

Figure 4 Effect of Section Size on Yield Strength for Three Steel Grades (AST Book, 1967)

The commonly known thickness limitation to develop uniform properties in heavy section steel products is the hardenability of the steel grade. Hardenability is the ability to get the heat treated properties in thicker sections. Since the ability to develop martensite in the steel depends on the cooling rate achieved; hardenability is a measure of an alloy grades ability to form martensite at slower cooling rates. Thicker steel sections are limited in the cooling rate since the heat is extracted at the surface and the cooling rate in the part is limited by the thermal conductivity of the steel. Higher alloy materials have higher hardenability and can develop uniform high properties in heavier sections. Figures 4 and 5 show the effect of limited hardenability of some common steel grades on yield strength and elongation. (AST Book, 1967) These alloys are not high in alloy content and are not able to be through hardened in the four inch section showing a drop in yield strength and an associated slight increase in ductility. Higher alloy steel can be through hardened to greater thicknesses. It is possible to make castings from martensitic stainless grades that will through harden in any section size. One function of a heavier section test coupon is to make sure that the alloy produced and heat treatment given, gives the properties required for a given component size. While this can be calculated accurately, in critical components there may be a reason to confirm that the properties have been achieved.

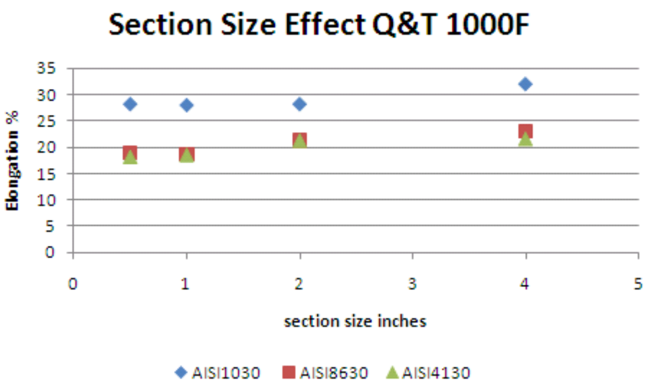

Figure 5 Effect of Section Size on Elongation for Three Steel Grades (AST Book, 1967)

Slow solidification rates in heavy section steel castings leads to larger grain sizes, larger oxide and sulfide inclusions, micro and macro-segregation, and micro-porosity. These effects are really the direct result of the thicker section sizes and the associated slower solidification rates. Since the heat is extracted from the casting surface, the solidification rate is fastest on the surface with the slowest rate being in the casting thermal center. The feeding modulus shown for a spindle casting in Figure 6 shows that the thermal center of a thick section has the highest feeding modulus, the slowest solidification rate and slowest cooling rate.

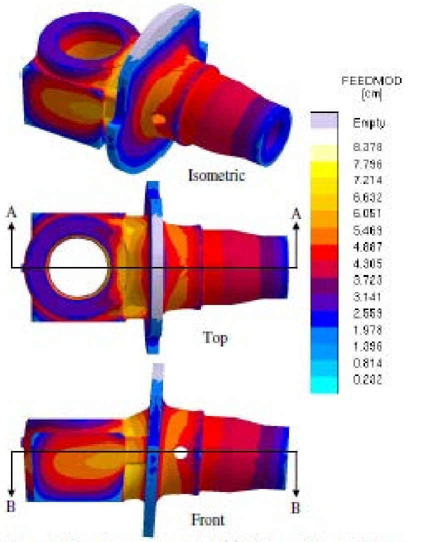

Figure 5. The color contour plot of feeding modulus is shown on the geometry.

Figure 6 Feeding Modulus on a Spindle Casting (C. Monroe, 2009)

The solidification grain size is set by the cooling rate. Grain size in forged or rolled components can be reduced by thermal-mechanical treatments that lead to re-crystallization. Since the heavy section required is thick, there is a limit on the amount of mechanical working available to the forging or rolling operation to use to improve mechanical properties. Casting producers are not able to refine grain size with this technique.

Grain size was thought to be a critical measure for the development of properties in large steel parts. Strength and toughness are improved with smaller grain size in steel products. Deoxidation practices using aluminum to limit grain size were developed and specified in the past to ensure that steel castings produced had small grains and achieve the properties required. Aluminum deoxidation to control grain size has been discontinued since it can lead to the formation of embrittling films of aluminum nitrides at the grain boundaries in heavy sections during solidification. This can be seen in the aluminum nitride formation prediction on the spindle casting. (C. Monroe, 2009)

More recent processing in heavy section steel castings show that with heat treatment, the grain size in steel castings is refined by multiple austenitizing cycles. If a steel casting is normalized and then austenitized before quenching and tempering, the grain size is reduced and this will improve the properties achieved. There appears to be little improvement when more than three austenitizing cycles are used.

In addition to the grain size effect of slow solidification, it also allows microsegregation in the interdendritic regions and at the grain boundaries. Segregation leads to enrichment of phosphorus, manganese and other segregating alloying elements that can reduce mechanical properties. Larger grains mean more complete micro-segregation and larger more dispersed oxides and sulfides. Macro-segregation patterns are aggravated by slower solidification rates but are not easily predicted.

Macro-porosity is characteristic of isolated heavier sections and is a manageable problem. It is possible to design risers, padding and chills to get the soundness required. Less easily controlled is micro-porosity. Micro-porosity is a function of Niyama criteria which is the local thermal gradient divided by the square root of the cooling rate. Lower Niyama numbers signal more porosity. Large complex castings are difficult to rig to avoid the formation of porosity.

Unlike steel castings, most steel products are produced by rolling an ingot, billet or continuously cast bar. Rolled steel products are made from cast material that has segregation, porosity, and inclusions that are distributed and shaped in rolling. The strength, ductility and toughness are highest when tested in the direction of rolling called the longitudinal direction. Across the direction of rolling called the long transverse direction, the ductility and toughness is normally reduced. The lowest properties are through the section thickness or in the short transverse direction. These directions can be seen in Figure 7.

(http://www.ndted.org/EducationResources/CommunityCollege/Materials/Mechanical/Mechanical.htm.)

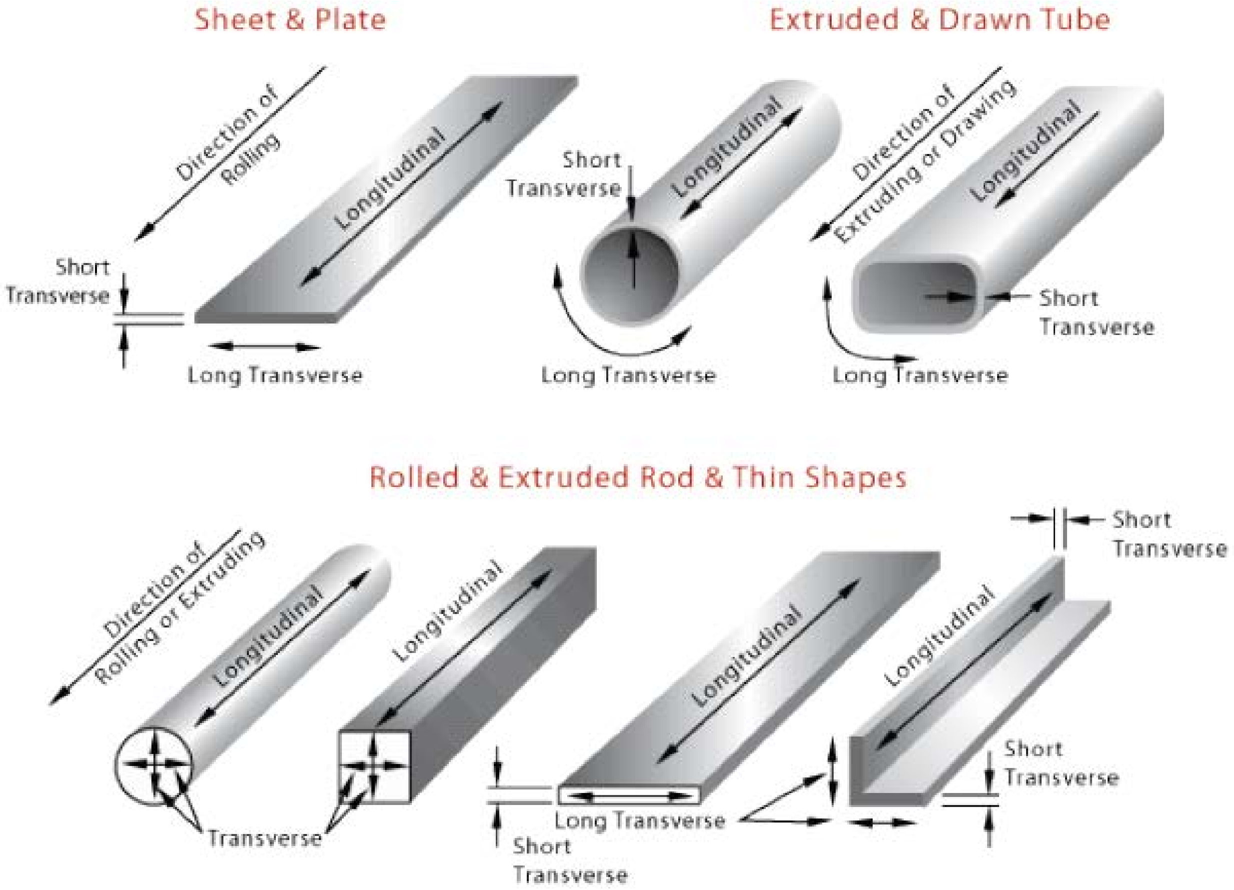

Figure 7 Directionality of Steel Long Products

Forgings will have this directionality of properties. Forgings commonly have a required reduction ratio of 3:1. For reduction, a square 30”x30”cross-section x 30” inches long (900 sq in) would need to be forged down to 300 sq in or for example a 15”x20” section 90 “ long. (Nisbett,2005) If there was an inclusion with radius r and it conformed to the reduction ratio, the new inclusion dimensions would be ½ r x 2/3 r x 3 r. So if we take the shadow of the inclusion as its effect on the mechanical properties, we might expect that the inclusion area 1 pre-reduction would have an area of 1/3 in the direction of rolling (the reduction ratio), 1.5 in the long transverse direction and 2 in the short transverse direction.

Forging large ingots provides the forging producer with a number of advantages over using a casting. The most significant advantage of forging operations is the ability to start with a sound casting that has been designed to give the best material properties. The ingot is designed to minimize porosity and to allow inclusions and segregation to be located in the riser and eliminated in processing. Casting producers are making near net shape components and must use their creative engineering skills to achieve the quality results required.

Heavy section steel products are normally thought of as steel sections that exceed some critical thickness. No uniform definition exists for a heavy section. For rolled structural shapes, AISC Specification A3.1c uses the term “heavy sections” for rolled shapes with flange thicknesses that exceed 2 inches. (AISC,1998) Plates are made up to 30 inches thick but not routinely. Plates 6 to 12 inches are made routinely. Steel section thicknesses exceeding 4 inches are less available from steel supply centers without special orders. Since rolled sections and forgings are made from cast ingots that are reduced, the original cast ingot is a heavier section than the final section size.

Large steel components made from thicker section steels can sometimes be formed from heavy bar or plate but are typically made as a casting or a forging. This has become increasingly true since integrated steel mills make less product with traditional heavy ingots and continuously cast most of their product. The limit for continuous casting is less than 20” thick with most thick slabs less than 10” thick. Complex-difficult to fabricate shapes are commonly produced as castings or forgings. Extensive studies are available to characterize the properties of steel castings in heavier sections (Willey, 1964).

The properties of most steel grades are more dependent on the composition of the steel grade, the shape of the part and the heat treatment applied and not on the product form, i.e. casting or forging.

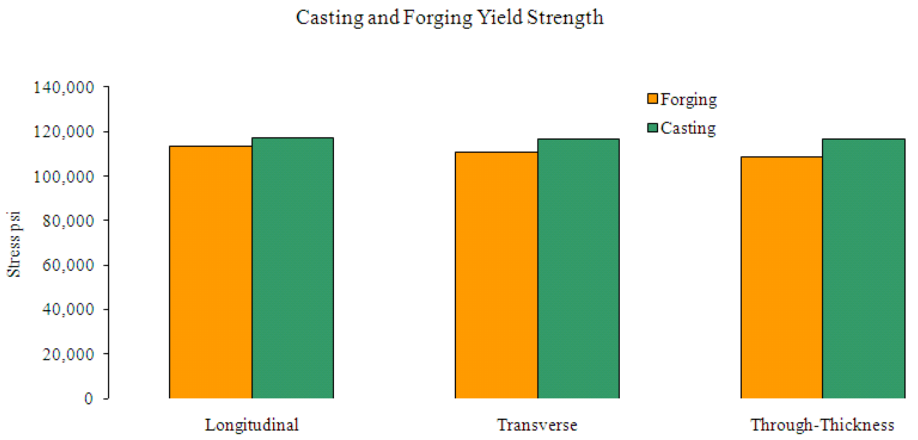

Figure 8 Variation in Forging and Casting Strength in similar grades and components (Zwirlein, 2005)

One company that produces their own castings and purchases forgings has converted a number of forging designs to castings, taking advantage of the ability to ensure sound design through solidification modeling. In Figure 8, the yield strength in different directions is shown with modest differences. Significantly more pronounced are the differences in properties with direction for ductility measured as reduction of area shown in Figure 9. As suggested by the simple analysis of inclusion deformation above, the longitudinal ductility exceeds the transverse ductility that exceeds the through-thickness ductility. Casting ductility remains relatively consistent in all directions. It is less than the longitudinal or transverse but exceeds the through thickness ductility (Zwirlein, 2005).

Designers and users of heavy section steel products need to understand the properties available for service in these products to design safe and effective equipment. The ability to predict the steels response to heat treatment and the properties achieved is good.

Knowledgeable steel experts can confidently predict the properties throughout the steel section but can be misled if there is segregation, poor heat treatment, unexpected porosity, etc. For these reasons depending on the criticality and importance of a heavy section steel product, testing of a heavier section test coupon is often specified.

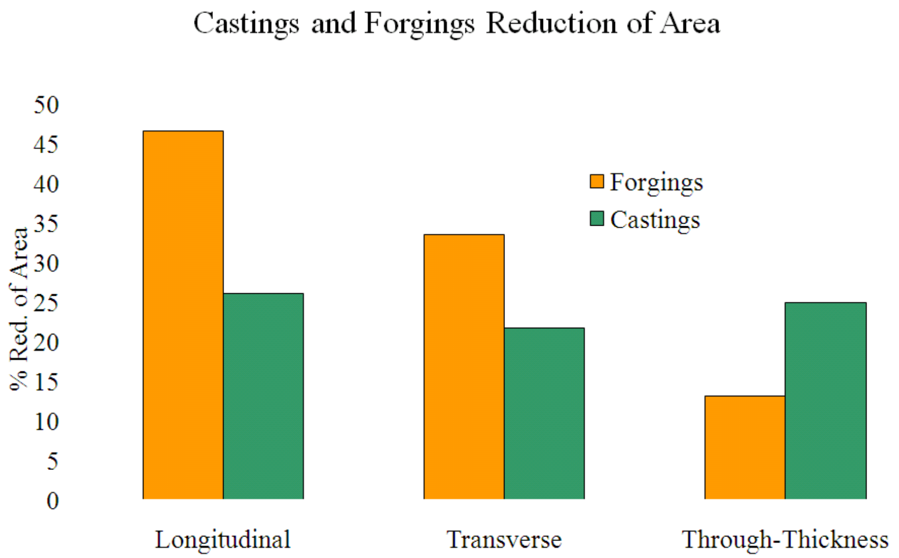

Figure 9 Variation in Forging and Casting Ductility in similar grades and components (Zwirlein, 2005)

Test Coupons and Heavy Sections

> *"Opinions exist in some quarters that the properties of the test bar removed from a casting and those obtained from testing an entire casting section should be identical. However, such opinions are fundamentally false."* (Willey, 1964)

Test coupons are used to extract samples for determining properties of the steel. Steel component manufacturing typically requires the purchaser to specify the final component shape, the steel grade or material used, and the quality or inspection requirements. The steel grade is normally specified by the composition, mechanical properties and heat treatment. In steel production, mechanical testing of test coupons from each heat is done to qualify that the grade of steel met the specification requirements and is not done to qualify the properties in each part.

Early in steel making, chemical composition data was limited. The effect of steel processing and composition was not fully understood. Only a few chemical elements were analyzed in a sample from the heat to determine the composition of the grade of each steel product. With the possibility of undetected contamination, mechanical tests from a standard test coupon were required to qualify the steel from each heat as being able to achieve the mechanical properties expected for that grade.

Because steel like other real materials has variations in properties throughout each piece, it is impossible to have one test from any coupon represent or give the properties everywhere in the piece. In rolled products like bars or plates, the properties of the steel vary with direction. The inability to use the mechanical rest results from anywhere in a steel product and expect to get these properties uniformly in the steel products is well known. ASTM A6, Standard Specification for General Requirements for Rolled Structural Steel Bars, Plates, Shapes, and Sheet Piling, recognizes that the test coupon cannot be used to determine the properties everywhere in a product in ASTM A6 X2.1:

> "The tension testing requirements of this specification are intended only to characterize the tensile properties of a heat of steel for the determination of conformance to the requirements of the applicable product specification. Such testing procedures are not intended to define the upper or lower limits of tensile properties at all possible test locations within a heat of steel…"

For steel castings in ISO 4990, "Steel castings – General technical delivery requirements," para. 6.2.2.2 Test Blocks;

> "The test results represent the material from which the castings have been poured. They do not necessarily represent the properties of the castings. These may be affected by solidification conditions and the rate of cooling during heat treatment, which are in turn influenced by casting thickness, size, and shape."

This language was taken primarily from the British Standard, BS3100 - 1976. (Behal,1983)

The mechanical properties of test coupons are to make sure the steel heat performed as expected of that grade of material. In castings, changes in section size, segregation patterns, macro and micro-shrinkage porosity can reduce the properties of a cast component. Faster cooling rates and thinner sections can increase the properties of a component compared to the test coupon. In rolled or forged sections, changes in testing direction, banding of segregation, or cold working can cause variations in properties. Test coupons are designed to qualify the steel product and not to provide the properties in every location.

Traditionally, casting buyers specify the casting by ordering a pattern or drawing to indicate the casting size and geometry, selecting a specification grade to set the composition and alloy composition, and imposing NDE requirements to assure the quality of the casting in critical sections. Mechanical testing is done on test bars from well fed keel blocks to qualify the heat as being made of the correct material that responds as expected to heat treatment. It is not intended to be a determination of the properties of the casting.

Obviously, the specification minimums for the casting grade are often used by designers for calculating the load capacity of the casting. Since the test coupon material is subject to the same heat treatment as the casting and is made from the same heat of steel, one expects and depends on the fact that the casting should develop the expected properties. These properties would vary with location and section size and are predictable and usable for design. Confirmation of properties of each casting or in critical sections can be done with a hardness test. So from an engineering perspective, we expect the casting to meet the properties of the steel grade in the test block and have the predicted properties in the varied sections of the casting. From a specification standpoint, there is no guarantee that test bars removed from the casting will meet or exceed the specification requirements.

Because in most casting specifications the composition is required, the test block can be a standard size. The designer knowing the alloy grade is able to predict the performance in each section of the casting. For ASTM A148, this is not possible since the producer is allowed to select the composition. So ASTM A148 defines sections over 3 inches as the transition to a heavier section that requires a heavier section test coupon. Since these grades of cast steel are sold on the basis of mechanical properties, it would be possible to heat treat small test bars to the same procedure as a large casting and achieve the required properties in the bar. A poor alloy selection on the part of the producer would allow the test bar to pass but fail to produce the desired properties in the casting. By specification, the product would be acceptable. To prevent this absurd outcome, ASTM A148 11.1.1 requires that if the purchaser indicates a ruling thickness, T, greater than 3 inches, the supplier is required to use a test coupon from ASTM A781 Supplement S15. The test block required is cast Tx3Tx3T up to a 5”x15”x15”. This makes sure that the alloy used for the casting is able to provide the properties in the casting ordered by the customer. It still does not guarantee the casting properties but does make sure that the casting alloy grade was capable of getting the properties in the desired section size. The limit on test coupon size in S15 of A781 is to avoid large test bars of excess weight. The maximum A148 coupon is over 300 pounds unrisered.

ASTM A781 S15 defines a number of alternative test coupons that can be used when the purchaser requires them and designates a thickness, “T”. For sections added to the casting for testing S15.3.1, the test is taken so that the gage section or critical test section is at least ¼ T from the surface. For separately cast test blocks S15.3.2, then test block is Tx3Tx3T and the test material must come at least 1/4T from the nearest surface and T from all others. Other options are available. The properties required by the material specification can be met with a standard test coupon unless the purchaser invokes a heavier section requirement. When an alternative test coupon is required, the producer get to negotiate the properties required.

ASTM A1001 was developed for High Strength Steel Castings in Heavy Sections. It defines section ranges from 3 to 7 inches. The 7 categories define a test bar for properties TxL where T is the diameter and L the length. The largest bar is 33 inches long and 33 inches in diameter. This is a bar over 8,000 pounds for a test article without a riser. It is not clear that this standard has seen wide use. It requires tests at T/8 and 3T/8 with lower tensile and ductility for the 3T/8 but constant CVN at all locations and section sizes. This may be an attempt to maintain the critical toughness in the heavy sections. This specification has not been active since adoption.

The requirement for heavy section test coupons is really not a casting requirement but was developed for users buying rolled sections like plates or forgings. Since the properties of rolled and forged products can vary with the reductions and other processing, samples from the product like prolongations produced on the forgings were necessary to know what properties were achieved in manufacturing.

In heavy section steel plates, properties are taken from the product. In this case the test location is ¼ T where T is the thickness of the product. In heavy section plates, a test coupon made separately is not appropriate since the properties of the product will be affected by the mechanical deformation of the manufacturing process. This use of ¼ T is common, requiring the test material to be characteristic of the section size. It would not be appropriate to require the material to come from the centerline where banding, segregation, porosity or other metallurgical effects may limit the properties measured. It would not be representative of the typical properties to take a test sample from near the surface with the higher levels of reduction and cooling rate. Since the part performance will be determined by the bulk product properties it is most useful and characteristic to take tests from the ¼ T section.

In forgings, ASTM A688 covers the requirements for carbon and alloy steel forgings for industrial use. Mechanical tests are to be done on prolongations with either a controlling section thickness T_c analogous to the casting ruling thickness T or a reduced section thickness T_p of the forging. Test material is taken below ¼ T and at least 3.5 inches from any other surfaces. The test material can be taken at a location identified by the purchaser if they identify the most critical location. Like plate, the forgings require that a prolongation be tested since the forging operation will affect the properties. Ascertaining the performance properties of the forging or plate requires that the test material experience the processing of the product. For forgings the test sample orientation is left to the producer but is required to be reported.

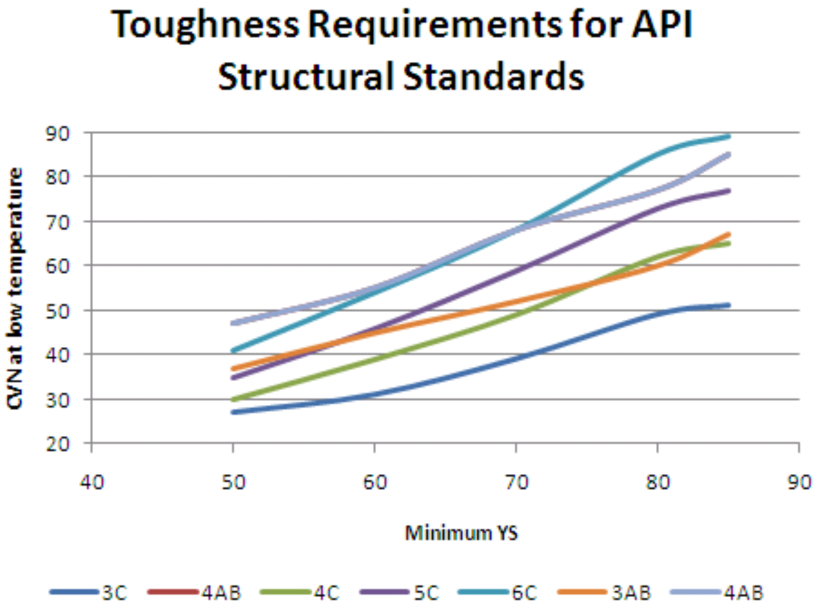

Figure 10 Charpy V-Notch minimum values for Low Temperature tests in thick sections and higher YS

API has been developing specifications for both castings and forgings for offshore structural applications. The specifications are similar in scope and structure. The specifications are for carbon and alloyed steel products that are typically heavy in section size. The forging specification requires a reduction ratio of at least 3:1. Properties are measured on a QTS qualification test sample. This sample must receive the same processing as the forging. Dimensions of the prolongation tested are at a minimum, TxTx2T+2in. T is the critical section defined by the producer. Test material comes from T/4 from the QTS. (API 2SF, 2010) In a similar way, API specifies steel castings. The test material must be in the same mold and receive the same treatment as the castings provided. Test material are at a minimum, TxTx2T+2in, where T is the critical section defined by the producer. (API 2SC, 2013)

The standard requires higher CVN values for thicker sections for both forgings and castings. Figure 10 shows that higher toughness is required as the section size increases and at higher strengths. This is contrary to the actual property development but appears to be an effort to assure that heavier sections have greater toughness to avoid premature failures. Fracture toughness analysis suggests that heavier sections with higher strength requirements would need higher toughness in the material grade selected.

Conclusions

1. Test coupons for steel products are a measure of the steel grade produced not intended to set a minimum or typical property level for the product.
2. All steel products fail because the performance loads exceed the product's capacity. The capacity of the product depends on the geometry of the component, the properties of the material and the character of the load.
3. Heavy section steel products often have lower capacities than thinner sections due to coarser structures. Segregation, porosity, and response to heat treatment are all affected by section size.
4. Heavy section components often fail when excessively loaded at the smallest cross section in a brittle appearing manner. This is due to a notch effect and due to the constraint reducing the ability of the part to be plastically deformed.
5. Fracture toughness is an analysis intended to predict performance capacity of heavy section parts that have limited plastic deformation due to size and geometry. The critical elements of fracture toughness analysis are the toughness of the material, the thickness of the part and the size of the notch or crack.
6. Critical steel forgings and castings are required and are capable of achieving the same properties for critical applications as seen in the API specification requirements.
7. Heavy section test prolongations are required in forgings and test material for thick plates are required to come from the plate to capture the effect of forming on steel properties.
8. All heavy section test coupons samples are taken ¼ T deep where T is the section size identified as critical by the purchaser and characteristic of the test coupon.

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