TEST COUPONS AND CASTING PROPERTIES

The mechanical test requirements for castings are given in the material specification in ASTM. Examples would be impact properties for grade LCC in A352, tensile strength requirements for grade 4N in A487, or ductility minimums for grade 70-40 in A27. The properties were developed for these alloy grades from keel block leg specimens. The mechanical test requirements are intended to venfy the quality of the steel and were not intended to establish the actual casting properties.

Most ASTM steel castings must conform to A781 or; if they are for pressure containing service, A703. Both of these specifications recognize that castings and test coupons exhibit different properties. In ASTM A781, this is indicated in Section 6--Tensile Requirements .

6.2 Unless otherwise specified by the purchaser, when mechanical properties are required by the product specification, test coupons may be cast integrally with the castings, or as separate blocks, in accordance with Figs. 1,2, or 3 except when Supplementary Requirement S 15 is specified. The test coupon in Fig. 3 shall be employed only for austenitic alloy castings with cross sections less than 2 1/2 in.[8]

[8] Information on the relationship of mechanical properties determined on test coupons obtained as specified in 6.2 with thoseobtained from the casting may be found in "The Steel Casting Handbook," Fifth Edition, Steel Founders' society of America, pp. 15-35 through 15-43, 1980.

In 6.2, unless required by purchaser, all mechanical properties are developed using specimens from standard keel blocks. Reference is made in Note 8, to the SFSA Steel Casting Handbook.

If casting properties are required, S14 is to be mandated. Since heavy section castings do not develop the same properties as test coupons, the properties and location of test specimens must be negotiated. S15 is for cast test coupons that have a thickness similar to the casting. Properties from this coupon are for the information of the purchaser unless the supplier agrees to meet the specification requirements in this heavy section coupon.

In 703, similar requirements hold, tensile test are given in Section 7.

7.4 Unless otherwise specified by the purchaser, test coupons may be cast integrally with the castings or as separate blocks in accordance with Fig. 1 and Table 2, with Fig. 2, or with Fig. 3, except when Supplementary Requirement S26 is specified. The test coupon in Fig. 3 shall be employed only for austenitic alloy castings with cross sections less than 2 1/2 in. [63.5 mm]. Tension test coupons shall be machined or ground to the form and dimension shown in Fig. 6 of Test Methods and Definitions A 370, except when investment castings are ordered. When investment castings are ordered, the manufacturer shall prepare test specimens in accordance with S3.2 of Specification A 732/A 732M.[12]

[12] Information on the relationship of mechanical properties determined on test coupons obtained as specified in 7.1 and 7.4 with those obtained from the casting, may be found in "The Steel Castings Handbook," Fifth Edition, Steel Founders' Society of America, 1980, pp 15-35 through 15-43.

Unless S26 is specified, test coupons from keel blocks are used. This paragraph has a similar note that refers to the SFSA Steel Casting Handbook.

S14. Tension Test from Castings

S14.1 In addition to the tension test required by the matenal specification, test material shall be cut from the casting. The mechanical properties and location for the test material shall be agreed upon by the manufacturer and purchaser.

Test Coupon Versus Casting Properties

Coupon properties refer to the properties of specimens cut and machined from either a separately cast coupon, or a coupon which is attached to, and cast integrally with the casting. Typically, the legs of the ASTM standard keel block (A370) serve as the coupons. The legs of this keel block are 1.25 in. (32 mm) thick.

Casting properties refer to the properties of specimens cut and machined from the production casting itself. A casting from which properties are determined in this manner is either destroyed in the process, or requires repair welding to replace the metal removed for testing.

Test Coupons. The ASTM double-legged keel block, Fig. 15-67, is the most prominent design for test coupons among those in use and among those recognized by ASTM's specification A370. Table 15-15 offers information on the reliability of tensile test results obtained from the double leg keel block. The data indicate that for two tests there is 95% assurance that the actual strength is within ±1,000 psi (6.9 MPa) of the actual ultimate tensile strength and within ±1,600 psi (11 MPa) of the actual yield strength. For tensile ductility the data show that two tests produce, with 95% assurance, the elongation results within ±3% and the reduction in area value within ±5%.

When 1.25-in. (32-mm) thick test coupons are suitably attached to the casting, and cast integrally with the production casting, the tensile properties determined for the coupon will be comparable to those from a separately cast keel block. Tables 15-16 and 15-17 contain data on this conclusion for numerous grades of cast steel.

Properties determined from keel block legs whose dimensions exceed those of the ASTM double leg keel block, i.e. which are thicker than 1.25 in. (32 mm), may differ, especially if the steel involved is of insufficient hardenability for the heat treatment employed to produce a similar microstructure to that in 1.25-in. (32-mm) section keel block legs. Data in Table 15-18 show slightly decreasing strength and ductility with increasing keel block section size of the annealed 0.26% carbon steel. Larger mass effects in Table 15-19 are evident for several of the quenched and tempered materials, and also for those in the normalized and tempered condition. These data apply to low alloy steels of similar carbon content, while those in Table 15-20 illustrate the mass effect in cast 8600 type Ni-Cr-Mo steel with carbon contents between 0.28 and 0.40%.

Product Requirements. The mechanical property requirements which individual cast steel grades must meet are listed in the applicable casting specifications. These properties must be met by test specimens that are removed from separately cast or attached ASTM test coupons. Specifications of this type do not recognize the mass effect and are only intended to monitor the quality of the metal from which the casting is made. Among the ASTM specifications which take mass effects into account are E208, A356, and A757. More specifications will do so in the future. In cases where mass effects are recognized by the specification, the casting purchaser has the opportunity to specify

TABLE 15-16 Properties of Coupons Cast Integrally to Castings and Separately Cast Coupons (1)

Type of Steel	No. 1 Carbon Steel		No. 2 Mn-Mo Steel		No. 3 Carbon Steel		Grade B Steel	
Type of Coupon	Keel	Att.	Keel	Att.	Keel	Att.	Keel	Att.
Hardness-BHN	153	148	241	241	—	—	—	—
Tensile Str.-ksi (MPa)	76 (524)	74 (510)	117 (807)	116 (800)	73 (503)	73 (503)	78 (538)	80 (552)
Yield Str.-ksi (MPa)	46 (317)	44 (303)	94 (648)	93 (641)	49 (338)	47 (324)	47 (324)	47 (324)
% Elongation	34.5	31.0	22.5	21.0	34.0	35.5	27.5	27.5
% Red. of Area	54.4	50.3	51.7	47.2	57.8	60.8	47.1	42.7

TABLE 15-17 Comparison of Mechanical Properties of Separately Cast Coupons and Coupons Attached to a Casting (Carbon Steel, Normalized) (1)

	Mean		Median value		Mode	
Type of Coupon	Keel	Attached	Keel	Attached	Keel	Attached
			Railroad Castings (20 heats)			
Yield Str.-ksi (MPa)	52 (359)	50 (345)	53 (365)	50 (345)	53 (365)	50 (345)
Tensile Str.-ksi (MPa)	78 (538)	78 (538)	78 (538)	77 (531)	74 (510)	76 (524)
Elong. %	28.8	27.6	28.7	27.5	28.5	27.1
Red. of Area %	48.3	42.1	49.0	42.0	48.8	43.0
			Miscellaneous Carbon Steel Castings (68 heats)			
Yield Str.-ksi (MPa)	52 (359)	46 (317)	53 (365)	46 (317)	53 (365)	46 (317)
Tensile Str.-ksi (MPa)	78 (538)	75 (517)	78 (538)	74 (510)	74 (510)	73 (503)
Elong. %	31.6	31.3	32.2	31.5	32.0	31.2
Red. of Area %	52.7	51.7	53.4	52.1	53.9	52.7

TABLE 15-18 Tensile Strength Variations with Specimen Location in Annealed Carbon Steel* Bars (30)

Cross Section of Bar in.	(mm)	Location of Specimen	Yield Strength ksi	(MPa)	Tensile Strength ksi	(MPa)	Elong. %	R.A. %
3 × 3	(76 × 76)	Center	45	(310)	72	(496)	29	39
		Top	45	(310)	72	(496)	28	35
		Bottom	45	(310)	74	(510)	28	40
		Corner	45	(310)	74	(510)	29	42
4 × 4	(102 × 102)	Center	45	(310)	71	(490)	29	39
		Top	46	(317)	71	(490)	29	43
		Bottom	45	(310)	72	(496)	30	46
		Corner	46	(317)	73	(503)	30	46
8 × 8	(203 × 203)	Center	42	(290)	69	(476)	27	36
		Top	42	(290)	70	(483)	26	40
		Top Center	43	(296)	68	(469)	26	40
		Lower Center	42	(290)	69	(476)	28	41
		Bottom	44	(303)	71	(490)	29	44
		Corner	44	(303)	72	(496)	29	44

*.26% C, .63% Mn, and .22% Si

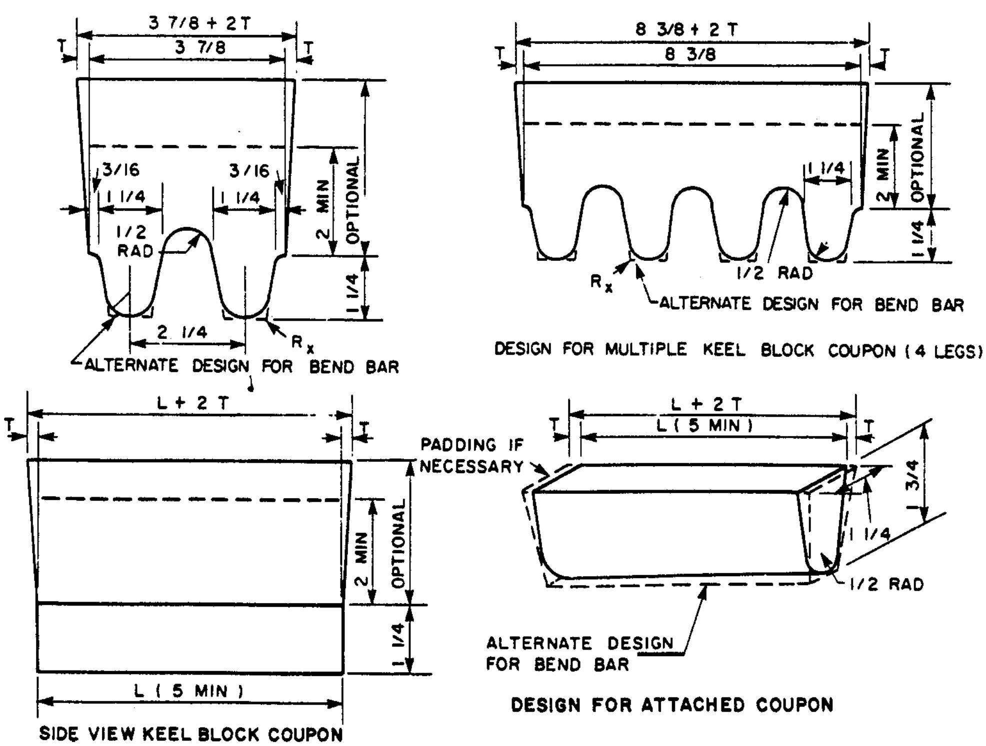

Fig. 15-67 Keel block coupon (ASTM A370—mechanical testing of steel products). Conversion: 1 in. – 25.4 mm.

TABLE 15-19 The Effect of Mass on the Tensile and Impact Properties* of Alloy Cast Steels of Similar Carbon Content (1)

	1-in. Bar (25 mm)		2-in. Bar (51 mm)		4-in. Bar (102 mm)	
Heat Treatment:	WQT**	NT**	WQT**	NT**	WQT**	NT**
Cast 1330:						
C 0.31, Mn 1.50						
Tensile Strength ksi (MPa)	103 (710)	95 (655)	98 (676)	93 (641)	93 (641)	88 (607)
Yield Point ksi (MPa)	71 (490)	55 (379)	68 (469)	55 (379)	58 (400)	58 (365)
Elongation—%	26	28	27	27	23	23
Reduction of Area—%	56	55	58	55	53	52
Charpy Impact***	40 (54)	30 (41)	38 (52)	25 (34)	36 (49)	22 (30)
Cast 8030:						
C 0.32; Mn 1.20; Mo 0.16						
Tensile Strength ksi (MPa)	115 (793)	97 (669)	107 (738)	94 (648)	93 (641)	93 (641)
Yield Point ksi (MPa)	95 (655)	65 (448)	90 (621)	62 (427)	60 (414)	61 (421)
Elongation—%	21	24	20	23	20	19
Reduction of Area—%	52	49	50	46	45	40
Charpy Impact***	30 (41)	20 (27)	25 (34)	22 (30)	22 (30)	17 (23)
Cast 8430:						
C 0.32; Mn 1.43; Mo 0.34						
Tensile Strength ksi (MPa)	122 (841)	104 (717)	117 (807)	107 (738)	104 (717)	103 (710)
Yield Point ksi (MPa)	104 (717)	75 (517)	98 (676)	76 (524)	81 (558)	77 (531)
Elongation—%	20	22	21	22	20	18
Reduction of Area—%	50	50	51	47	48	42
Charpy Impact***	33 (45)	21 (28)	34 (46)	24 (32)	32 (43)	21 (28)
Cast 9530:						
C 0.29; Mn 1.41; Ni 0.60;						
Cr 0.60; Mo 0.37						
Tensile Strength ksi (MPa)	130 (896)	114 (786)	128 (883)	116 (800)	125 (862)	113 (779)
Yield Point ksi (MPa)	112 (772)	89 (614)	110 (758)	93 (641)	110 (758)	91 (627)
Elongation—%	18	18	20	18	17	16
Reduction of Area—%	42	44	45	42	44	40
Charpy Impact***	25 (34)	20 (27)	28 (38)	24 (33)	24 (33)	18 (24)

*Properties determined at the center location of the 1, 2, and 4 in. (25, 51, and 102 mm) bars.
**WQT = water quenched and tempered
NT = normalized and tempered
***Keyhole Notch—ft. lb (J)

mechanical property testing of specimens which are machined from test coupons sized proportionally to the heaviest critical section of the casting. Typically, the test specimens are removed from the 1 /4 T location of the coupons, i.e. at mid-distance between the surface and center. The cost of such procedures is substantially larger than that involved in machining and testing specimens from the standard coupons shown in Figure 15-67. Customers therefore order tests from larger coupons only when the substantial extra cost is justified.

Casting Properties. The preceding discussions of the effects of section size on mechanical properties of carbon and low alloy steel and of discontinuities have clearly indicated that differences may exist between coupon properties and casting properties, i.e. the mechanical properties of specimens removed from the component may differ from properties of the component itself. With increasing frequency casting buyers are specifying that one or more castings be destroyed by cutting a coupon for testing from some section of the casting. These tests may serve to verify that expected quality levels are actually met because they reflect composition, heat treatment and especially gating and risering procedures which control the soundness or freedom from shrinkage discontinuities. The trend toward determination of casting properties is limited, however, by cost considerations as well as the limited value of these tests. Composition and heat treatment can be verified at lower cost, more readily and more reliably by alternate conventional means, and discontinuities are in most instances assessed at lower cost by nondestructive testing. Moreover, the tensile properties determined from castings do not reliably reflect casting performance in terms of fatigue or sudden fracture. Full scale tests which duplicate service conditions offer the only reliable means of evaluating the performance of a component.

Thinner-walled castings, with sections of 3 in. (76 mm) or less tend to be less susceptible to the effect of section size. The mechanical properties are, of course, subject to the effect of discontinuities that may be present. One customer audit of tensile properties at random casting locations in 0.25% carbon steel castings from nine foundries indicated the ultimate tensile strength, at a 1 /4 T distance from the surface, to be 75 ksi (517 MPa), or 10 ksi (69 MPa) over the

TABLE 15-20 The Effect of Mass and Carbon Content on the Tensile and Impact Properties* of Nickel-Chromium-Molybdenum Cast Steel Bars (1)

	1-in. Bar (25 mm)		2-in. Bar (51 mm)		4-in. Bar (102 mm)	
	WQT**	NT**	WQT**	NT**	WQT**	NT**
Cast 8620: C 0.20; Ni 0.60; Cr 0.54; Mo 0.17						
Tensile Strength ksi (MPa)	110 (758)	84 (579)	98 (676)	82 (565)	94 (648)	81 (558)
Yield Point ksi (MPa)	88 (607)	57 (386)	76 (524)	53 (365)	72 (496)	50 (345)
Elongation—%	25	28	25	31	23	27
Reduction of Area—%	58	57	56	56	52	53
Charpy Impact***	40 (54)	28 (38)	39 (53)	28 (38)	35 (47)	26 (35)
Cast 8630: C 0.29; Ni 0.71 Cr 0.60; Mo 0.19						
Tensile Strength ksi (MPa)	125 (862)	103 (710)	117 (807)	99 (683)	106 (731)	95 (655)
Yield Point ksi (MPa)	107 (738)	75 (517)	96 (662)	68 (469)	79 (545)	60 (414)
Elongation—%	20	22	21	20	20	17
Reduction of Area—%	53	52	52	48	47	38
Charpy Impact***	34 (46)	21 (28)	32 (43)	23 (31)	28 (38)	21 (28)
Cast 8640: C 0.40; Ni 0.66; Cr 0.55; Mo 0.17						
Tensile Strength ksi (MPa)	138 (951)	115 (793)	130 (896)	119 (820)	122 (841)	110 (758)
Yield Point ksi (MPa)	119 (820)	81 (558)	109 (752)	78 (538)	100 (689)	74 (510)
Elongation—%	19	18	17	18	16	16
Reduction of Area—%	42	39	37	35	33	30
Charpy Impact***	23 (31)	14 (19)	23 (31)	12 (16)	24 (33)	8 (11)

*Properties determined at the center location of the 1, 2, and 4 in. (25, 51, and 102 mm) bars.
**WQT = water quenched and tempered
NT = normalized and tempered
***Keyhole Notch ft. lb (J)

minimum specified for specimens removed from keel blocks. Only 2% of the tests were below the minimum value (Table 15-21). The percent elongation values averaged 25%, 5% above the minimum value for specimens from keel blocks. Of the tests, 21% were below the minimum (Table 15-21).

For heavier-wall castings, with sections in excess of 3 in. (76 mm), the effect of mass or section size is very important for quenched and tempered low alloy steels if the alloy content is insufficient to produce through-hardening. Figure 15-68 shows properties for separately cast coupons and those determined at different locations in actual castings. Lower strength values are evident for specimens removed from 5.5-in. thick sections of large Mn-Mo production castings. The composition of these steels is indicated in Table 15-22. The percentage decrease in tensile strength from surface to center of the 5.5-in. (140-mm), quenched and tempered Mn-Mo steels is of the order of 10%. The Charpy V-notch impact toughness at room temperature is significantly lower compared to the coupon. Tensile ductility, especially the reduction in area values, reveals the effects of section size and microporosity .

The steels with greater hardenability (Mn-Mo-V and Ni-Cr-Mo of Table 15-22) exhibit no appreciable decrease in strength as a function of specimen distance from the casting surface (Figure 15-69). Toughness for these steels does in fact increase with distance

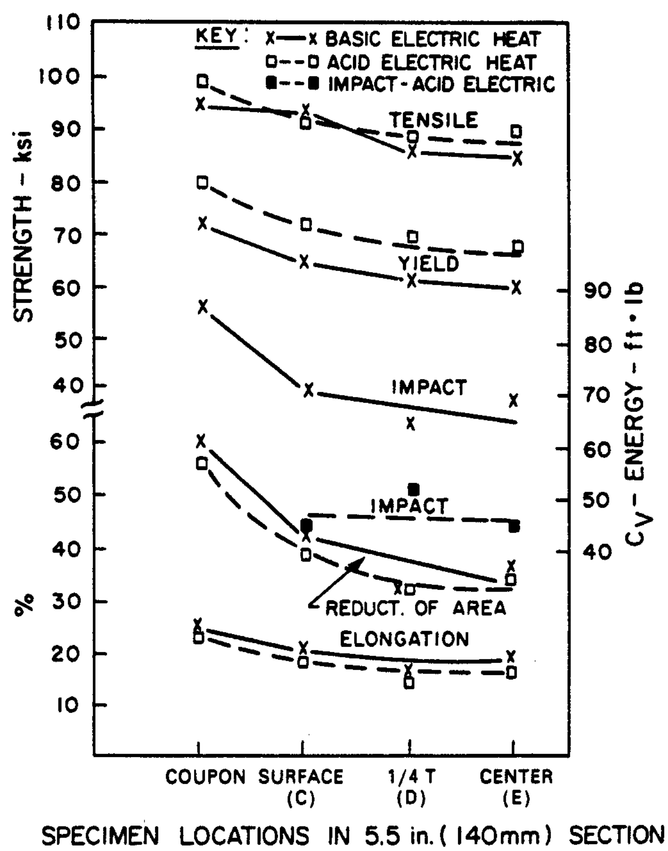

Fig. 15-68 Mechanical properties of specimens cut from various locations of two quenched and tempered Mn-Mo production castings (Composition in Table 15-22) (1). Conversion: 1 ksi = 6.895 MPa, 1 ft·lb = 1.356 J.

TABLE 15-21 Audit of Casting Properties at 1/4 T Locations in Randomly Selected Areas of 0.25% Carbon Steel Castings

Ultimate Tensile Strength—ksi (MPa)
[65 ksi (448 MPa) = Minimum for Specimens from Keel Block]

Supplier	n[1]	Average	Sigma	Low	High
A	4	78 (538)	2 (14)	75 (517)	80 (552)
B	10	79 (545)	4 (28)	74 (510)	86 (593)
C	16	77 (531)	5 (34)	67 (462)	83 (572)
D	22	76 (524)	5 (34)	63 (434)	81 (558)
E	18	77 (531)	4 (28)	69 (476)	83 (572)
F	18	73 (503)	4 (28)	67 (462)	82 (565)
G	26	73 (503)	5 (34)	64 (441)	85 (586)
H	12	72 (496)	8 (55)	50 (345)	78 (538)
I	17	75 (517)	2 (14)	71 (490)	80 (552)
Average		75 (517)			

Tensile Elongation—%
(20% = Minimum for Specimens from Keel Block)

Supplier	n[1]	Average	Sigma	Low	High
A	4	30	3	28	33
B	10	25	9	13	40
C	16	20	7	10	33
D	22	23	13	9	57
E	18	30	12	10	55
F	18	26	8	10	38
G	26	23	5	14	32
H	12	18	6	7	27
I	17	30	5	20	40
Average		25			

[1] No. of castings tested

from the surface, proportional to the slight loss in strength. Tensile ductility values reflect the effect of mass and microporosity.

For heavy-walled annealed carbon steel castings, with sections in excess of 10 in. (254 mm), the strength properties near the casting surface are comparable to those of the specimens from keel blocks or attached coupons (Figure 15-70) as illustrated by tests on a large pivot arm casting (Figure 15-71). A 5 to 10% decrease is noted in 22-in. (559 mm) sections at the 1/4 T and center locations. As expected, the tensile ductility values are quite sensitive to mass and microporosity-a loss of up to 30% was observed in sections up to 22 in. (559 mm) thick (Figure 15-72). Room temperature Charpy V-notch impact properties are not affected by the location within the casting (Figure 15-73).

For heavy section normalized and tempered 0.17% C - 2% Ni steel castings, uniform tensile strength and room temperature Charpy V-notch impact toughness values were reported for a 15-ton turbine blade casting with sections up to 30 in. (762 mm). The variation in strength with section size was within 10%, while toughness values were entirely uniform

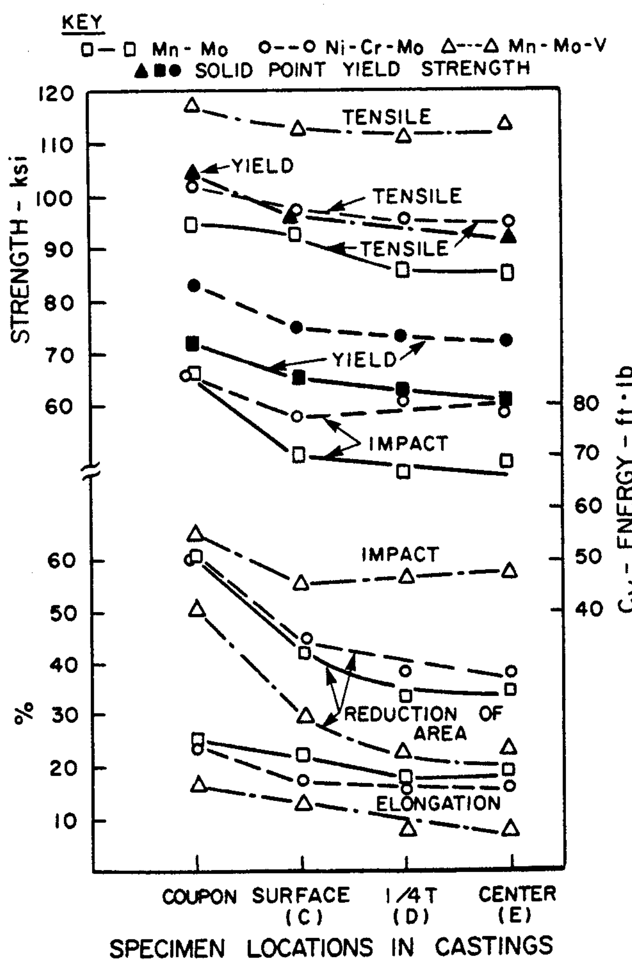

Fig. 15-69 Mechanical properties of specimens cut from various locations of quenched and tempered low alloy steel production castings (Compositions given in Table 15-22) (**1**). Conversion: 1 ksi = 6.895 MPa, 1 ft·lb = 1.356 J.

TABLE 15-22 Analyses of Four 5.5 in. (140 mm) Thick Low Alloy Steel Castings (1)

		Composition—%								
Process	Type	C	Mn	Si	P	S	Ni	Cr	Mo	V
Acid	Mn-Mo	0.29	1.10	0.46	0.033	0.030	—	—	0.47	—
Basic	Mn-Mo	0.29	1.08	0.32	0.014	0.010	—	—	0.32	—
Basic	Mn-Mo-V	0.36	1.33	0.35	0.019	0.018	—	—	0.46	0.11
Basic	Ni-Cr-Mo	0.26	0.61	0.25	0.015	0.018	1.42	0.77	0.30	—

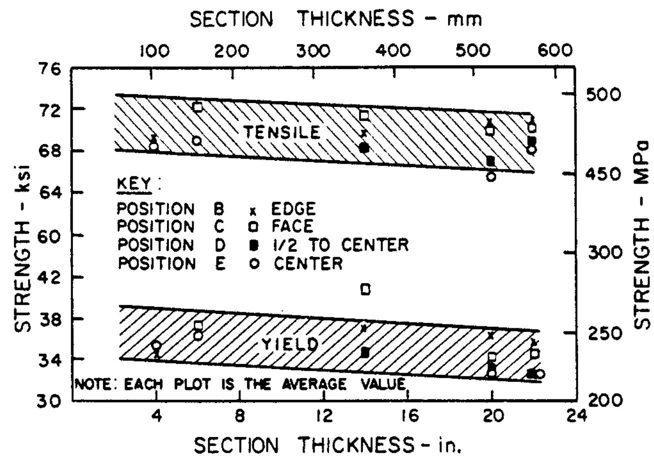

Fig. 15-70 Tensile and yield strength as a function of section size and location within the annealed pivot arm of carbon steel in Figure 15-71 (1).

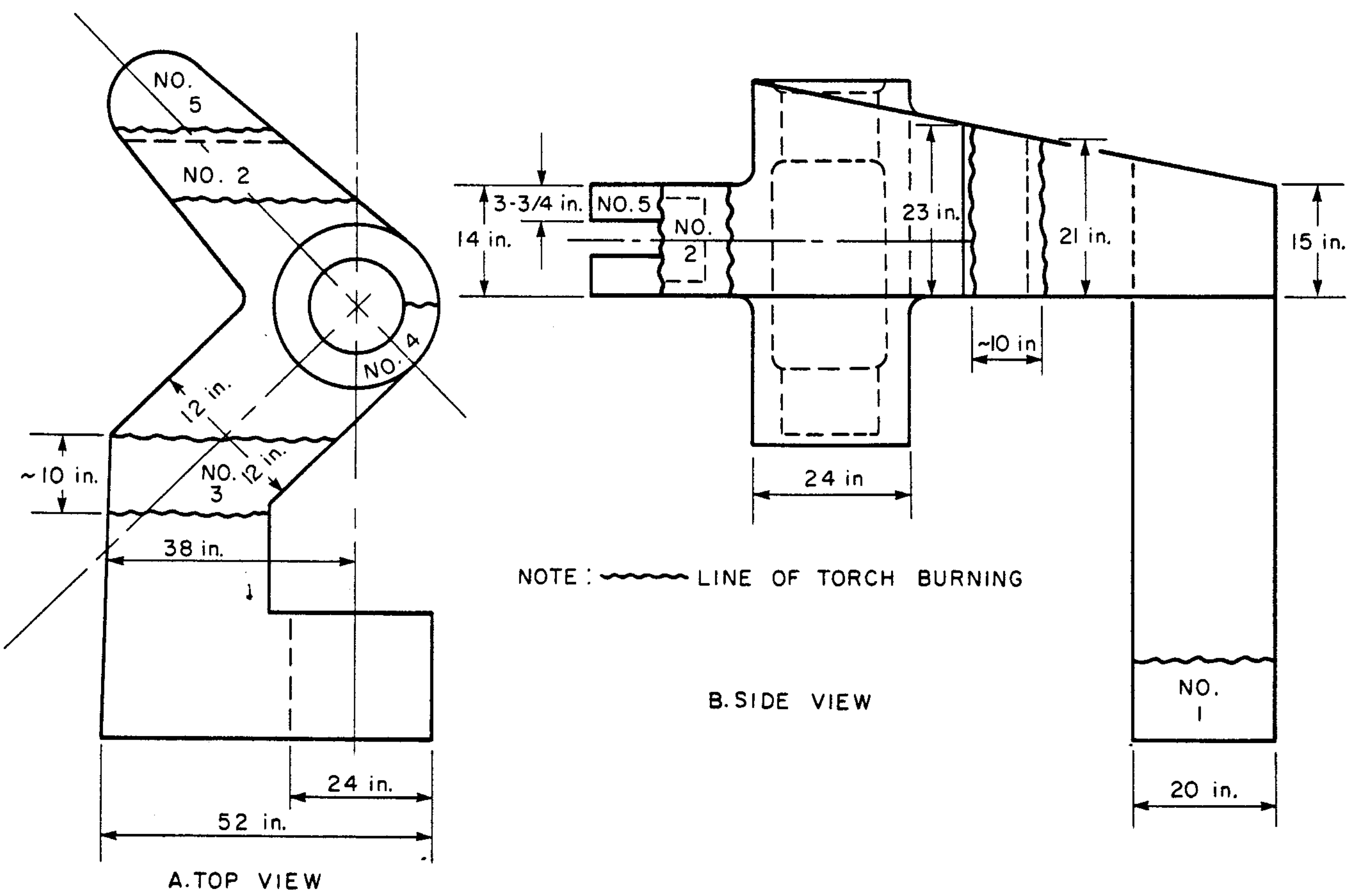

Fig. 15-71 A. Top view of pivot arm with significant dimensions. B. Side view of pivot arm with significant dimensions. Conversion: 1 in. = 25.4 mm.

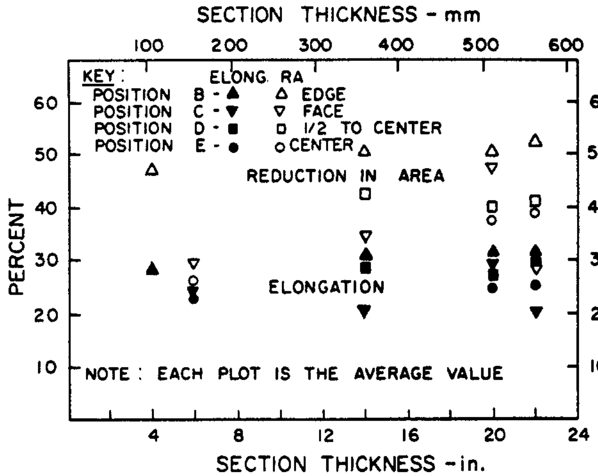

Fig. 15-72 Elongation and reduction in area as a function of section size and location within the annealed pivot arm of carbon steel in Figure 15-71 (1).

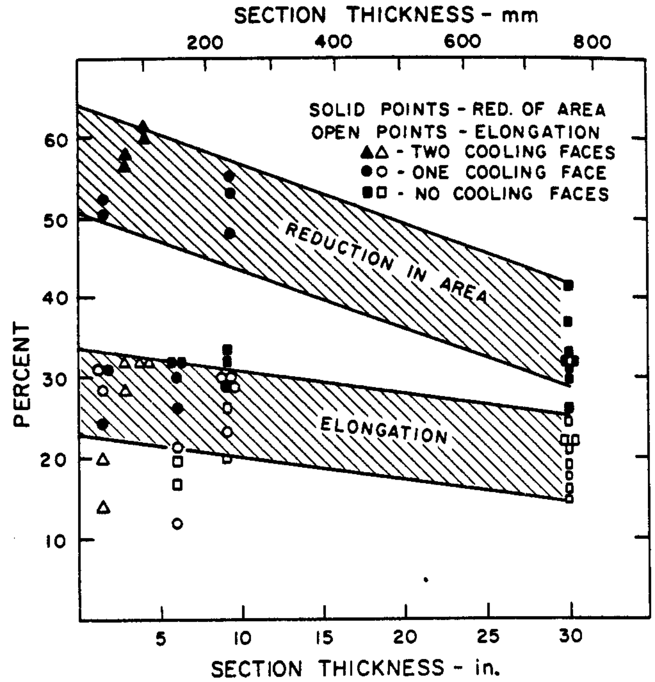

Fig. 15-75 Effect of section size on tensile ductility, at 1/4 T and center locations, of a normalized and tempered turbine blade casting of Ni steel (0.2%C, 2.4%Ni) (1).

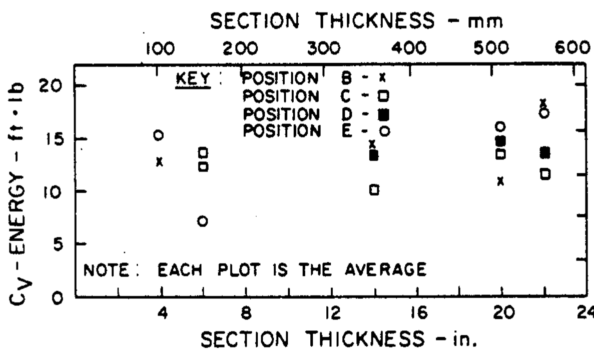

Fig. 15-73 Room temperature Charpy V-notch impact properties as a function of section size and location within the annealed pivot arm of carbon steel in Figure 15-71 (1).

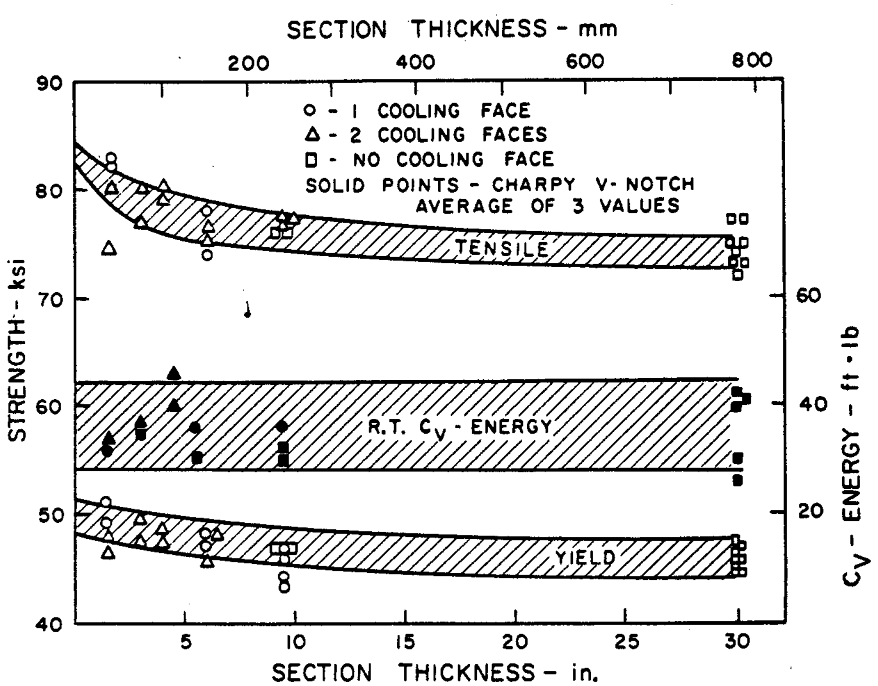

Fig. 15-74 Effect of section size on tensile and impact properties, at the 1/4 T and center locations, of a normalized and tempered turbine blade casting of Ni steel (0.20%C, 2.4%Ni) Conversion: 1 ksi = 6.895 MPa, 1 ft·lb = 1.356 J (1).

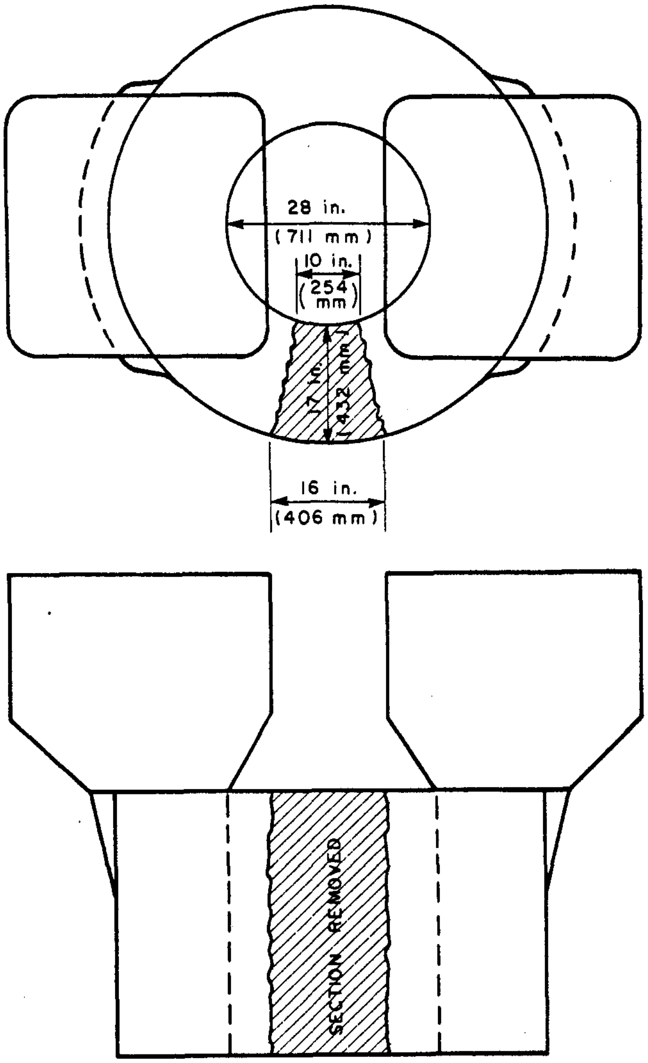

Fig. 15-76 Sketch of cast gear, quenched and tempered cast 8630 steel, showing location of section from which trepanned specimens were removed.

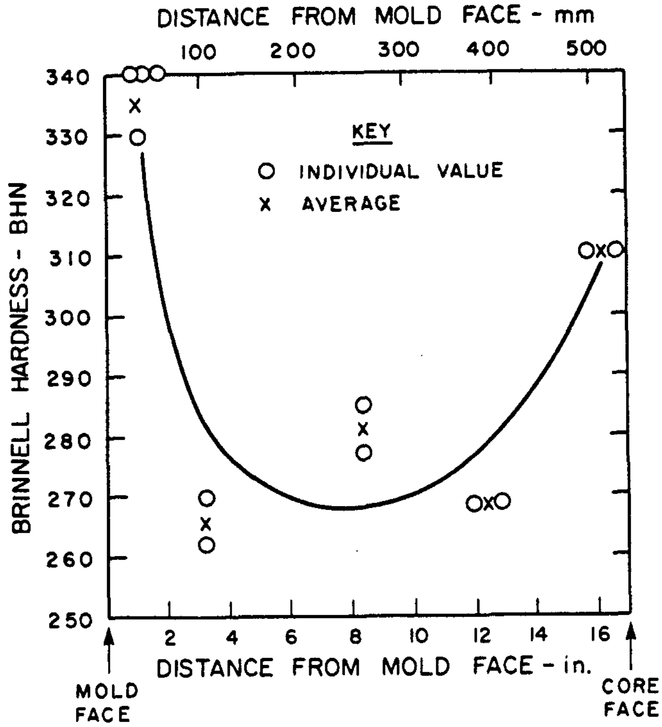

Fig. 15-77 Effect of distance from cooling faces (mold and core) on hardness of a gear blank face shown in Figure 15-76 (1).

because this grade of steel develops uniform microstructure and because toughness is not as sensitive to microporosity as tensile ductility (Figures 15-74 and 15-75).

Insufficient hardenability of low alloy steels will, of course, cause major variations in heavy section quenched and tempered components. An example (Figure 15-76) of a 17-in. (432-mm) thick gear blank of Ni-Cr-Mo cast 8635 steel illustrates the major variations in hardness and toughness that may occur because the steel is unable to develop a uniform microstructure across the component section (Figures 15-77 and 15-78).

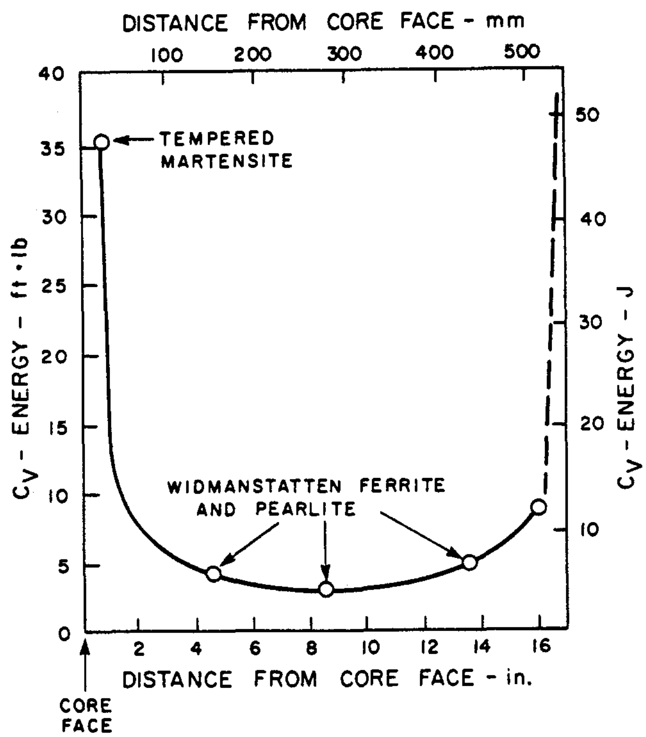

Fig. 15-78 Effect of distance from casting face on Charpy V-notch impact energy at 0°F (−18°C) of a gear blank shown in Figure 15-76 (1).

THIS PROBLEM HAS BEEN COMMENTED ON AT SOME LENGTH IN THE PROCEEDINGS - 1st INTERNATIONAL STEEL FOUNDRY CONGRESS.

Understanding Various National and International Specifications

Raymond W. Monroe
Research Director
Steel Founders' Society of America
Des Plaines, Illinois

Whenever possible, it becomes the responsibility of specification writing bodies to try and resolve the conflict by reasonable requiements that are meaningful to the customer but still economical ly attainable by the foundry. The mechanical properties of a steel casting depend primarily on the interaction of casting design, section size, chemistry and heat treatment. Mechanical properties requirements in materials specifications are arrived at by statistical analysis of test results from standard test bars. It is commonly recognized that the mechanical properties can decrease as the casting section size increases, especially toughness and ductility in carbon and low alloy steels. In BSI standards, there is a note that: "The mechanical properties required shall be obtained from test bars cast either seperately from or attached to the castings which they refer. The test values so exhibit represent, therefore, the quality of the steel from which the casting have been poured; they do not repersent the properties of the castings themselves, which may be affected by solidification conditions and rate of cooling during heat treatment, which in turn are influenced by casting thickness, size and shape".

One source of conflict with customers in the difference in properties between the test bar and castings. Some published guidelines are available but there needs to be more concrete specification work on the properties and casting thickness relationship. Either a table of requirements showing mechanical properties minimums at various section sizes or a thickness limitation on the already established minimums for various grades of cast steel materials should be established. The uniform section thickness and shape of wrought steel forms allows a tight specification at the actual mechanical properties in each product form. Steel castings manufacturers should respond with specification guidelines to the design engineer so that castings do not suffer in the market place.

Specifications; Cause, Effect and Some Examples

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Capacity: 3,500 t/mo
No. Employed: 700
Steels: Carbon, low alloy, high alloy
Products: All

ABSTRACT

Definition, origin, purpose and sources; Component parts and implications; and Detailed requirements are normally found in specifications for steel castings. One area that is poorly understood by some users is the interpretation of mechanical properties' values and mass effect. Tightening of specifications can be a result of problems encountered by customers, for example, the Al-N test method proposed as a new addition to ASTM A703. Also discussed is Quality Assurance - reason and documentation. There is a hugh cost of North American adversary system that is prevalent in our industry - pitting production versus quality control. Following specifications to the letter is inappropriate - beware of loopholes and consequences.

WHAT IS A SPECIFICATION?

A SPECIFICATION IS A WRITTEN STATEMENT OF THE REQUIREMENTS, BOTH TECHNICAL AND COMMERCIAL, FOR A PARTICULAR PRODUCT OR SERVICE.

Figure 1.

As shown in Figure 1, specifications are written statements of the requirements, both technical and commerical, for particular products or services.

They come about from the need to provide a uniform basis of information to vendors, including acceptance criteria.

New specifications and revisions of those existing are the result of experience in service, new service demands or technological developments.

Most specifications are produced by national specification writing bodies, such as ASTM, DIN, AFNOR BSI and others, regulatory agencies such as ASME or international agencies such as ISO. There are also specifications produced by military agencies and even private companies, though in most cases this is a duplication of efforts which tend to complicate further an already complex situation.

While specifications are written in different ways, there are at least three main constituents:

1. SCOPE:

The scope describes what the specification is applicable to.

2. MANDATORY REQUIREMENTS:

Mandatory requirements are contained in the body of the specification and usually consist of a number of paragraphs, each addressing a specific requirement such as chemical composition, heat treatment, mechanical properties, repair, etc.

3. SUPPLEMENTARY REQUIREMENTS:

Supplementary requirements are applicable only if called up in the inquiry and order. These cover special requirements which may be called for in the case of some specific applications, usually depending upon the severity of service or when product failure would have serious consequences.

SPECIFICATION — ESSENTIALS (Technical)

1. CHEMICAL COMPOSITION —
(Categories for service, residuals, Carbon Equivalent)

2. MECHANICAL PROPERTIES —

(Heat Treatment, to suit service requirements)

3. DISCONTINUITIES —

- **Systematic & statistical**
- **Surface, sub-surface**
- **NDE Methods, RT, MT, PT, UT**
- **Acceptance standards & criteria**

4. DIMENSIONS — Drawings

5. IDENTIFICATION — Traceability

6. DOCUMENTATION — Records

SPECIFICATION ESSENTIALS: Figures 1-6

In the case of steel castings, the first specification essential is the chemical composition, which is selected on the basis of service requirements, i.e. strength, ductility and environmental factors such as temperatures, corrosion, etc.

Specifications do not guarantee that all chemical compositions within the specified limits shall meet the requirements for mechanical properties, regardless of heat treatment. It is necessary to select the proper limits within the specification ranges, to assure the attainment of the mechanical properties specified.

For some applications, the heat treatment may be specified, to assure a desired quality which is not necessarily expressed by the requirements for mechanical properties. For other applications, the choice of heat treatment is left to the option of the manufacturer. For instance, ferritic steels intended for high temperature service are not permitted to be liquid quenched, to prevent degradation of creep strength; for low temperature service, ferritic steel castings are water quenched to enhance low temperature ductility.

Mechanical properties are also specified additionally, and many specifications reference other specifications, common to standards of the same type. Usually the latter deal strictly with the methods of testing, to determine chemical composition, mechanical properties and other criteria such as soundness, finish, etc.

Supplementary requirements are stated, as applicable. Let us consider for a moment, the ramifications of the difference in chemical composition.

Figures 2 and 3 were chosen to illustrate the drastic influence of a change in chemical composition by the addition of just a single element, on the mechanical properties of the steel.

EFFECT OF MOLYBDENUM ON MECHANICAL PROPERTIES OF C-Mn STEEL, WHEN HEAT TREATED IDENTICALLY FOR AAR GRADES C AND E

	C	Mn	P	S	Si	Ni	Cr	Mo	Al
AAR SPEC.	.32 max.	1.85	.040	.040	1.50	—	—	—	—
DF & S 1331 (AAR GR. C)	.28/ .32	1.55/ 1.75	.020	.020	.35/ .45	—	—	—	—
ANALYSIS	.32	1.61	.015	.012	.40	.02	.10	.012	.068
		D.I. = 2.20"			C.E. = .61				
DF & S 1431 (AAR GR. E)	.28 .32	1.40/ 1.60	.020	.020	.35/ .45/	—	—	.35/ .45	—
ANALYSIS	.31	1.63	.016	.010	.40	.02	.07	.40	.040
		D.I. = 4.27"			C.E. = 0.68				

Figure 2.

Figure 2 shows that the chemical composition of Dofasco grade 1331 and 1431 is practically identical, except that the latter grade contains .40% molybdenum. The difference in chemistry resulted in an increase in the Ideal Critical Diameter quench hardenability (D.I.) value from 2.20 to 4.27" and in the carbon equivalent from .61 to .68%.

$$(C.E. - C + \frac{Mn}{6} + \frac{Cr + V + Mo}{5} + \frac{Ni + Cu}{15})$$

EFFECT OF Mo ON MECHANICAL PROPERTIES OF C-Mn STEEL
MECHANICAL PROPERTIES
(1" x 6" x 15⅛" TEST COUPONS)

HEAT TREATMENT 1750°F W.Q. — TEMPER 1150°F A.C.

	UTS KSI	YS KSI	R %	E %	CVN @ -40°F FT.LB.	HARDNESS BHN	NDTT @ °F
AAR GR. C	90.	60.	45.0	22.0	25	179 – 241	–70
DF & S 1331	101.6	78.4	48.8	22.0	25	207	–80
AAR GR. E	120.	100.	30.0	14.0	20	241 – 311	–70
DF & S 1431	128.	113.	32.1	14.0	27.5	302	–80

Figure 3.

Figure 3 shows that when standard ASTM type test bars were subjected to identical heat treatment consisting of austenitizing at 1750°F and water quenching, followed by tempering at 1150°F, the lower hardenability steel (no molybdenum) met all of the mechanical properties for the AAR Grade C - Quenched and Tempered (90 ksi min. tensile strength) while the molybdenum steel met the higher strength requirements (120 ksi min. tensile strength) of the AAR Grade E specification.

It is worth noting that the 1331 steel exceeds the minimum strength requirements by a large margin, so that a higher tempering temperature would no doubt improve the reduction of area, elongation and Charpy "V" notch values.

The same is true for the molybdenum-bearing steel but the tempering temperature was selected here to show the effect of molybdenum alone, under the same heat treatment conditions.

It is also noteworthy that the nil ductility trapition temperature (N.D. T.T.) was -80°F, in both cases, regardless of the large increase in strength and hardness of the molybdenum steel.

Figure 4 shows the effect of different heat treatment, i.e. water quenching and tempering versus normalizing and tempering, on the mechncial properties.
The same grade of molybdenum steel was used as above, (1431) and the aim was to attain a similar tensile strength level of approximately 100 ksi, as was previously attained in the carbon-manganese steel (1331), without molybdenum.

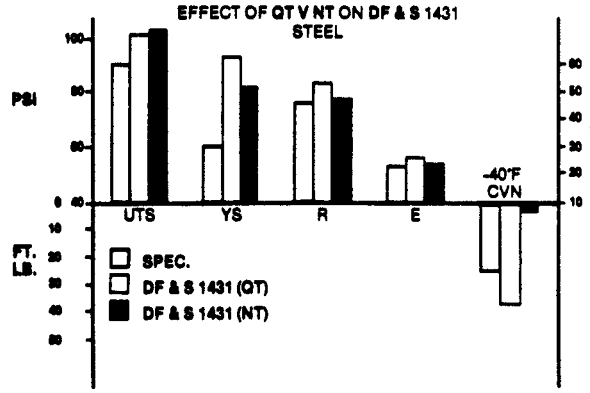


Figure 4.

While the water quenched and tempered steel exhibited superior properties, the most dramatic improvement may be noted in the Charby "V" notch values, where at -40° F (C) the normalized and tempered steel exhibits an impact strength of approximately 5 ft. lbs. compared to 35 ft. lbs. for the water quenched and tempered steel.

Due to recent changes in AAR requirements, calling for further improved properties, particularly Charpy "V" notch and nil ductility transition tempertures in specimens removed from heavy section castings, 1331 and 1431 steels are no longer used. A chromium-nickel-molybdenum alloy steel of the 8722 or similar type is now being used, for the water quenched and tempered grades of AAR C and E.

An important point to note here is exactly what the values obtained from test bars, either attached or poured separately, truly represent. Most ASTM specifications require the test bars to be processed in accordance with requirements of Methods Specifications A370 and heat treated in production furnaces to the same procedure as the castings they represent. Even if the test bars are attached to the castings and heat treated with them, (though most castings are represented by separately cast test bars) the values attained do not necessarily represent the values attainable if the test specimens were to be removed from the castings the test bars represent.

TESTING

PROPERTIES OBTAINED FROM SEPARATELY CAST - OR ATTACHED BARS REPRESENT QUALITY OF STEEL CAST.

Figure 5A BS 3100-1976

HOWEVER

BARS DO NOT REPRESENT PROPERTIES OF CASTING

BECAUSE
- **SOLIDIFICATION CONDITION**
- **COOLING RATE DURING**
- **HEAT TREATMENT**

CASTING
- **THICKNESS**
- **SIZE**
- **SHAPE**

Figure 5B BS 3100-1976

As shown in Figures 5A and 5B, this problem is very appropriately addressed in British Specifications for steel castings, which carry the following note in the testing section: "The mechanical properties required shall be obtained from test bars cast either separately from or attached to, the castings to which they refer.

The test values so exhibited represent, therefore, the quality of steel from which the castings have been poured; they do not necessarily represent the properties of castings themselves, which may be affected by solidification conditions and rate of cooling during heat treatment, which in turn are influenced by casting thickness, size and shape."

Assuming soundness of the metal in both the castings and the test bars, the main difference in the mechancial properties is due to the so-called mass-effect. The standard 1" square test bar cools faster than the casting if the casting section is heavier and the rate of cooling determines the austenite transformation product during heat treating, as may be observed by comparison of microstructures.

DF & S 8730 MODIFIED

CHEMISTRY	**C .28**	**Ni .81**
	MN .97	**Cr .68**
	P .014	**Mo .49**
	SUL .016	**Al .040**
	Si .25	

HEAT TREATMENT

NORM. 1750°F — TEMP. 1250°F AIR COOL
NORM. 1650°F W.Q. — TEMP. 1275°F W.Q.

Figure 6.

Figures 6, 7 and 8 show the comparison of mechanical properties in 1", 2-1/2" and 10" sections of a heat of steel of the 8730 type, All specimens were removed with their axes at more than 1/4=T (thickness), following heat treatment in the same furnace, at the same time, for the same time cycle.

DF & S 8730 MODIFIED
MECHANICAL PROPERTIES

	U.T.S. KSi	Y.S. KSi	% R.A.	% E.	C.V.N. @ —75°F
SPEC	90	70	35.0	18	20
1" STAND BAR	109	93	53.8	22	48
2-1/2" SEC.	107	88	57.2	33	54
10" CUBE	95	74.5	33.1	19	7

Figure 7.

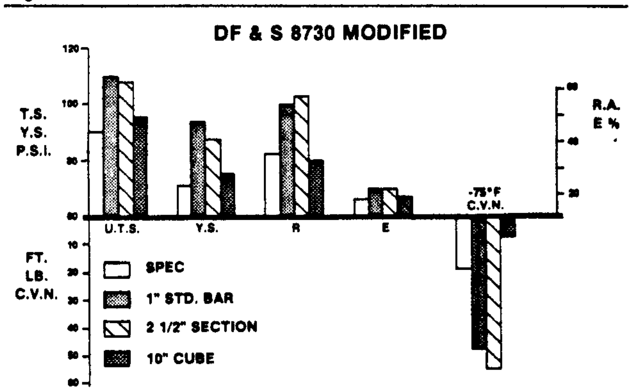


Figure 8.

It may be readily seen that while the

tensile properties are met in all three sections, except for a slight drop below the minimum in the reduction of area of the 10" section, there is a drastic drop-off in the Charpy "V" notch value at -75° F from 48 ft. lbf. in the 1" section to 7 ft. lbf. in the 10" section, while the 2-1/2" section exhibits an even better value than the 1" section, due no doubt to the lower hardness and correspondingly lower strength of the specimen.

Higher tempering temperatures for the 1" test bar, to lower the hardness and strength to that comparable with the 2-1/2" section results, would no doubt increase the Charpy values of the 1" bar specimen to exceed those of the 2-1/2" bar.

CAUTIONARY NOTE

USERS SHOULD NOTE THAT HARDENABILITY OF SOME OF THE GRADES MENTIONED MAY RESTRICT THE MAXIMUM SIZE AT WHICH THE REQUIRED MECHANICAL PROPERTIES ARE OBTAINABLE.

Figure 9.

In Figure 9, ASTM A352, a specification for ferritic and martensitic steel castings for pressure-containing parts suitable for low temperature service, carries the following cautionary note:

"Users should note that hardenability of some of the grades mentioned may restrict the maximum size at which the required mechanical properties are obtainable."

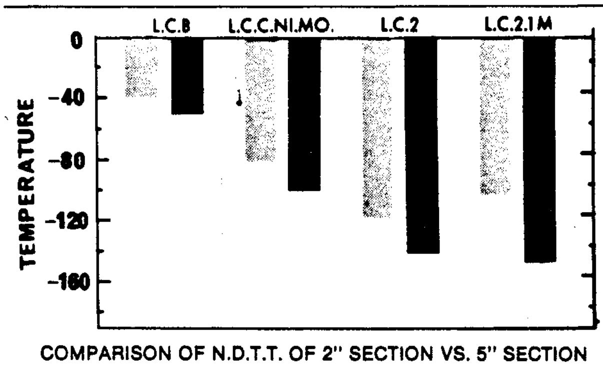


Figure 10

Figure 10 illustrates this fact, by comparing the nil ductility transition temperature of four different grades of steel, in 2" and 5" sections.

The steel examined are:

1. ASTM A352, grade LCB - plain carbon steel.

2. LCC - Nickel - Molybdenum - Nominally:

   1.75% nickel
   0.25% molybdenum
   Now ASTM A757, grade C1Q.

3. ASTM A352, grade LC2 - 2.0 to 3.0% nickel steel.

4. LC2.1M - Nominally:

   3.0% nickel
   1.50% chromium
   0.50% molybdenum
   Now ASTM A757, grade E1Q.

The graph shows not only the limitations of the first two grades, but also the superiority of the E1Q grade compared to LC2, because while the NDTT of both grades is almost equal or even slightly better in LC2, the strength levels of LC2 are 70 ksi tensile, 40 ksi yield, compared to the 90 ksi tensile and 65 ksi yield strength of E1Q.

ASTM A356, A757 and ASME Nuclear Code provide for other heavier test blocks from which specimens representing heavy castings are to be taken, or other means to provide a similar cooling rate during heat treating of the test bars and the castings, in an attempt to ensure that the test results are more representative. To that end, new clauses which would apply to all steel casting specifications are being considered for addition to A781 and A703.

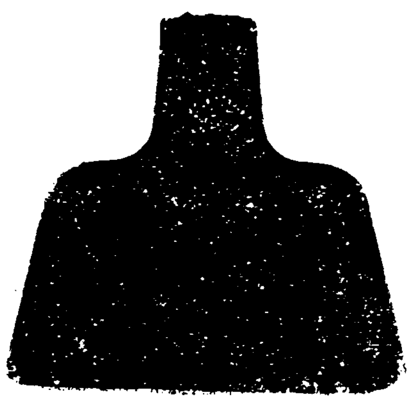
DEVELOPMENT OF NEW SPECIFICATIONS

Recently, a failure, which was traced to aluminum nitride, occurred in two valve body castings in service. As a result, the user proposed a new requirement considered for placement into ASTM standards, in an attempt to preclude reoccurrence of such failures.

The proposal involves the inclusion in the supplementary requirements, the requirement of an acid etch test to prove the presence of absence of aluminum nitride, when the steel contains aluminum over a certain minimum. This instance serves to indicate how additional requirements come about.

Figure 11 shows the primary austenitic network, indicating a severe condition of aluminum nitride precipitation along the grain boundary.

NICKEL ALLOY CAST STEEL
CONCHOIDAL NETWORK — ALUMINUM NITRIDE



CHEMICAL COMPOSITION %

C	Mn	P	S	Si	Cu	Ni	Cr	Al	Mo	V
0.23	0.50	0.021	0.028	0.52	0.08	5.0	0.11	0.11	0.035	0.013

Figure 11.

DISCONTINUITIES

Discontinuities are either systematic or statistical, the former being the result of the production technique and usually correctable - such as shrinkage, whereas statistical discontinuities, such as gas holes or inclusions are random and may vary from casting to casting, even in the same heat.

Discontinuities may be surface or subsurface and become defects only if they exceed the limits of the acceptance criteria specified for the part.

Identical type and size of discontinuities may be acceptable for one application, while they may not be for another.

NDE methods, such as radiography (RT) and ultrasonics (UT) exists for the detection of subsurface discontinuities and magnetic particle (MT) for surface and near surface discontinuties in ferro-magnetic steels, while liquid penetrant (PT) may be used for the detection of surface discontinuties in all steels.

Specifications covering the methods as well as the acceptance criteria are available and referenced in the material specifications, where applicable. In ASTM, for instance, they are E94 and E142 - Radiographic Inspection Method and Quality Standards, while E446/E186/ E280 consist of comparison radiographs depicting the actual acceptance standards. Similar specifications exist for other NDE methods.

Dimensions are usually specified on the applicable drawings, and separate specifications exist, such as SFSA's, that deal with tolerances.

NEW SPECIFICATIONS

Either because of problems encountered in the field or the seriousness of the consequences of failure of parts in the field, a whole new brand of specifications appeared in the recent past. They involve a severe tightening of existing specifications and all deal with Quality Assurance. These specifications cover such things as the identification and traceability of parts through processing, to assure that processing had been conducted in accordance with the specification and contractual requirement s. Previously, such specifications applied only to parts subject to highly critical service, such as aircraft components, etc.

The final part of these Q.A. standards is documentation, that is records, ranging from test reports cross-referencing castings to heat numbers by individual serial numbers, to welding procedures, welders' qualification records, weld repair maps, heat treat furnace charts and NDE personnel qualifications and results of examination of castings.

Many of the requirements currently encountered in this regard, have been brought upon industry by itself due to inadequate quality control in the past.

Some of these quality-related problems may be traced to the adversary system so prevalent in North America, where Product ion personnel consider all "Quality" oriented personnel, i.e. Metallurgical, Quality Control and Inspection, as an unnecessary evil, only hindering production.

"If a specification stipulates only periodic testing, to assure maintenance of a certain quality level on a statistical basis, why stop production and investigate the cause of an occasional failure, instead of passing the failed lot and testing another one? After all, the spec, does not call for testing of each heat and who knows what we pass when we do not need to test each heat?"

Some time ago, a manufacturer shipped castings containing 4.0% manganese for a specification allowing .85% manganese maximum, and while the test bar, poured early in the heat, met requirements, castings poured from the tail end of the heat containing the high manganese due to a method of ladle alloying which caused Mn and C enrichment during the last part of the pour, were as hard as 400 Brinell and failed, Ever since, all manufacturers of this huge tonnage steel casting product must take the sample for chemical analysis from the first 25% of the heat poured and another sample, for manganese determination and report, from the last usable casting of each heat from which such castings are poured.

It is precisely this kind of reasoning and error that gets industry into trouble, loses business to competition and eventually results in the further tightening of specifications, which will then call for 100% inspection, thus raising costs.

It is necessary to live up to not only the letter of specifications, but more importantly, to the spirit or intent and this will be achieved in the future only through the fullest cooperation of all personnel and the realization that all departments of any company work toward the common goal and that is to satisfy the customers demands.

Stretching specifications does not pay, as is well illustrated in Figures 12, 13 and 14.

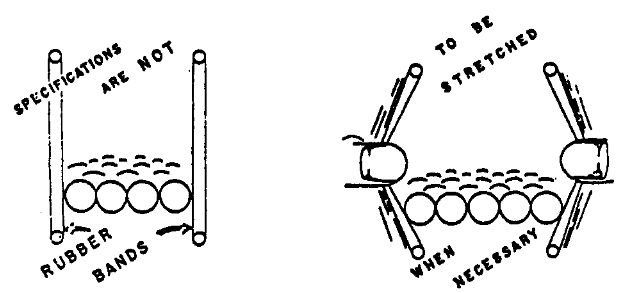


Figure 12.

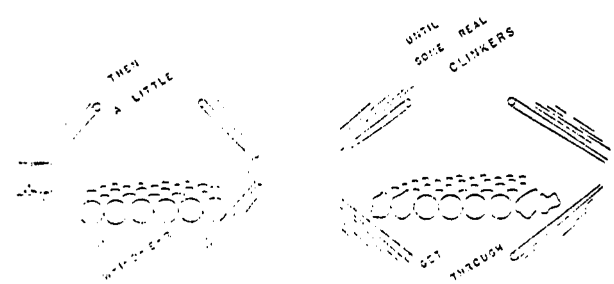


Figure 13.

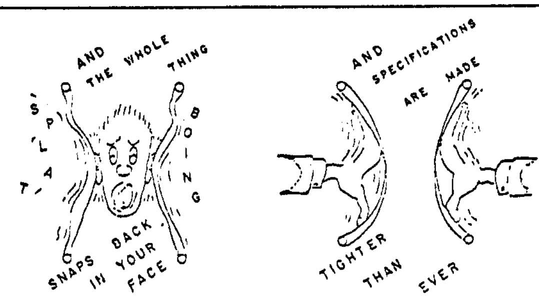


Figure 14

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2. British Standards Institution - Specification BS3100:1976 - Steel Castings for General Engineering Pur poses.

3. 1983 Annual Book of ASTM Standards, Section 1, Volume 0.1-02 - Ferrous Castings; Ferroalloys: Ship Building - ASTM A352-82 - Ferritic and Martensitic Steel Castings for Pressure-Containing Parts Suitable for Low Temperature Service,

4. Julian Toulouse, Owens - Illinois Glass Company.

Mechanical Properties of Heavy Section Castings: An Overview

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INTRODUCTION

The effect of section size on properties in castings can be separated into either a geometrical or metallurgical size effect. The geometrical size effect is apparent when testing different size specimens with the same metallurgical origin. On the other hand, the metallurgical size effect is the testing of similarly sized specimens machined from castings of different sizes.(1,2) In heavy section casting, both section size effects are evident. An understanding of both types of size effects will help the producer minimize the adverse impact of section size on the service life of the casting.

The properties of interest to the modern designer include tensile, impact, fracture toughness, and fatigue. Yield strength was the classical engineering property used as a basis for design. However, most components that fail, fail starting from a flaw and exhibit an absence of plastic deformation or yielding. The failure may have occurred starting at the flaw with a single load application (fracture toughness) or the flaw may have provided a site for a crack which grew to critical size only after multiple applications of the load (fatigue and fracture toughness).(3) Fracture toughness and fatigue tests are successful in allowing design calculations to avoid these failures.

METALLURGICAL SIZE EFFECT

The metallurgical size effect is attributed to the changes of microstructure inherent in producing and heat treating different size castings. Included in this category are normal effects, like changes in grain size, and lack of through-hardening; and defects more prone to occur in large cast sections such as large inclusion size, temper embrittlement, rock candy, microshrinkage, surface roughness, and surface pick-up. All of these effects normally increase as the section size of the casting increases.

Grain Size and Heat Treating Effects. The grain size of steel increases with an increase in casting section size as given in Table 1.(4,5,6) In general, the mechanical properties of a steel are related to the grain size.(7) Figure 1 shows the benefits of grain refinement on the tensile properties of mild steel.(7, 8,9) As the grain size becomes smaller - the tensile strength increases. Similarly, Figure 2, shows how the grain size affects the fracture strength, a fracture mechanic's measure of the resistance to crack propogation. (7)

The fatigue behavior of steel is also affected by the grain size.(8) The fatigue limits of two steels with different grain sizes are compared in Figure 3.(8) There was an increase of endurance limit with a decrease in grain size. Larger grain size associated with larger casting sections lead to some decrease in tensile strength, fracture toughness and fatigue behavior.

Table I. Average Prior Austenitic Grain Size for Quenched and Tempered Grades as a Function of the Section Size.

	5"	3"	1"
LCC	4.6	5.6	6.3
LC1	4	6	7
LC2	4	4.5	5.5
LC3	4	5	5.8
CA15	3	4	4
CA6NM	3	3	3.6
TOTAL AVERAGE	3.7	4.7	5.4

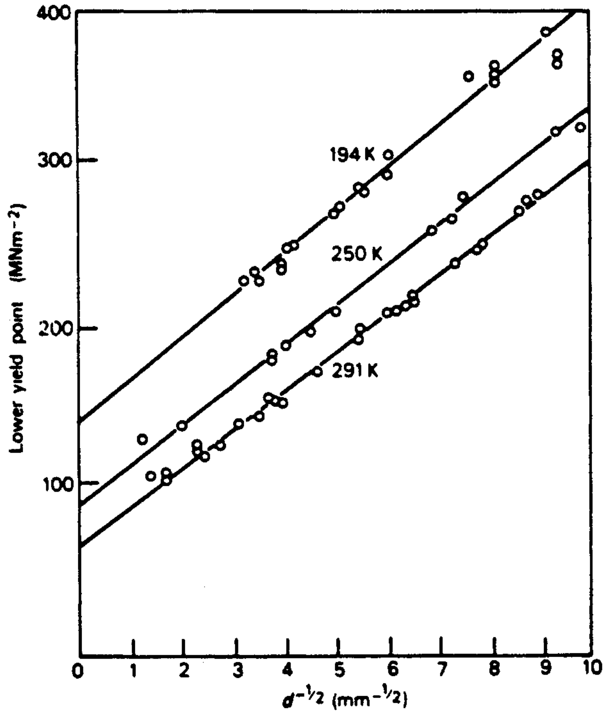

Figure 1. Dependence of the lower yield stress of mild steel on grain size.

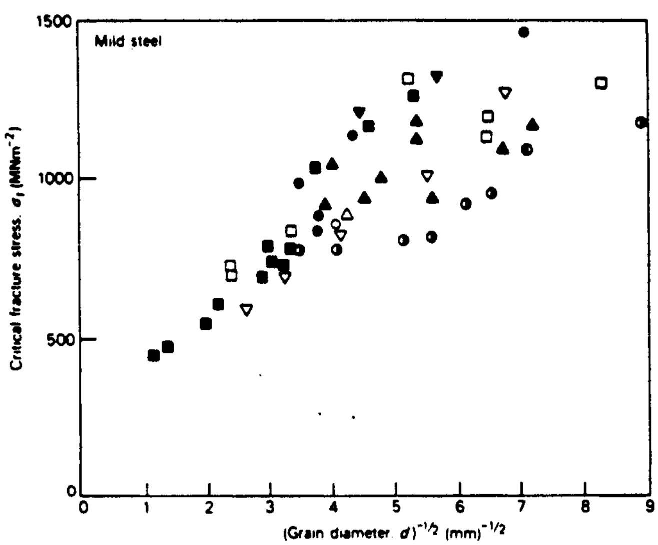

Figure 2. Dependence of local fracture stress of on the grain size of mild steel.

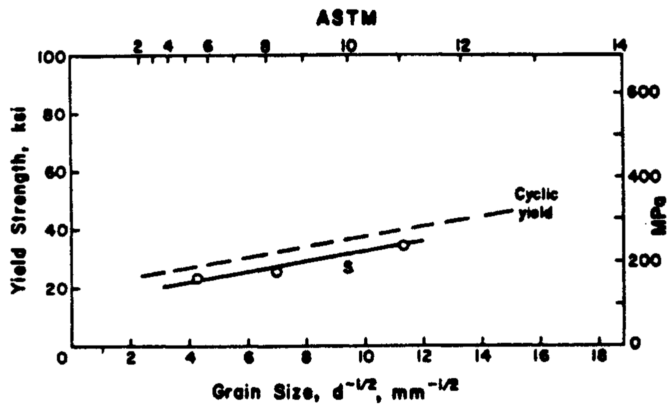

Figure 3. Effect of grain size on endurance limit of a low-carbon steel.

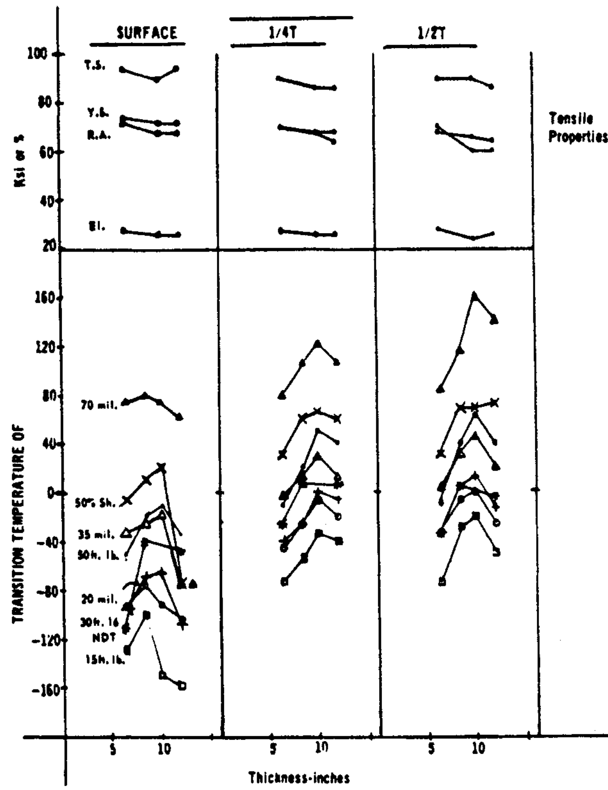

Figure 4. Surface to center variation of tensile and impact properties in 5 to 10 inch sections.

The microstructure of a steel casting can normally be refined by heat treatment. Heat treatment can produce finer microstructures than the as cast microstructure. However, this finer microstructure depends on the cooling rate from the austenitizing temperature. In thicker sections it is impossible to cool the center of a casting as quickly as the edge. The finer microstructure nearer the surface gives better mechanical properties as shown in Figure 4 and 5.(1,6,9,10,11,12,13,14,15) In Figure 4, sections of about 5 to 10 inches were tested for tensile and impact properties.(14) The variation from surface to center is shown and; as expected, the tensile strength is less in the center and the transition temperature is higher. The fatigue endurance limits of some various steels in 1-1/4", 3" and 6" sections are shown in Figure 5.(16) In the 1030 specimens, normalized and tempered, the properties are fairly insensitive to section size up to 6 inches, with the endurance limit being about 37,000 psi. With the 8630 material, normalized and tempered, the endurance limit improved with a value of 44,000 psi in the center of the 1-1/4" thickness. The 8635 material, quenched and tempered, had endurance limits of 54,000 psi, 48,000 psi, and 38,000 psi in the center of the 1-1/4", 3", and 6" thickness. The section size variations are the most pronounced in the quenched and tempered condition; since quenching cannot always extract the heat in the center of a thick section fast enough to form martensite.

The single most important and least avoidable effect of section size is the coarseness of the microstructure, since the cooling rate at the center of thick sections will never be rapid.(1) Intercritical heat treatment might allow some refinement of the microstructure in thick sections. (17,18)

Casting Discontinuities and Defects

Casting larger section sizes can agravate a number of casting discontinuities like the larger inclusion sizes reported in Table II. (4,6) The larger inclusion sizes do not have much of an effect on tensile strength but do lower the impact strength, Figure 6, throughout the range. Larger inclusions also lower the fatigue resistance, Figure 7, particu-

Table II. Effects of the Section Size on the Average Length of Type II Inclusions.

(Length of Inclusions in Microns)

	1"	3"	5"	Average % Sulfur
WCA	80	80	80	.022
WCB	70	150	295	.018
WCC	180	350	700	.035
LCC	445	460	550	.030
LC2	66	230	265	.018
LC3	105	145	270	.021
WC6	70	180	235	.015
WC9	40	80	525	.025
TOTAL AVERAGE	132	209	365	

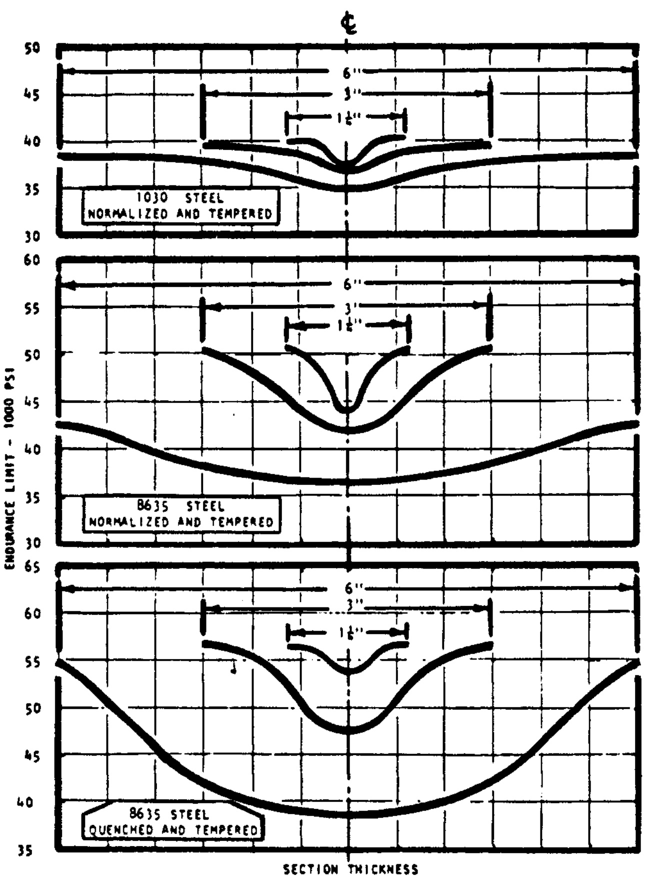

Figure 5. Distribution of endurance limit across the thickness of steel castings of several section thicknesses.

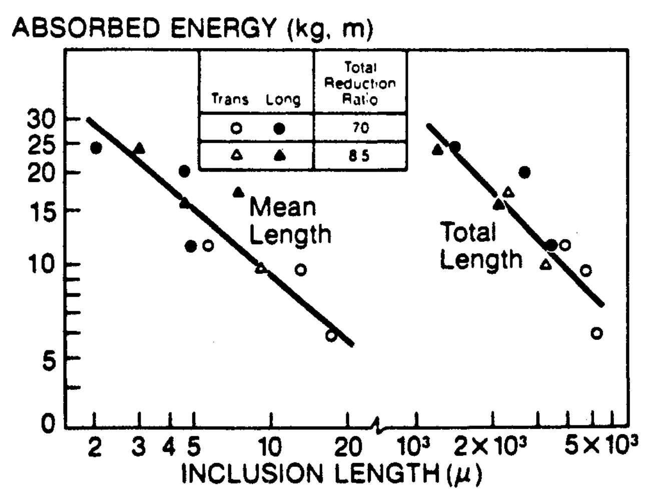

Figure 6. Effect of inclusion length on absorbed energy in the longitudinal and transverse direction.

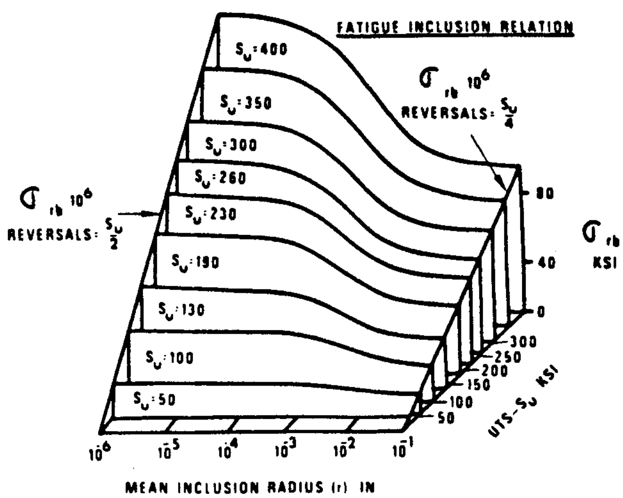

Figure 7. Effect of inclusion size on fatigue (σ_{rb}) as a function of ultimate tensile strength (S_u).

larly in higher strength steels.(8,10, 11,19,20)

One source of embrittlement agravated by larger section sizes is aluminum nitride, or "rock candy" fractures. Figure 8 illustrates the decreasing tolerance for aluminum and nitrogen with a decreasing cooling rate. This concern and inclusion type control shows the need for a well thought out and tested deoxidization practice for heavy section castings. (4,21)

Another problem agravated by thick

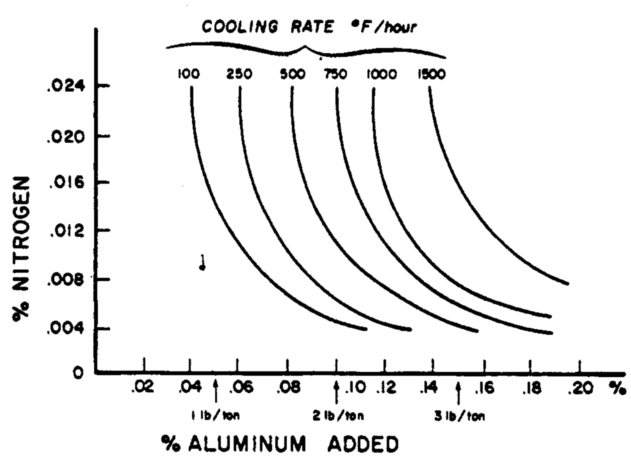

Figure 8. A chart to indicate approximate limits of nitrogen and aluminum that may be tolerated in a base analysis containing 0.30% C, 1.60% Mn, 0.50% Si, 0.50% Cr, and 0.35% Mo without development of intergranular type fracture.

sections is temper embrittlement. Temper embrittlement is caused by the segregation of impurities such as phosphorus, arsenic, antimony, and tin into the grain boundary areas. The embrittlement shows as an upward shift of the transition temperature after exposure to temperatures in the range of 750-1100° F. Temper embrittlement can occur in large sections during cooling from the tempering.(5,7,22) Cooling from welding can also induce temper embrittlement. (22)

Other defects are more prone to happen in thick sections such as microshrinkage, surface roughness, and surface contamination. These defects can also cause some deleterious effects on the properties of steel castings.(1,4,5,10, 11,23)

GEOMETRICAL SIZE EFFECT

The geometrical size effect is measured as the difference in properties obtained when different sized specimens of similar metallurgical background are tested. This size effect has been investigated for tensile, impact and fatigue properties. In general, the mechanical properties of a steel are not as favorable in the larger size specimens. This decrease in properties with larger specimens had been explained by greater probability of favorable grain orientation on the surface or larger flaws when a greater amount of material is tested. (16) While this statistical explanation does offer some rationale for the poorer properties found in larger specimens, fracture mechanics offers a more satisfying explanation. (22)

Fracture Mechanics - Linear Elastic Fracture Mechanics (LEFM) was developed to explain the failures of brittle materials in the presence of defects at stresses well below the strength of the material. LEFM was subsequently extended to explain the behavior of steels especially high strength steels in the presence of a flaw. (3,5,7,10,24,25, 26,27) The beauty of LEFM is the use of one variable that relates load, flaw size, and part configuration to failure. This allows the use of LEFM test results to be used in design to prevent brittle type failures. The most widely used variable use to characterize LEFM behavior of materials is K_{IC}. Other variables have been used such as G and J_{IC}. J_{IC} has some advantages over K_{IC} in lower strength steels since it was developed for material exhibiting larger amounts of yielding in failure; however, K_{IC} is the most common measurement. (26,27)

K_{IC} relates stress and flaw size and has the units, ksi /in. The relationship of Kc, the critical stress intensity for static loading, to the plate thickness is shown in Figure 9. As the plate thickness increases, the plastic constraint increases until a plane strain condition exists; and the Kc value decreases to the K_{IC} value. Once the K_{IC} value has been determined, it can be used as a material property in design. Because of the effect of increasing section size, increasing the plastic constraint and establishing plane strain conditions, it should not be surprising that thicker sections fail in the more brittle manner explained by LEFM, rather than by tensile - yield relationships.

Fatigue - When a stress is applied to a steel part and the existing defects are below critical size, the part will not fail on a single application of the load. However, if the load is repeated, a crack can initiate from existing defects, grow, and finally induce failure. The final failure occurs in a manner previously described in LEFM, but the process of crack initiation and growth under repeated loads is known as fatigue. Fatigue can be discussed as crack initiation and crack growth. Crack growth can be examined as growth rate (da/dN) for repeated applications of a load (K range of stress intensity). In Figure 10, there are fatigue crack propogation rates for six steels. The fatigue crack initiation or growth rates are not very affected by section size. However, heavy sections with their increased plastic constraint are less resistant to the final failure from the fatigue crack.(25)

CONCLUSIONS

(1) The section size effect is a combination of metallurgical section size effect, tested with

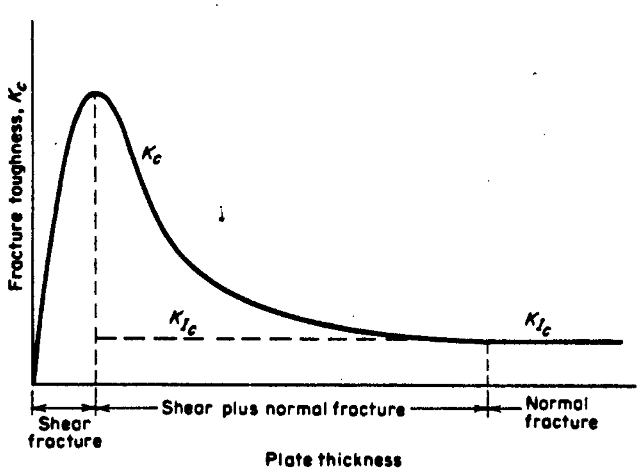

Figure 9. Schematic variation of the fracture toughness as a function of the plate thickness.

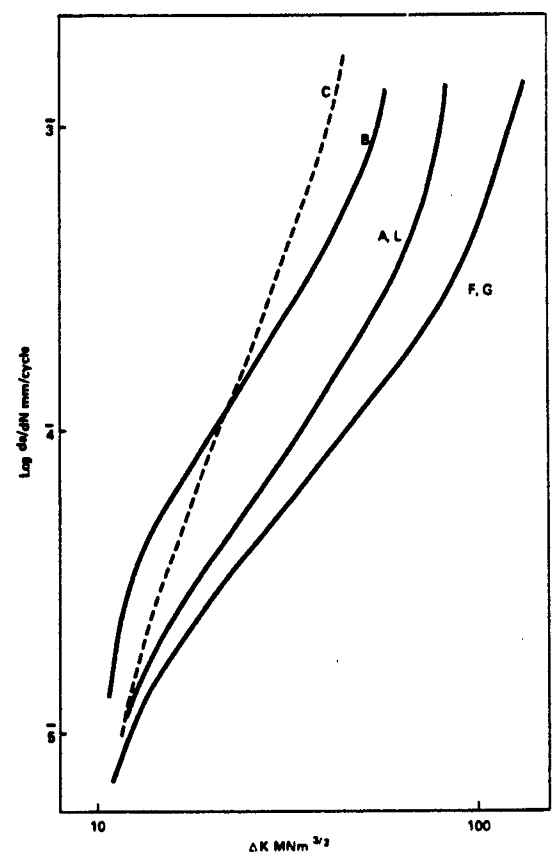

Figure 10. Fatigue crack propagation curves for six steels (A = 1½%Mn, B = ½%Cr - ½%Mo - ¼%V, C = 1½%Mn - ¾%Ni -½%Cr-Mo, F = 1½%Mn-Mo, G = 1½%Ni-Cr-Mo, L = 0.54%C).

similar specimens from different sized castings, and geometrical size effect, tested with different size specimens from the same size castings.

(2) The metallurgical section size effect is primarily due to the lack of fine microstructures due to the inability to cool the center of large sections rapidly. This results in larger grain sizes, coarser microstructures and difficulty in obtaining martensite in the center of the casting.

(3) Another effect of larger casting size is a greater tendency to form discontinuities and defects such as larger inclusions, rock candy fractures, temper embrittlement, and others.

(4) The geometrical size effect is primarily the increase in the plastic constraint of the larger section sized material approaching plane strain conditions and causing failures in a brittle-fracture mechanics mode.

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Mechanical Properties of Test Bars

Compared to Castings

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Abstract:

A request was made for a material with a .40 maximum carbon equivalent which could produce a tensile of 85,000 psi, yield of 55,000 psi, 22% elongation , 35% reduction of area and charpies of 20 lb-ft at -40°F. Based on historical data, it was determined that the request could be achieved in keel block test bars. But, the design engineer wanted these properties in the castings themselves, because castings will be used in service, not the test bars. A finite element analysis done on the parts used the required properties in determining the safety factors designed into the parts. A position was taken that it was not possible to achieve these properties with the .40 carbon equivalent restraint. Due to the design engineer's concerns about the weldability of the parts, he would not relent on the .40 carbon equivalent. Discussions as to the possibility of making these properties out of the castings led to the question of what properties were possible. This prompted the tests which are presented in this paper.

A question was also raised about the physical properties of the two other materials used in this project. These were expected to meet the necessary requirements, but testing was requested to satisfy any questions.

In this paper are results from three different materials from seven different casting configurations. These actual values could then be used by the design engineer to assure proper safety factors.

Introduction:

The results of this testing is divided into three sections from each analysis, The first section is the ASTM A 743 grade CA6NM. This material is produced in the 1 ton or 3 ton induction furnace. The second section is the ASTM A148 grade 105/85. This material is produced in the 9 ton acid lined arc furnace. The alloy used is an 8625 grade, quench and tempered. The third section of the results is the carbon steel grade which does not have an ASTM equivalent. It is produced in the arc furnace as a 1022 carbon steel with the .40% maximum carbon equivalent. It is also quenched and tempered.

The test bar results and specification requirements are listed on each table of results for comparison.

Section 1 - CA6NM:

Two different castings from separate heats were tested. The results in Table 1 are from the first casting configuration, identified as Casting 1. It weights 155 lbs. and the test coupon was taken from a 1 1/2” section. The results reported in Table 2 are from a 60 lbs. casting, identified Casting 2. The test coupon was taken from a 3” section.

Table 1. Mechanical properties of a155lb casting with a 1 1/2” section thickness (CA6NM class).

	Tensile(psi)	Yield(psi)	%E	%RA	Charpy(lb-ft)	Avg.
Casting 1	***120,500***	***99,500***	***22***	***60***	***36,41,42.5***	***39.8***
Test Bar	122,000	98,000	21	52	42,32,28	34
Requirement	110,000	80,000	15	35	20lb-ft At –40°F	
% of Test Bar	99%	102%	104%	115%		117%
% of Req.	110%	124%	147%	171%		199%

Table 2. Mechanical properties of a 60lb casting with a 3” section thickness (CA6NM class).

	Tensile(psi)	Yield(psi)	%E	%RA	Charpy(lb-ft)	Avg.
Casting 2	**117,000**	**99,500**	**22**	**52**	**20,23,23**	**22**
Test Bar	118,500	102,000	23	62	22,25,22	23
Requirement	110,000	80,000	15	35	20lb-ft At –40°F	
% of Test Bar	99%	98%	96%	84%		96%
% of Req.	107%	124%	147%	149%		110%

As expected the mechanical properties of the castings corresponded to the reported test bar results. The yield, % elongation, % reduction of area, and charpy results exceeded the customers requirements of Casting 1. The customer was satisfied with these results so no further testing was required to prove the keel block bar represents the castings made of CA6NM.

Section 2 - 105/85:

Two identical castings from separate heats were tested. The casting weighs 55 lbs., with the coupon cut from a 1 1/4" section thickness. Tables 3 and 4 show the results. The castings have been identified as Casting 3a and Casting 3b to reflect they are the same casting but cast on different heats.

Table 3. Mechanical properties of a 55lb casting with a 1 1/4" section thickness (105/85 class).

	Tensile(psi)	Yield(psi)	%E	%RA	Charpy(lb-ft)	Avg.
Casting 3a	**109,000**	**89,500**	**20**	**55**	**43,33,50**	**42**
Test Bar	111,500	91,500	20	60	36,46,49	43.7
Requirements	105,000	85,000	17	35	20lb-ft At –40°F	
% of Test Bar.	98%	98%	100%	92%		96%
% of Req.	104%	105%	118%	157%		210%

Table 4. Mechanical properties of a 55lb casting with a 1 1/4" section thickness (105/85 class).

	Tensile(psi)	Yield(psi)	%E	%RA	Charpy(lb-ft)	Avg.
Casting 3b	**105,500**	**87,000**	**20**	**50**	**35,32,31**	**32.7**
Test Bar	105,000	87,000	22	57	35.5,39,46.5	40.3
Requirements	105,000	85,000	17	35	20lb-ft At –40°F	
% of Test Bar.	100%	100%	91%	88%		81%
% of Req.	100%	102%	118%	143%		164%

As expected the mechanical properties of the castings corresponded to the reported test bar results. The yield, % elongation, % reduction of area, and charpy results exceeded the customers requirements of Castings 3a and 3b. The customer was satisfied with these results so no further testing was required to prove the keel block bar represents the castings made of the 105/85 class material.

Section 3 - Carbon Steel Results:

This material is a 1022 carbon steel with a .40 maximum carbon equivalent, which is quenched and tempered. These castings are welded into assemblies by the customer, therefor, they would not give any relief on the carbon equivalent. As mentioned previously in this paper, it was possible to meet these requirements in the keel block test bars but it was questionable if the castings could. These initial requirements are listed below:

Tensile	**Yield**	**%E**	**%RA**	**Charpy**
85,000	55,000	22	35	20 lb-ft At -40°F

These requirements are not listed in the tables contained in this section but are used for the calculations of the percent of the requirements. Four different casting configurations were tested of this material. Two of these were only tested once, casting 5 in Table 7 and casting 6 in Table 8. One configuration was tested twice, casting 4 in Tables 5 and 6. The most critical casting in this material is casting 7. Sixteen test coupons were cut from 8 castings and the results are shown in Tables 9 through 15.

The results shown in Tables 5 & 6 are from two castings from separate heats. The casting weighs 30 lbs. with the coupon cut from a 1/2" section thickness. The castings have been identified as Casting 4a and Casting 4b to reflect the different heats they were poured on. Subsized test bars were used and no charpy results were obtained.

Table 5. Mechanical properties of a 30 lb. casting from a 1/2" section thickness (85/55 class).

	Tensile(psi)	Yield(psi)	%E	%RA	Charpy(lb-ft)	Avg.
Casting 4a	**82,000**	**62,000**	**25**	**39**		
Test Bar	86,000	57,000	28	57		
% of Test Bar.	95%	109%	89%	68%		
% of Req.	96%	113%	113%	111%		

Table 6. Mechanical properties of a 30lb casting with a 1/2" section thickness (85/55 class).

	Tensile(psi)	Yield(psi)	%E	%RA	Charpy(lb-ft)	Avg.
Casting 4b	**84,500**	**63,500**	**27**	**63**		
Test Bar	86,000	62,000	27	62		
% of Test Bar.	98%	102%	100%	102%		
% of Req.	99%	115%	123%	180%		

The yield strength in the casting exceeded the test bar results. This can be attributed to the thinner cross section of the casting. The tensile strength in the castings was lower than the test bar which was expected and will be discussed later in the paper.

Table 7 shows the results from a 180 lbs casting which is the largest part cast in this material. The test coupons were taken from a 2" section directly below a 6" diameter exothermic riser. The casting has been identified as casting 5.

Table 7. Mechanical properties of a 180lb casting with a 2" section thickness (85/55 class).

	Tensile(psi)	Yield(psi)	%E	%RA	Charpy(lb-ft)	Avg.
Casting 5	**80,500**	**60,500**	**23**	**51**	**32,20.5,17**	**23.2**
Test Bar	86,000	64,500	24	58	30,32,33	31.7
% of Test Bar.	94%	94%	96%	88%		73%
% of Req.	95%	110%	105%	146%		116%

As expected the mechanical properties of the casting were lower than the reported test bar results. The yield strength, % elongation, % reduction of area and charpies exceeded the customers requirements but like casting 4a and 4b, the tensile strength was below the required 85,000 psi.

Table 8 shows the results from a 17 1bs casting with a 1" section thickness. The casting has been identified as casting 6.

Table 8. Mechanical properties of a 17lb casting with a 1" section thickness (85/55 class).

	Tensile(psi)	Yield(psi)	%E	%RA	Charpy(lb-ft)	Avg.
Casting 6	**74,000**	**60,000**	**7**	**33**	**29,37,24.5**	**30.2**
Test Bar	86,000	65,000	26	65	47,46.5,44	45.8
% of Test Bar.	86%	92%	27%	51%		66%
% of Req.	87%	**109%**	32%	94%		**151%**

Even though this is the lightest casting made in this material, these results are the most informative. It is indicative of why mechanical properties should not be taken from castings. As seen in the results the casting did not achieve the ductility standards in the static test, however, the results obtained in the charpy test prove that the material is ductile. Upon further investigation the bar was found to have some shrink, class CA2, at the point of fracture. This shrink caused the tensile to be low and greatly effected the percent elongation and reduction in area. The yield requirement, which is the most critical property to the design, was met even with this defect.

Tables 9 through 16 are all tests from the same casting configuration. This casting is the most critical part to the customer. It weighs 125 lbs. with two different section thickness', a 1" plate section with 2" sections protruding 90° from the plate. Out of these 8 castings 3 tests were taken from the 1" plate section with 13 taken from the 2" section. As it turns out the 2" section is the highest stressed area of all the parts made of this material.

Table 9. Mechanical properties of a 125lb casting with a 1" section (heat code J431, master heat 60880, 85/55 class) .

	Tensile(psi)	Yield(psi)	%E	%RA	Charpy(lb.-ft)	Avg.
Casting 7a	**83,000**	**57,000**	**26**	**61**	**23,21,23**	**22.3**
Test Bar	87,000	66,000	24	60	43,39,31	37.7
% of Test Bar.	95%	86%	108%	102%		59%
% of Req.	98%	104%	118%	174%		112%

Table 10. Mechanical properties of a 125lb casting with a 1" section (heat codes J525 and J526, master heat 61085, 85/55 class)

	Tensile(psi)	Yield(psi)	%E	%RA	Charpy(lb-ft)	Avg.
Casting 7b	**83,500**	**62,500**	**28**	**64**	**24,19,22**	**21.7**
Test Bar	85,500	65,500	28	61	59,69,54	60.7
% of Test Bar.	98%	95%	100%	105%		36%
% of Req.	98%	114%	127%	183%		108%
Casting 7c	**85,500**	**63,500**	**26**	**62**	**17,22,25**	**21.3**
Test Bar	85,500	65,500	28	61	59,69,54	60.7
% of Test Bar.	100%	97%	93%	102%		35%
% of Req.	101%	115%	118%	177%		106%

Tables 9 and 10 show the results from the 1" plate section. At this point all of the data above had been presented to the design engineer. From the customer design view all of the parts were acceptable, even though the tensile strength did not meet the initial requirements. This was largely due to yield strength of the castings meeting the requirements. There was some concern with fatigue due to the low tensile strength. When the data was used in the finite element models, the required safety factors were achieved.

The only remaining concern the customer had was with the 2" section because of the high stresses. The previous results had been more consistent than expected, therefor, it was assumed that one more test out of the 2" section would answer all of the customer concerns. As can be seen in Table 11 this was not the case.

The 2" section did not perform as needed, making only 77,000 psi tensile strength. Also the yield strength of 54,000 psi, did not make the requirement. After looking at the fracture surface of the test bar, hydrogen was suspected in causing the low results. To prove this a second bar, taken from the same 2" section, was aged for 4 hours at 400°F. After aging, the properties of the bar increased dramatically. The results in Tables 12 and 13 show the same effect. If we could achieve the properties of the aged bar the customer was willing to accept this material.

Tables 14 and 15 are the culmination of a process change to achieve the desired results. The time spent in heat treatment was increased to a 6 hour quench cycle and 5 hour temper cycle. These results show the successful hydrogen removal, which satisfied the customers requirements and expectations. The design engineer put these results in the computer model and was able to maintain the desired safety factors.

Table 11. Mechanical properties of a 125lb casting (heat code J525, master heat 61085, 85/55 class)

	Tensile(psi)	Yield(psi)	%E	%RA
Test Bar	85,500	65,500	28	61
1" Section	83,500	62,500	28	64
2" Section	77,000	54,000	22	33
2" Section aged	81,000	59,000	27	59

Table 12. Mechanical properties of a 125lb casting (heat code J526, master heat 61085, 85/55 class)

	Tensile(psi)	Yield(psi)	%E	%RA
Test Bar	85,500	65,500	28	61
1" Section	85,500	63,000	26	62
2" Section	76,000	52,000	16	30
2" Section Aged	80,000	57,500	27	56

Table 13. Summary of data taken from previous tables.

	Tensile(psi)	Yield(psi)	%E	%RA
Test Bar	85,500	65,500	28	61
Avg. of 1" Section	84,500	62,750	27	63
Avg. of 2" Section	76,500	53,000	19	31.5
Avg. of 2" Section Aged	80,500	58,250	27	57.5
Difference 2" vs. T B	9,000 10.5%	12,500 19%	9 32%	29.5 48.4%
Difference 2" vs. 1"	8,000 9.5%	9,750 15.5%	8 29.6%	31.5 50%
Improvement 2" vs. 2" aged	4,000 5%	5,250 10%	8 42%	26 83%

Table 14. Mechanical properties of a 125lb casting with extended heat treat (heat codes J424 and J425, master heat 60880, 85/55 class)

	Tensile(psi)	Yield(psi)	%E	%RA
Test Bar	87,000	66,000	24	60
J425 2"	85,000	61,900	30	65
J425 2" Aged	82,800	61,600	26	63
J424 2"	83,500	62,500	24	44
J424 2" Aged	81,000	58,000	24	53

As Table 14, the 2" section, with the extended heat treatment met the design requirements. No signs of hydrogen were evident in these test bars. After aging the bars did not increase as had been the case when the hydrogen was present. Table 15 shows the properties of the 2" section are repeatable with the modified heat treatment.

Table 15. Mechanical properties of a 125lb casting, Casting 8, with extended heat treat (MH 61359, 85/55 class)

	Tensile(psi)	Yield(psi)	%E	%RA
Test Bar	86,000	61,000	35	68
2" Section	83,000	60,500	24	42

Table 16. Comparison of all mechanical properties recorded in testing

Casting	Tensile(psi)	Yield(psi)	%E	%RA	Charpy Avg.
4a	82,000	62,000	25	39	
4b	84,500	63,500	27	63	
5	80,500	60,500	23	51	23.2
6	74,000	60,000	7	33	30.2
7a	83,000	57,000	36	61	22.3
7b	83,500	62,500	28	64	21.7
7c	85,500	63,500	26	62	21.3
8	83,000	60,500	24	42	
Average	**83,143**	**61,188**	**25.6**	**54.6**	**23.7**
Test Bar					
4a	86,000	57,000	28	57	
4b	86,000	62,000	27	62	
5	86,000	64,500	24	58	31.7
6	86,000	65,000	26	65	45.8
7a	87,000	66,000	24	60	37.7
7b	85,500	65,500	28	61	60.7
7c	85,500	65,500	26	62	
8	86,000	61,000	35	68	
Average	**86,000**	**63,312**	**27.2**	**61.6**	**44.0**
Difference	2,853	2,124	1.6	7.0	20.3
	3%	**3%**	**6%**	**11%**	**46%**

Summary:

- The CA6NM and 105/85 materials have enough alloying that the section thickness' and casting geometry's for this project do not adversely effect their mechanical properties. The test bars do represent the properties in the castings.

- The thinner section casting, 1/2", had a higher yield strength but the tensile strength was lower.

- The heaviest casting achieved 94% of the tensile and yield achieved from the test bar.

- Shrinkage had little effect on the yield strength, which is the most important factor from the designers point of view. This shows that castings, even with shrinkage in them, are very reliable and structurally sound. A question was raised concerning the fatigue limit because of the low tensile strength. Fatigue failures normally occur from surface defects. Since shrinkage normally occurs in the center of a section it is in the lowest stress area of the section. Also, if tensile could be taken from the outer surface, the strength would be higher. This would result in a better fatigue limit.

- The way castings are rigged, the configuration, section size, material and other unknown factors can greatly effect the mechanical properties within a castings. Casting 7 had a difference of 8000 psi (9.5%) in tensile, 9750 psi (15.5%) in yield, 8 percentage points (30%) in elongation, and 31.5 percentage points (50%) in reduction of area when comparing the 1" plate section to the 2" section, even in a small (125 lb) casting.

- The results show that hydrogen does diffuse out of castings. This is shown in the results of the aged bars J525 and J526, Tables 11 and 12. Its is also show in the results of bars taken from the castings with the increase in heat treatment but were not aged before testing.

- The charpy results from the castings met the 20 ft-lbs. requirement but were 46% lower then the results obtained from the test bars in the carbon steel materiel.

Conclusion:

From Table 16, excluding shrinkage and hydrogen effects, the castings averaged 3% lower than the test bars for the tensile and yield in carbon steel. The elongation was 6% lower and the reduction of area was 11% lower.

It is called out by the Association of American Railroads Mechanical Division in specification M201-92, which was adopted 1923 and revised 17 times since, section 7.1.1 that at the manufacturing option to attach the test coupon are from keel blocks. But in section 7.2.5 it outlines that if test specimens are cut from castings they only must have at least 80% of the tensile and yield properties. This testing of castings is to be agreed to at the time the parts are purchased between the foundry and the purchasing company. (1)

When this point was first brought up to the design engineer, the notion was to raise the test bar requirements by 80%. But by using all the data presented in this paper and several discussions about the excellent properties of steel castings the 80% increase was not necessary. Actually, no increase or change was needed to satisfy the design criteria.

References:

[1] Association of American Railroads, “Specification M-20 1-92 Steel Castings,” Manual of Standards and Recommended Practices. 1923 Revised 1933,1934,1936,1945,1946,1947, 1952, 1953,1960, 1962, 1966, 1979,1981, 1982, 1983, 1984, 1992