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Mechanical Properties of Test Bars and Castings Sections and an Analysis of the Cost of Equivalent Round Test Bars

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Abstract American Foundry Group worked in partnership with SFSA, UI and UAB to perform a case study in which the mechanical performance of tensile and Charpy specimens were analyzed and correlated to simulated results. These specimens were pulled from various test bars and sections of a casting. This was done as part of the Digital Innovative Design for Reliable Casting Performance (DID) project.

During this process we recorded the costs of making these test bars to shed light on the high cost of Equivalent Round test blocks, possible savings and differences in mechanical performance between various test bars.

Note: this paper is an interim report based on current findings. Additional material is to be tested and a complete analysis to correlate modeling will be done later along with additional work such as modeling of properties based on heat treatment.

4.0 Introduction

This project was started by means of a request from SFSA to have American Foundry Group pour a heat of various test bars and castings, process them together, and have SFSA analyze and compare the mechanical properties of the different test bars as well as the castings.

Mechanical properties differ throughout a casting. Differences in section thickness can cause different cooling rates. The way a part is rigged can also cause differences in soundness. In order to design high performance castings, these variables as well as others need to be considered in the casting design process. It is our hope that the data provided in this study can help populate the databases behind the Digital Innovative Design for Reliable Casting Performance (DID) project. The DID project aims to develop a set of design tools that allow modern engineers to design castings confidently and elegantly. This set of design tools, based on comprehensive property measurements, will allow engineers to create cast parts that are reliable, high performance, and cost efficient for critical DoD and commercial applications.

In this study a 3" globe valve body was chosen as the casting to be poured with the test blocks. The test blocks included a keel block, a keel block designed for Charpy specimens (further referred to as Charpy Block) and an Equivalent Round test block. AFG had also developed an experimental Equivalent Round test block (also referred to as ER Mod) that we hoped would be adopted by our customers. This experimental test block was designed with the goal of reducing the weight and processing time of an Equivalent Round test bar. We decided to make this a two-fold project both analyzing the mechanical performance of various test bars and analyzing the cost of creating those test bars.

5.0 Experiment details

5.1 Casting and Test Bar Selection

The casting and test bars used were chosen based the desire to pour at least two of each casting and test bar while melting in a 3800 lb. furnace. The test bars used were a keel block, Charpy block, Equivalent Round (E.R.) test block and an Experimental E.R. test block. AFG uses a "short" keel block and ER for a tensile specimen, and a "long" keel block and ER for charpy specimens (3). The differences between our current E.R. and the experimental E.R. can be seen in Figure 1 (the cylindrical protrusion is used for machining setup). The pour weight of these test blocks left approximately 750 lbs. for castings. SFSA had requested a casting with varying section thickness. We decided to go with a valve body that had sections large enough to pull tensile and Charpy specimens from the flanges and seat area while staying under the remaining pour weight. This production valve body has been approved and released for production by our customer and can be seen in Figure 8a. Table 1 lists the pouring order of the castings and test bars.

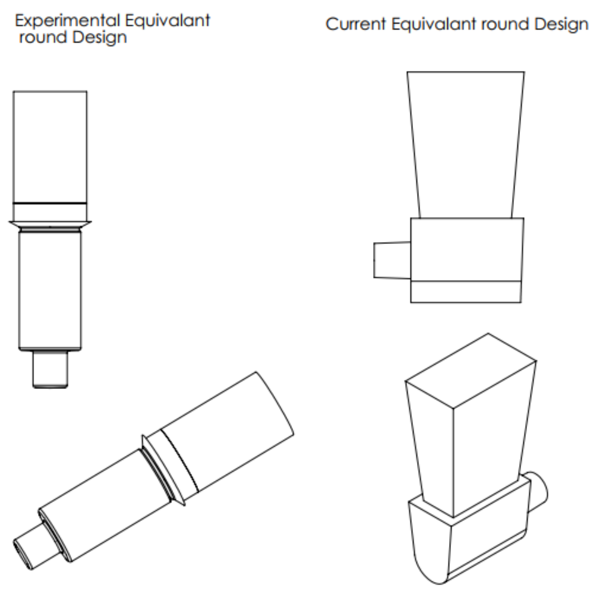


Figure 1 shows the difference between a traditional E.R. Test bar and our Experimental E.R. Test bar.

Table 1: Pour Order. Note that LK1061 ER 5" MOD had significant centerline shrinkage and was not tested for properties. Keel blocks were not given a serial code.

Mold #	Serial Code	Part Description
1	LK1052	Valve #1, Charpy & Tensile
1.5		Keel Blocks, Charpy & Tensile
2	LK1054	ER 3" #1, Charpy & Tensile
3	LK1057	ER 4" #1, Charpy & Tensile
4	LK1058	ER 5" #1, Charpy & Tensile
5	LK1061	ER 3, 4, 5" #1 MOD, Tensile
6	LK1053	Valve #2, Charpy & Tensile
6.5		Keel Blocks, Charpy & Tensile
7	LK1055	ER 3" #2, Charpy & Tensile
8	LK1056	ER 4" #2, Charpy & Tensile
9	LK1059	ER 5" #2, Charpy & Tensile
10	LK1060	ER 3, 4, 5" MOD, Tensile

5.2 Casting and Heat Treat

Typical valve body rigging was used and verified in *MAGMAsoft*. The rigging included a sprue, split gating, side risers, top risers, chills and insulated sleeves. The molds were made from a phenolic urethane bonded silica sand. The chemistry of the heat is shown in Figure 2.

Material Type Spec:	4C	Heat #	P1695F
Operator Name:	PC	Division:	AA2

Run	FE%	C	Mn	Si	Cr	Ni	Mo	P	S	V
Avg	96.9688	0.2113	0.8261	0.4095	0.5038	0.4972	0.2462	0.0148	0.0023	0.0131

	Cu	W	Co	Sn	Sb	Zn	Al	Pb	Ti	Mg
Avg	0.1623	0.0053	0.0072	0.0092	0.0093	0.0028	0.0412	!0.0000	!0.0000	0.0006

	N	Nb	As	B	Bi	Ca	Ce	La	Ta	Te
Avg	0.0250	0.0054	0.0034	0.0001	0.0086	0.0015	0.0037	!0.0000	0.0176	0.0026

	Zr
Avg	0.0008

Figure 2 shows the chemistry of the heat poured to create the test bars and castings.

The heat was transferred to a ladle, moved to the first mold and a ladle temperature was recorded at 2929°F (1609°C). The molds were poured, and a video was taken to record pour times. The castings were then allowed to cool before shaking out. Oxy-acetylene torch and arc air was used to remove the risers and feeder pads on the casting and test bars. The casting and test bars were then loaded on a rack as shown in Figure 3 and heat treated.

Figure 3 Shows how each casting and test bar was loaded on the rack.

The heat treat procedure for this load included; Normalize at 1700°F, Solution at 1650°F with water quench and Temper at 1225°F. See figure 4-6 for heat treat charts.

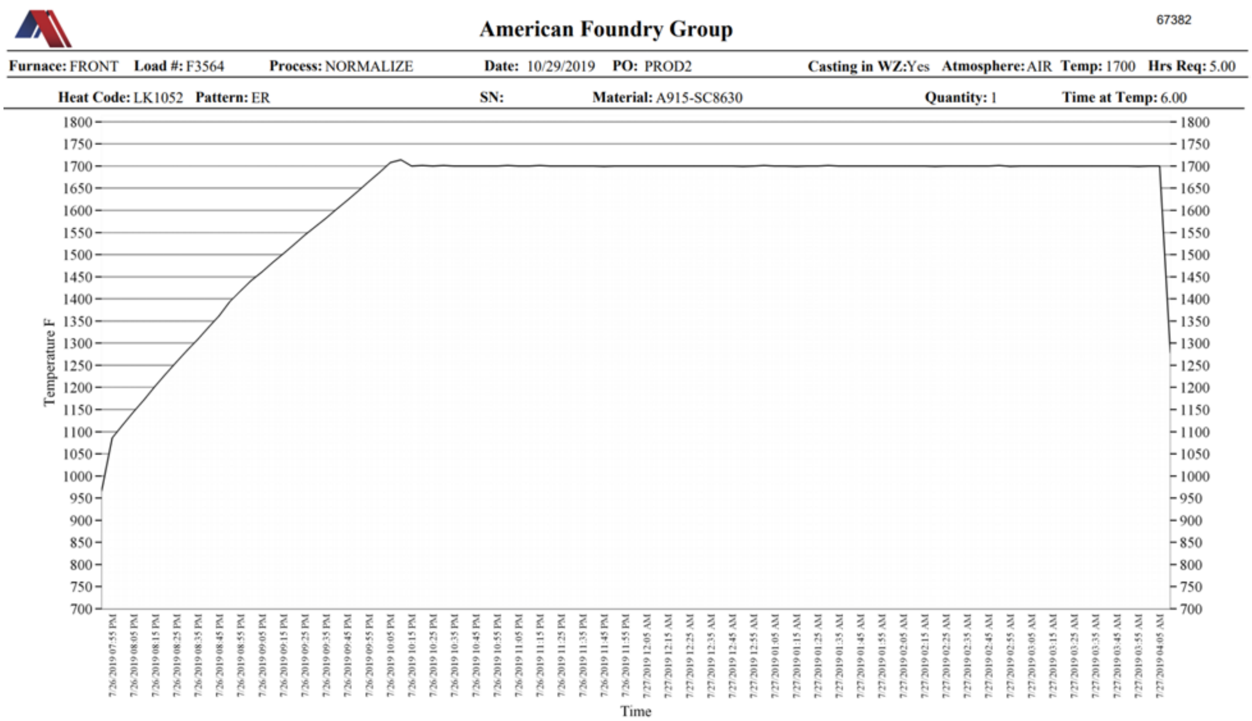


Figure 4 shows the time and temperature of the load shown in Figure 3 during the normalizing process

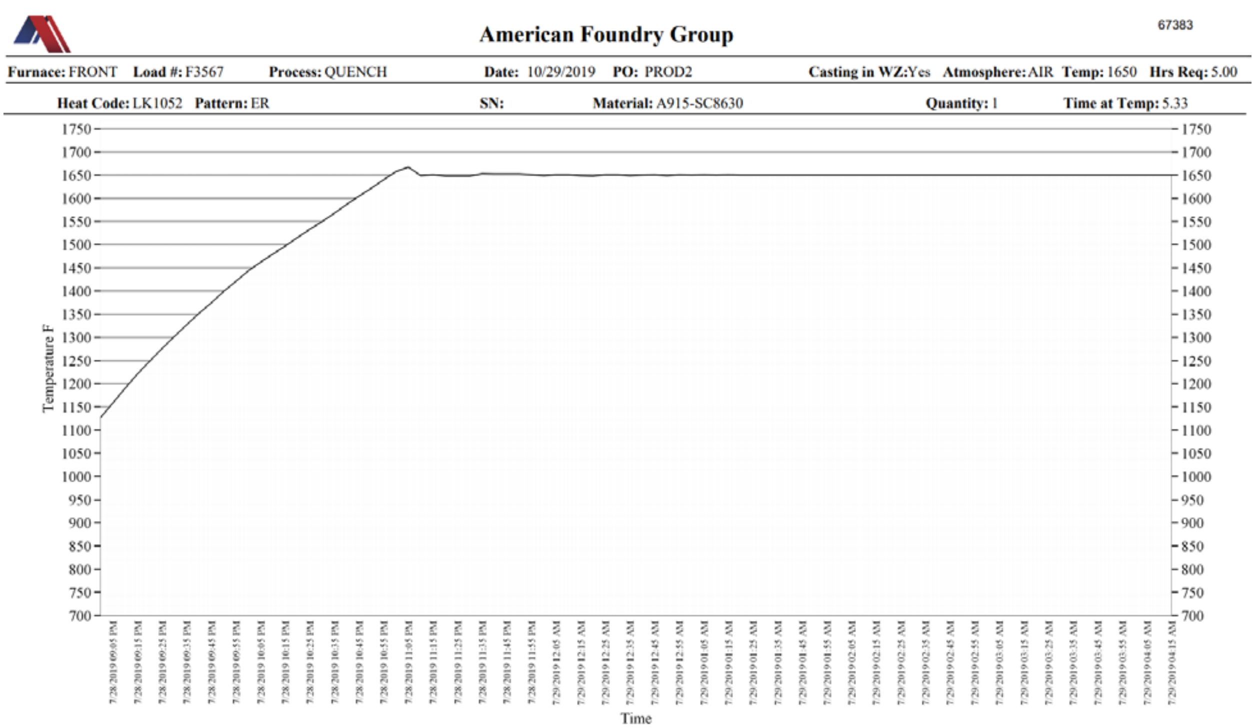


Figure 5 shows the time and temperature of the load shown in Figure 3 during a solution heat treatment. The load was taken into water quench within 30 seconds of being removed from the furnace.

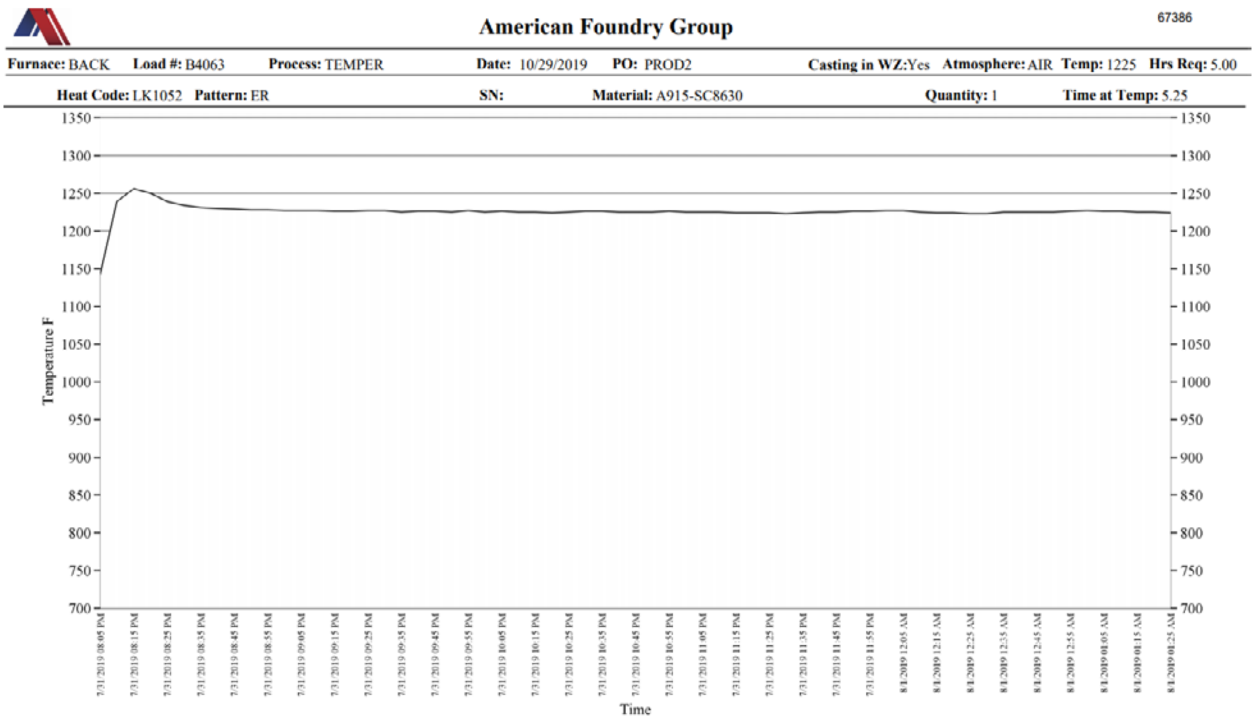


Figure 6 shows the time and temperature of the load shown in Figure 3 during the temper process.

5.3 Simulation Description

The casting process for the valve body was performed using the casting simulation software *MAGMAsoft* [1]. The alloy cast was ASTM A487 4B. Using the chemistry poured, *IDS* software [2] (version 2.0.7) was used to generate the temperature dependent thermophysical properties used in the casting simulations to generate filling and solidification results (porosity, cooling rate, Niyama Criterion etc.). The solidification curve from *IDS* is shown in Figure 7, and the temperature dependent properties are given in Figure 8. Because of the additional model parameters needed to run macrosegregation calculations, an alloy from the *MAGMAsoft* database was used to calculate these simulation results. The alloy used from the software's database to calculate the macrosegregation results given here was ASTM A216 WCB, since it most closely matched the poured alloy composition and solidification curve.

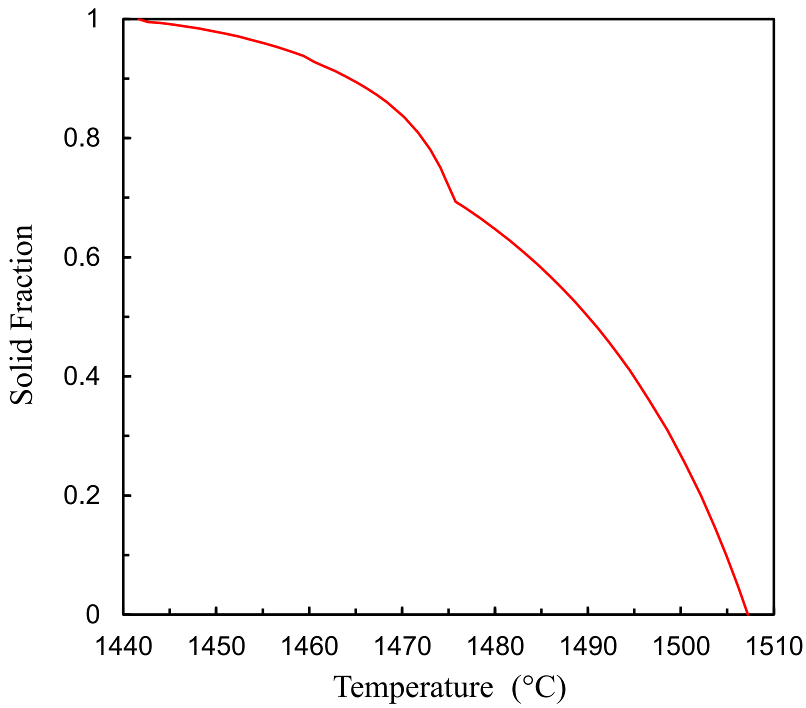


Figure 7. Solid fraction temperature curve (solidification curve) for the ASTM A487 4B alloy. The liquidus temperature is 1507 °C (2745 °F) and solidus temperature is 1441 °C (2626 °F).

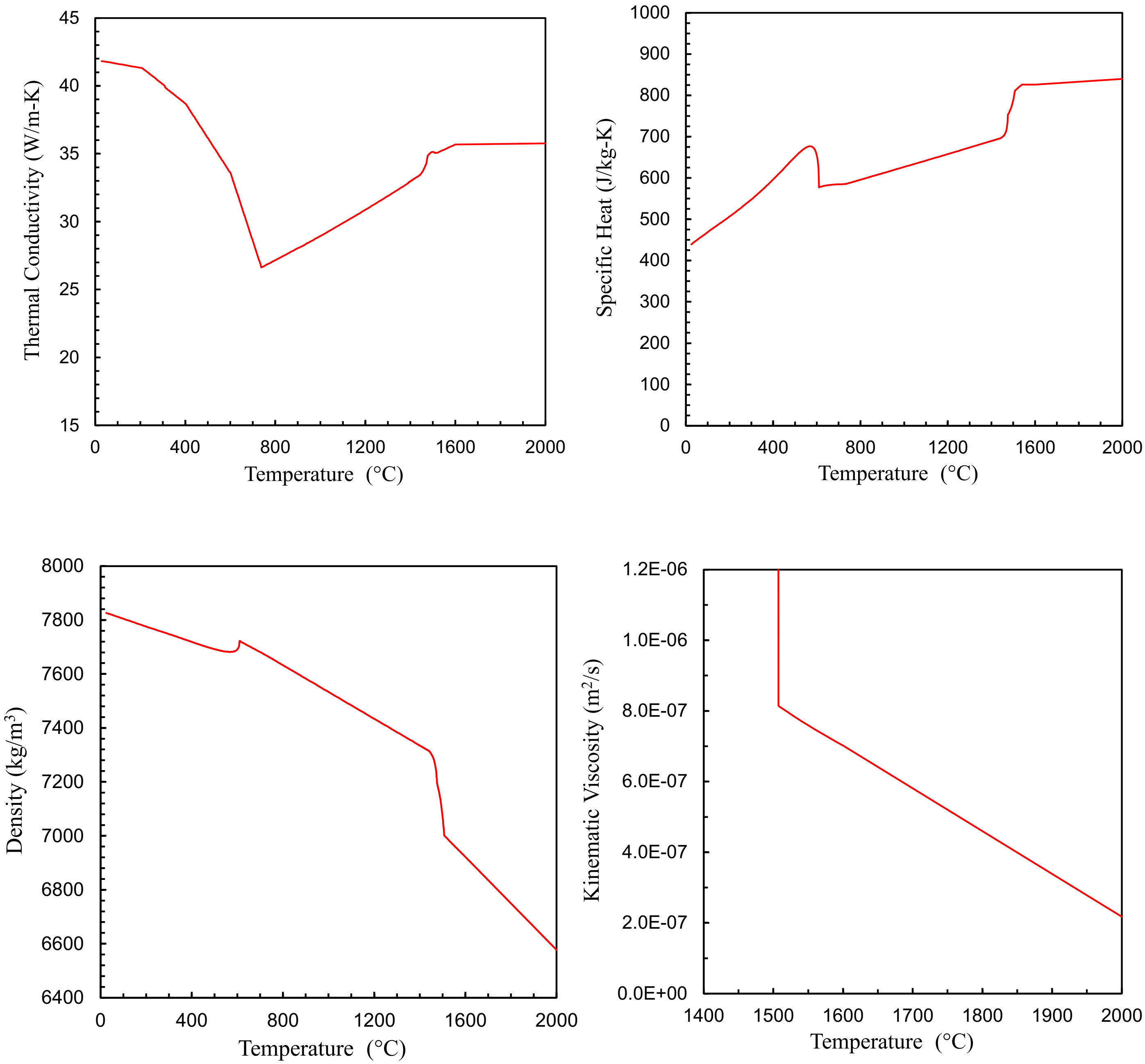


Figure 8. Temperature dependent properties for the ASTM A487 4B alloy calculated by *IDS*. (a) Thermal conductivity, (b) specific heat, (c) density and (d) viscosity.

The two castings poured in the foundry were timed to fill in 22 and 26 seconds. Considering this, the fill time used in the simulations was 24 seconds. The castings were poured at 2929°F (1609°C), and this was used in the filling simulation. The software's database properties used for the mold was no-bake silica sand, and the sleeve, hot topping and steel chills were modeled using default database properties. Heat transfer coefficients used between the steel and mold were defined by a temperature dependent curve having a value of 1000 W/m^2-K above 1330°C, ramping down at a constant rate to 50 W/m^2-K at 600°C, and was then a constant 50 W/m^2-K at lower temperatures. Between all other materials a constant 800 W/m^2-K heat transfer coefficient was used.

The simulation case performed using filling, solidification with convection and macrosegregation calculations required the longest run time. This case was run on 8 cores of a Linux workstation with two Intel Xeon E5-2637 v4 CPUs running at 3.5 GHz and 256 GB of RAM. The case required 5.5 hours of run time using 725,000 metal cells.

5.4 Test bar processing

In order to process a typical tensile bar, a band saw is used to cut the legs from the keel block. The leg is then put into a lathe and turned down to shape. For Charpy specimens the legs of a Charpy block are cut off the block using a band saw. One leg will make three Charpy specimens. The leg is loaded into a mill, and the profile of three specimens are milled out. The Charpy leg must then go back to the band saw where it is cut into three pieces. Figure 9 shows an image of two Charpy leg being processed. Table 2 shows time to process typical tensile and Charpy bars.

Figure 9 Shows two Charpy leg after it has gone through its first machining operation. Each leg is being cut into three pieces before the final machining operation.

Each specimen is loaded back into the mill and the final side is machined. For an E.R. Charpy block all four sides of the Charpy block must be saw cut. See Figure 10. The saw cut block is then roughed milled to the shape of a typical Charpy leg. Once this is done it follows the same process as a typical Charpy leg. E.R. Tensile blocks are saw cut on all four sides before being loaded into a lathe and turned down to shape. See Table 3 for E.R. test bar processing time.

Figure 10 Shows an E.R. charpy bar being cut down to shape before it goes to the mill.

Table 2 shows the time to process our typical test bars is shown below.

Average time to process Typical Charpy and tensile specimens in Minutes			
	Band saw	Set up Rough and finish	
Charpy block	8	25	34
Keel Block	4	5	9

Table 3 shows the time to process the E.R. test bars in this study.

Average time to process a 3 charpy specimens from an ER in Minutes			
Description	Bandsaw	Set up, Rough and finish	Total
ER 3"	16.5	180	196.5
ER 4"	21.5	180	201.5
ER 5"	26	180	206
Average time to process a tensile bar from an ER in Minutes			
Description	Bandsaw	Set up, Rough and finish	Total
ER 3"	11.5	31	42.5
ER 4"	15	31	46
ER 5"	17.5	31	48.5
Average time to process a tensile bar from an ER MOD in Minutes			
Description	Bandsaw	Set up, Rough and finish	Total
ER MOD 3"	N/A	34	34
ER MOD 4"	N/A	70	70

When pouring typical test bars, AFG pours down the riser but with E.R. test bars a split gate is used and the mold is filled from the bottom. For E.R. test bars, AFG pours two bars in one mold. One is for the tensile specimen and one is for the charpy specimens. With the Experimental E.R. test bar, weight savings was only seen in the tensile specimens. The weight of our typical Charpy block is 50 lbs. and the weight of our keel block is 25 lbs. For our E.R. patterns, we have the following weights.

Table 4 shows the weights of our E.R. test bars and gating.

Pour Weight of E.R.s patterns in LBS				
	Total Pour Weight	Tensile Block and riser	Charpy Block and riser	Gating
3" E.R.	216	61	92	62
4" E.R.	292	89	134	67.48
5" E.R.	435	141	212	81.04

Table 5 shows the weights of Experimental E.R. test bar.

Pour weight of Experimental E.R. Pattern in LBS			
	Total Pour weight	Tensile block and riser	Gating
3" E.R. MOD	65	44	21
4" E.R. MOD	75.6	54.6	21
5" E.R. MOD	89.6	68.6	21

5.5 Removing test specimens from the Valve body

Figure 11b shows the location of the test specimens in the casting. The specimens were taken from both ½ T and ¼ T locations. See figures 11 and 12 for the specific location of the test specimens. Note that charpy no. 2 and .25" tensile no. 2 have not been removed from the casting. The lab that machined and tested the specimens machined all .25" bars at a diameter of .16 this was an error on the part of the lab. To avoid confusion we will continue to refer to these bars as .25" bars.

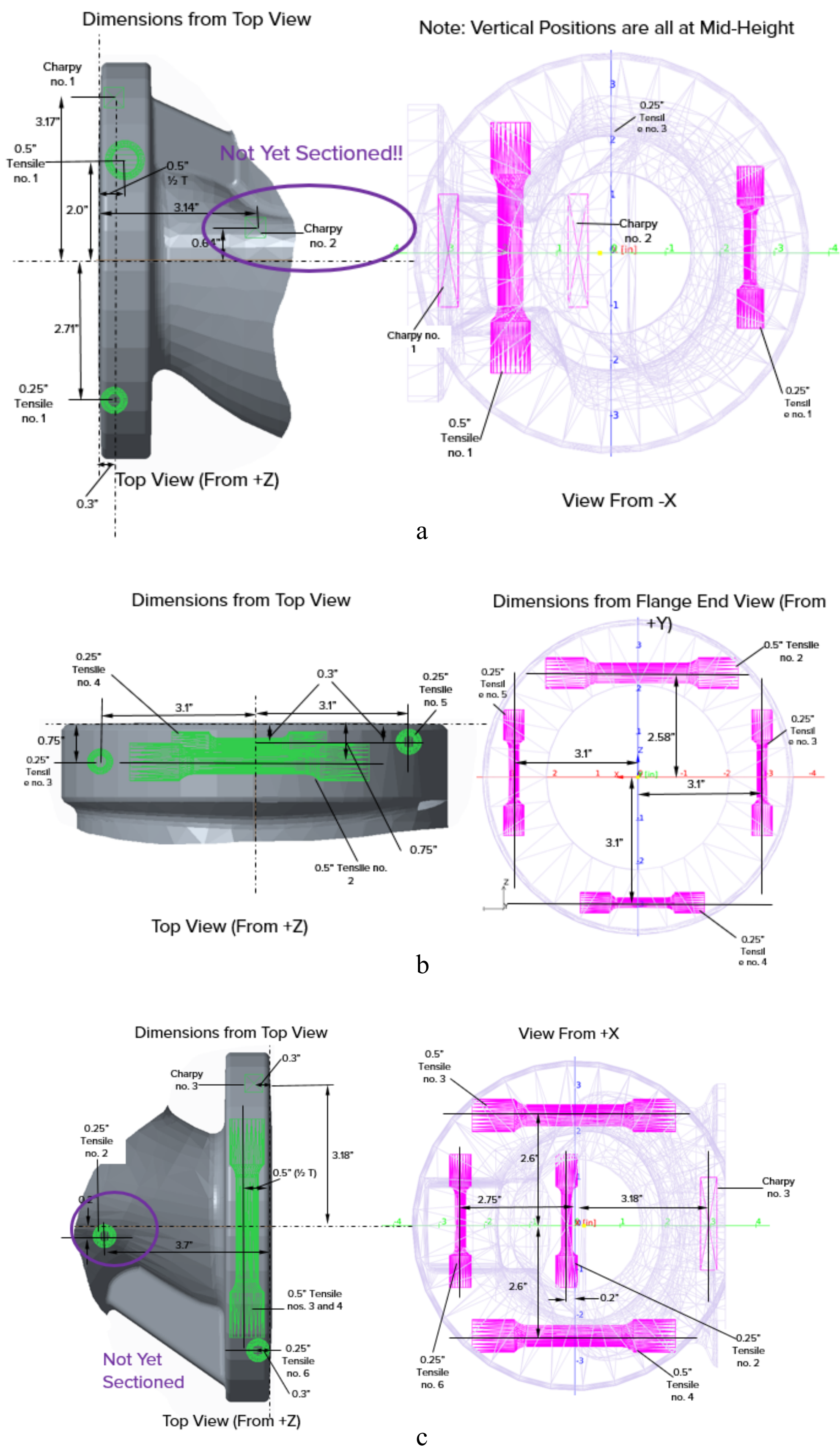


Figure 11 shows the location the test bars were taken from the casting. 11a and c show the inlet and outlet flange while 11b shows the inlet flange.

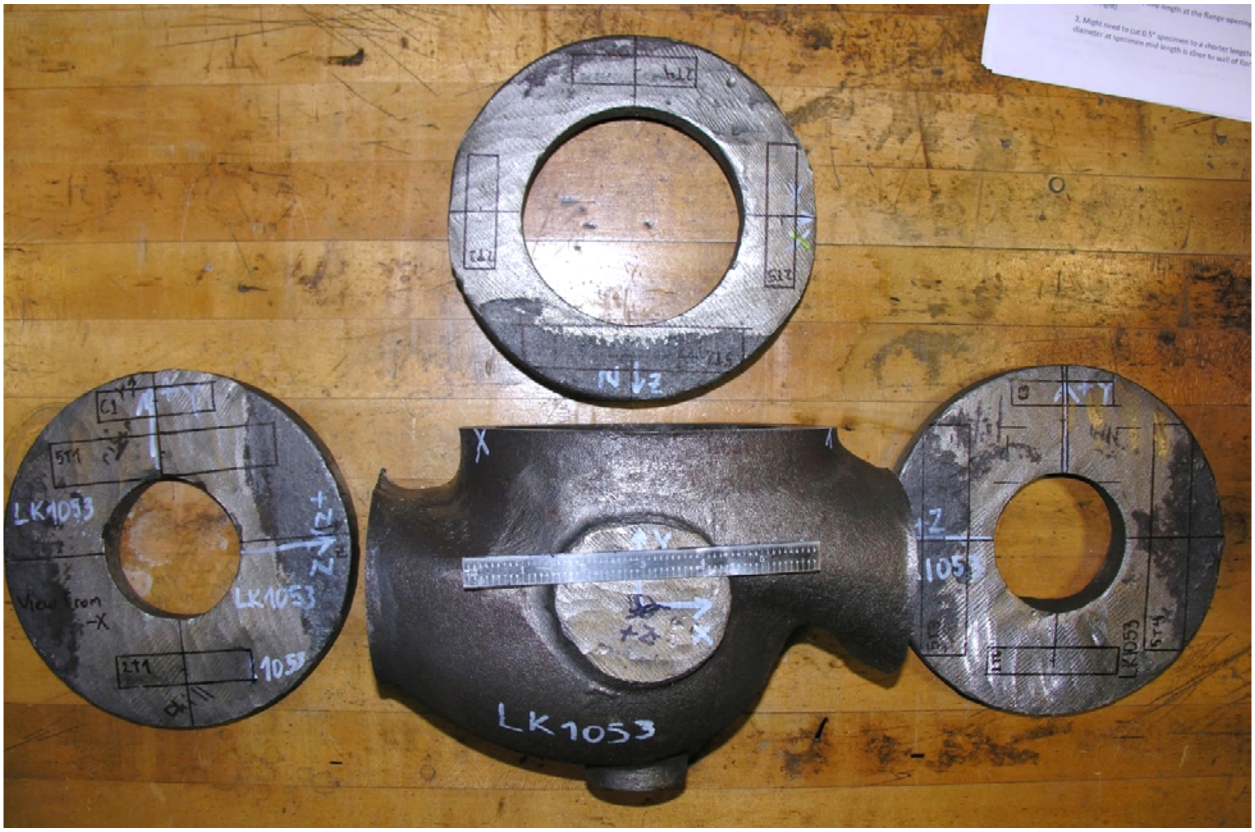


Figure 12 Shows the casting with flanges cut off and the location where the test bars will be pulled from

6.0 Results

<u>6.1 Simulation Results</u>

In Figure 13a the valve body casting is shown in the orientation it was cast with the "Z" axis of the coordinate system shown pointing upwards. In Figure 13b the casting is shown in the same orientation, but with the casting surface shown as transparent, and the mechanical test specimens are shown as blue shaded objects at the locations they were extracted from inside the casting. As indicated in the figure, there are six cylindrical 0.25" diameter (ϕ) specimens, four 0.5" ϕ cylindrical specimens, and three block-shaped Charpy specimens. Most of the specimens are taken from the three flanges, and two are taken from the wall section. The orientation of the specimens shown in Figure 13b will be used to display the casting simulation results for the specimen in Figures 14 and 15. Table 6 provides results from the simulations, showing the minimum and maximum values predicted in the gage or fillet sections of the specimens for solidification rate, Niyama Criterion (or referred to here as just Niyama), porosity, and carbon segregation ratio (ratio of final to initial carbon concentrations). The fillet locations are included in the evaluation of results in case specimens break outside the gage length (or in the fillets), and the predictions there might prove helpful in explaining the cause. Figures 14a, 14b, 15a, and 15b show the simulation results at the specimen locations for solidification rate, Niyama Criterion, porosity, and carbon segregation ratio (referred to here as just segregation ratio), respectively. Examining Table 5 and these figures, the following conclusions are drawn:

- 0.25” ϕ number (#) 1 and Charpy #3 specimens are nearest the chills and have the highest solidification/cooling rates, and lower segregation ratio. The 0.25” ϕ specimen #1 has porosity predicted to form at the upper end of the gage section indicated by porosity level in Figure 15a by low Niyama values in Figure 14b.

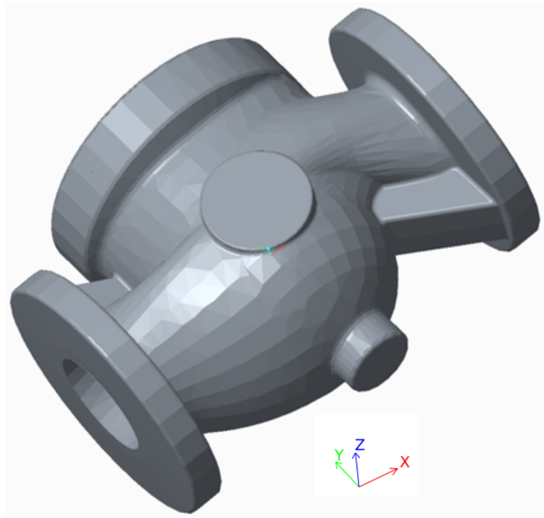
- The 0.5” ϕ specimen #1, Charpy #1, and 0.25” ϕ specimens #3, #5, and #6 have the lowest cooling rates as they are at/near feeder contacts, and they have higher segregation ratios, except for #6 which has a range near its upper end. Of these, a moderate level porosity (microporosity) is predicted to form in 0.25” ϕ specimens #3 and #6.

- The 0.5” ϕ specimens #2 and #3 are predicted to have the highest porosity as they are in cope end of the casting and relatively far from feeders. They also have variability of solidification rate and segregation ratio along their lengths.

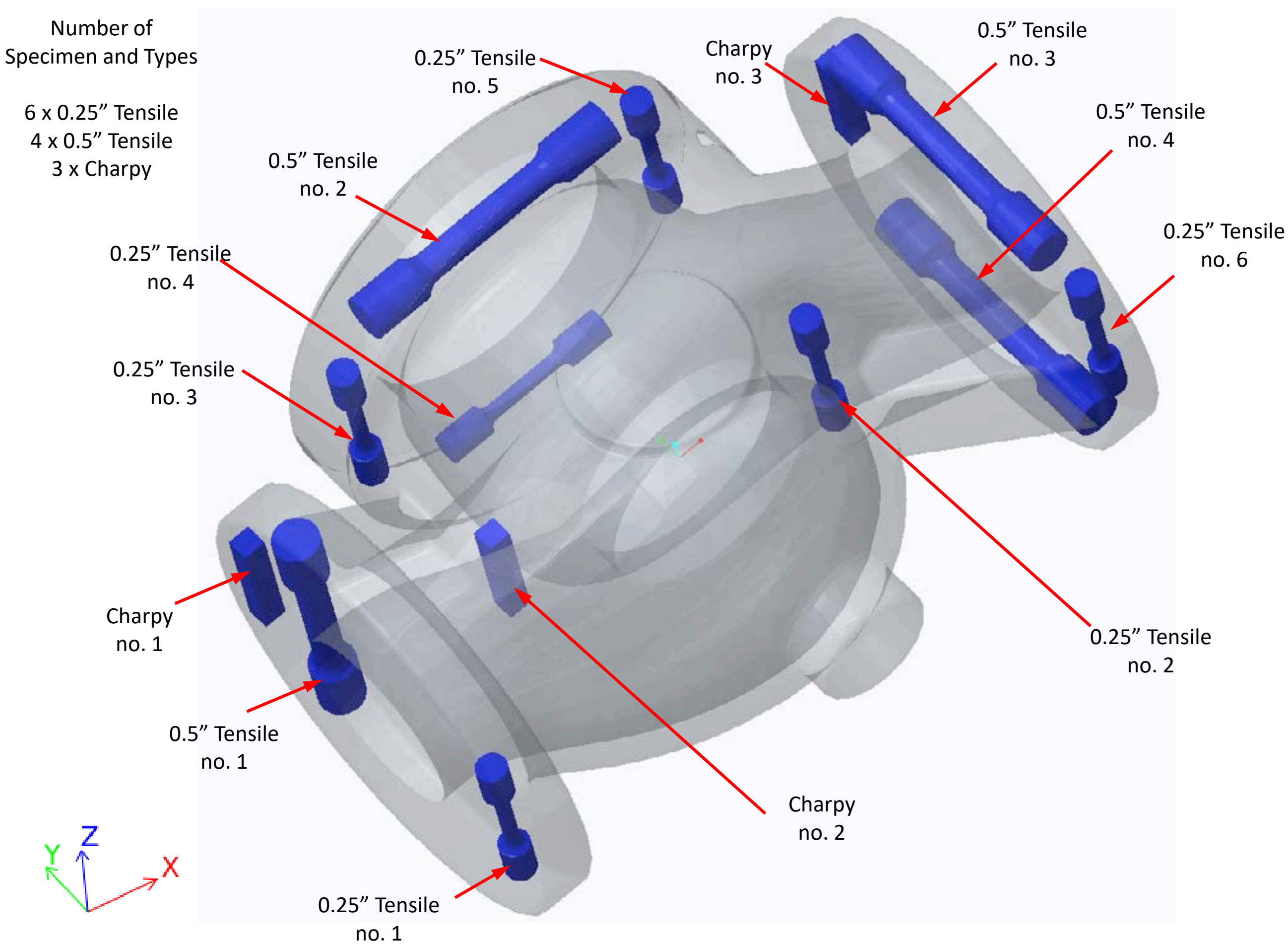
- The 0.5” ϕ specimen #4 shows a range of cooling rate and segregation ratio along its length, and uniformly low porosity prediction.

- The remaining specimens, Charpy #2 and 0.25” ϕ specimens #2 and #4 have a moderate range of segregation ratio between them but have uniformly low porosity and moderate cooling rates.

Figures 14 and 15 show that the specimen locations have variability in predicted results between each other, and within the same specimen in some cases. This demonstrates that the selection of these specimen locations in the casting should provide a good range of conditions to investigate for variables affecting mechanical properties.



(a)



(b)

Figure 13. (a) Valve body casting used in the mechanical property study. (b) Casting shown as transparent and specimens for the property study shown in blue, and labeled, at locations taken from the castings.

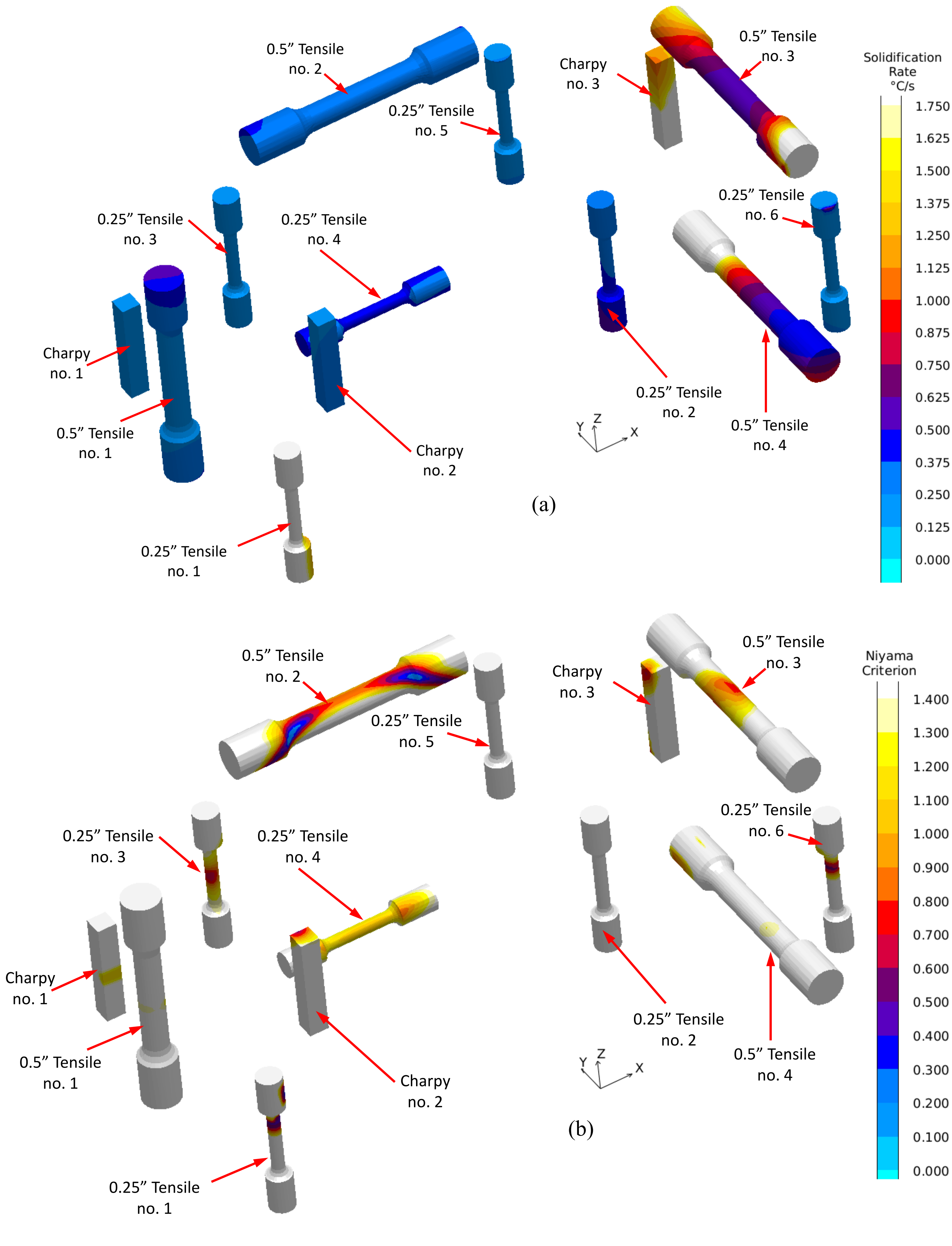


Figure 14. (a) Solidification rate at the specimen locations. (b) Niyama Criterion at the specimen location.

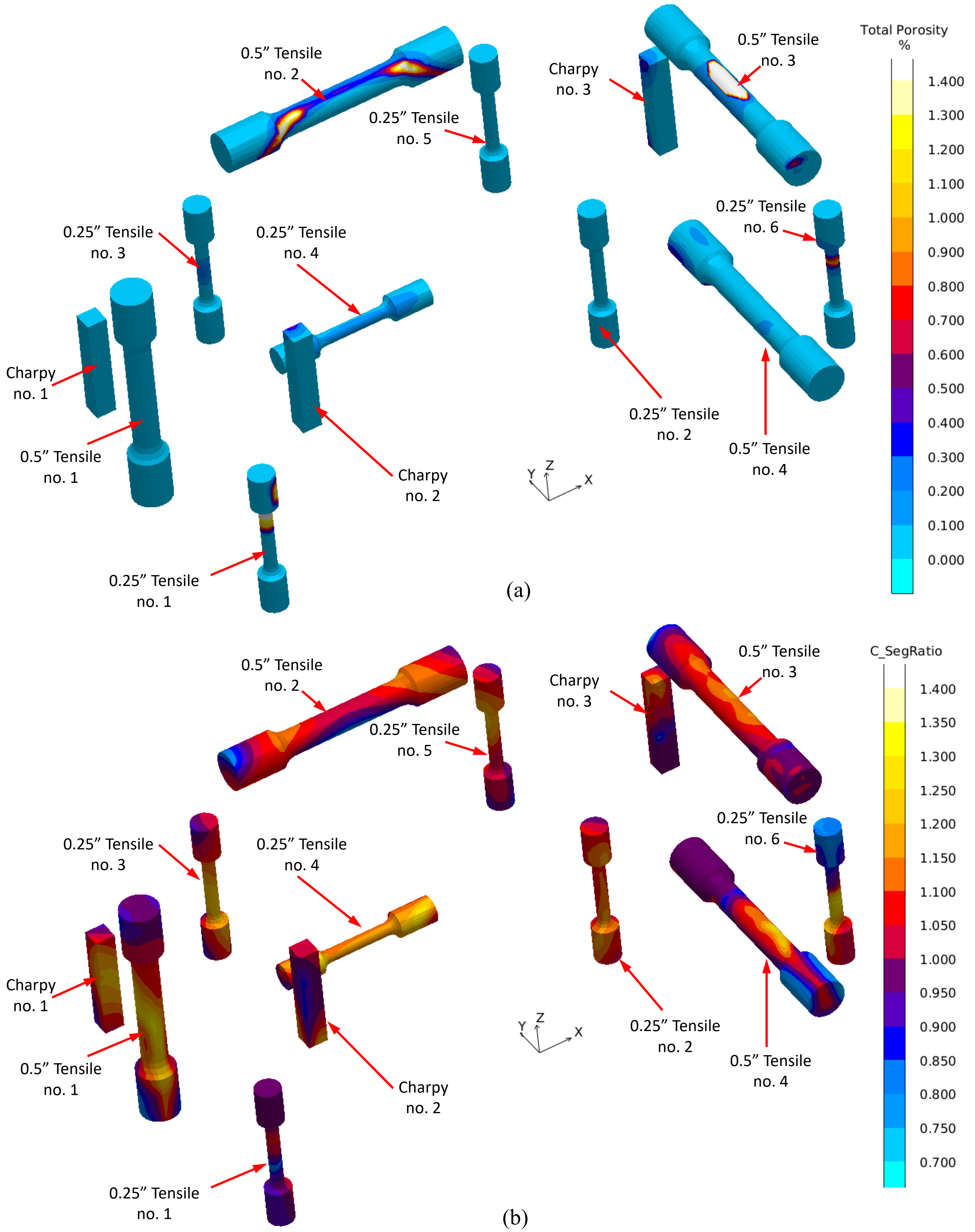


Figure 15. (a) Porosity at the specimen locations. (b) Segregation ratio at the specimen locations.

Table 6. Results from casting simulation giving minimum and maximum values predicted in the gage or fillet sections of the specimens for solidification rate, Niyama Criterion, porosity, and segregation ratio.

		Solidification Rate (°C/s)		Niyama Criterion (°$C^{1/2}s^{1/2}mm^{-1}$)		Porosity (%)		Segregation Ratio	
Specimen Type	Number	Min	Max	Min	Max	Min	Max	Min	Max
0.5" ϕ Tensile	1	0.127	1.176	2.200	5.800	0.029	0.090	1.130	1.320
0.5" ϕ Tensile	2	0.300	0.310	0.800	3.300	0.090	3.400	0.760	1.120
0.5" ϕ Tensile	3	0.470	0.770	2.400	5.200	0.060	67.000	0.960	1.200
0.5" ϕ Tensile	4	0.380	1.460	3.800	5.800	0.070	0.070	0.840	1.300
0.25" ϕ Tensile	1	1.900	4.800	1.100	6.300	0.040	2.300	0.850	0.998
0.25" ϕ Tensile	2	0.270	0.370	4.700	5.200	0.040	0.050	1.100	1.200
0.25" ϕ Tensile	3	0.140	0.150	2.000	3.500	0.100	0.050	1.200	1.300
0.25" ϕ Tensile	4	0.310	0.310	2.900	3.000	0.080	0.080	1.130	1.120
0.25" ϕ Tensile	5	0.170	0.170	3.800	4.200	0.040	0.040	1.020	1.200
0.25" ϕ Tensile	6	0.120	0.150	0.770	4.000	0.050	0.460	0.880	1.280
Charpy	1	0.110	0.120	3.000	4.300	0.040	0.060	1.300	1.190
Charpy	2	0.210	0.260	2.200	4.700	0.050	0.120	0.960	1.080
Charpy	3	1.060	3.130	4.400	6.500	0.040	0.060	0.910	1.140

6.2 Mechanical Properties of test specimens

The Charpy V-notch (CVN) properties are summarized in Table 7. Charpy specimens from the valve body castings were taken at 1/4T. Only 1 Charpy sample was taken at each location in the valve while there were 3 Charpy samples for each E.R bar. There were no CVN values for the experimental E.R. bars.

Table 7. Charpy Impact Properties at -40F of ASTM A487 Grade 4B Samples Taken from Valve Castings and from Equivalent Rounds

Serial Code	Part	Energy	Average	Std. Dev.
	Descript.	(ft-lb)		
LK1052	Valve #1 Charpy #1	40.0		
LK1052	Valve #1 Charpy #3	36.0		
LK1053	Valve #2 Charpy #1	38.0		
LK1053	Valve #2 Charpy #3	35.0		
LK1054	ER 3" #1	43.0, 43.0, 46.0	44.0	1.4
LK1055	ER 3" #2	45.0, 40.0, 44.0	43.0	2.2
LK1056	ER 4" #1	17.0, 42.0, 29.0	29.3	10.2
LK1057	ER 4" #2	56.4, 47.1, 30.0	44.5	10.9
LK1058	ER 5" #1	34.0, 31.6, 38.4	34.7	2.8
LK1059	ER 5" #2	50.3, 26.4, 53.0	43.2	12.0

The tensile properties are summarized in Table 8. Tensile specimens were taken at different locations in the valves as discussed in the previous section. The CVN and tensile properties for both valves #1 and #2 were averaged and compared to the average of the E.R. bar samples (Table 9). It should be noted that the samples from the keel blocks and Charpy blocks are still being tested so test block properties are only represented by E.R. bars.

Table 8. Tensile Properties of ASTM A487 Grade 4B Samples Taken from Valve Castings and from Equivalent Rounds

Serial Code	Part Descript.	Location	Description	UTS (ksi)	YTS (ksi)	Elongation (%)	RA (%)
LK1052	Valve #1	1/2 T	0.5" tensile #1	105.1	86.8	21	54
LK1052	Valve #1	1/4 T	0.25" tensile #1	105.7	86.3	22	56
LK1052	Valve #1	1/2 T	0.5" tensile #2	102.5	84.4	*	*
LK1052	Valve #1	1/2 T	0.25" tensile #3	94.7	76.9	6.5	19
LK1052	Valve #1	1/4 T	0.25" tensile #4	105.6	85.5	23	59
LK1052	Valve #1	1/4 T	0.25" tensile #5	105.4	84.5	23	69
LK1052	Valve #1	1/2 T	0.5" tensile #3	101.6	83.2	19	47
LK1052	Valve #1	1/2 T	0.5" tensile #4	101.6	83	25	47
LK1052	Valve #1	1/4 T	0.25" tensile #6	99.1	77.9	25	53
LK1053	Valve #2	1/2 T	0.5" tensile #1	104.9	87	20	55
LK1053	Valve #2	1/4 T	0.25" tensile #1	108.6	88.1	28	63
LK1053	Valve #2	1/2 T	0.5" tensile #2	102.3	83.9	18	45
LK1053	Valve #2	1/2 T	0.25" tensile #3	93.9	76.7	19	40
LK1053	Valve #2	1/4 T	0.25" tensile #4	108.1	88.6	27	59
LK1053	Valve #2	1/4 T	0.25" tensile #5	103.6	85.7	14	13
LK1053	Valve #2	1/2 T	0.5" tensile #3	104.6	86.5	20	45
LK1053	Valve #2	1/2 T	0.5" tensile #4	103.6	85	22	57
LK1053	Valve #2	1/4 T	0.25" tensile #6	101.7	80.8	25	53
LK1054	ER 3" #1	1/2 T	0.5" tensile	96.4	73.7	22	57
LK1055	ER 3" #2	1/2 T	0.5" tensile	95.1	72.3	21	88
LN1060	ER 3" #1 MOD	1/2 T	0.5" tensile	97.3	75	20	44
LN1061	ER 3" #2 MOD	1/2 T	0.5" tensile	97.6	76.3	20	48
LK1056	ER 4" #1	1/2 T	0.5" tensile	94	69.6	14	56
LK1057	ER 4" #2	1/2 T	0.5" tensile	95.2	71.4	20	37
LN1060	ER 4" #1 MOD	1/2 T	0.5" tensile	93.2	71.3	23	56
LN1061	ER 4" #2 MOD	1/2 T	0.5" tensile	100.1	78	20	47
LK1058	ER 5" #1	1/2 T	0.5" tensile	93.4	69.9	21	47
LK1059	ER 5" #2	1/2 T	0.5" tensile	93.3	70.3	18	34

*Values not reported due to errors in testing.

Table 9. Average and Standard Deviation of Mechanical Properties for Valves and Test Blocks

		Valve	Test Blocks
UTS (Avg +/- Std Dev)	(ksi)	102.9 +/- 3.8	95.6 +/- 2.2
UTS (min)		93.9	93.2
YTS (Avg +/- Std Dev)	(ksi)	83.9 +/- 3.5	72.8 +/- 2.7
YTS (min)		76.7	69.6
Elongation (Avg +/- Std Dev)	(%)	21.0 +/- 5.0	19.9 +/- 2.3
Elongation (min)		6.5	14
RA (Avg +/- Std Dev)	(%)	49.0 +/- 14.0	51.4 +/- 14.2
RA (min)		13.0	34
Impact Energy (Avg +/- Std Dev)	(ft-lb)	37.3 +/- 1.9	39.8 +/- 9.8
Impact Energy (min)		35.0	17

Note: current results for the valve castings are only for specimens from the flange, which has a thickness of about 1". Testing of the keel block specimens has not yet been completed.

The properties for the valve castings were compared to the test block samples using a Student's t-test. A t-test checks if the difference between means of 2 groups are statistically significant. In the test, the null hypothesis assumes that the means for both groups are equal. The test determines if this null hypothesis can be rejected (i.e. averages are different) or accepted (i.e. averages are not different). Using a significance level (α) of 0.05, a two-tailed t-test was ran in MS Excel. It was assumed that the variances for each group were unequal. A two-tailed t-test was chosen since we do not want to assume which group has better properties. A one-tailed test only determines if one mean is greater than or less than another but it cannot do both. A two-tailed t-test accounts for both possibilities. The test calculates several parameters: P value and t values. The null hypothesis can be rejected if the P value (α) is less than 0.05, calculated t statistic is less than the negative of the t critical, and t statistic is greater than t critical.

Tables 10 to 14 summarize the results of the Student's t-tests. In this analysis, only the two-tail t critical and P values should be considered in the tables. There seems to be a significant difference between the UTS and YS of the samples from the valves and the test blocks. On one hand, the ductility values do not seem to be different although the variance of %RA is extremely large. Similarly, there is statistical difference in the Charpy impact properties between the valve samples and the test block samples. CVN values for the test block also have a high variance. Further investigation may need to be done to understand the scatter in the ductility data and the CVN of the test blocks.

Table 10. Student's t-test Results for Ultimate Tensile Strength (UTS) of Valve Castings and Test Blocks

UTS, KSI	*Valves*	*Test Blocks*
Mean	102.92	95.56
Variance	15.39	5.18
Observations	18.00	10.00
Hypothesized Mean Difference	0.00	
df	26.00	
t Stat	6.28	
P(T<=t) one-tail	5.95*10^-7	
t Critical one-tail	1.71	
P(T<=t) two-tail	1.19*10^-6	
t Critical two-tail	2.06	

Table 11. Student's t-test Results for Yield Strength (YS) for Valve Castings and Test Blocks

YTS, KSI	*Valves*	*Test Blocks*
Mean	83.93	72.78
Variance	13.27	8.26
Observations	18.00	10.00
Hypothesized Mean Differenc	0.00	
df	23.00	
t Stat	8.92	
P(T<=t) one-tail	3.14*10^-9	
t Critical one-tail	1.71	
P(T<=t) two-tail	6.28*10^-9	
t Critical two-tail	2.07	

Table 12. Student's t-test Results for % Elongation for Valve Castings and Test Blocks

%EL	*Valves*	*Test Blocks*
Mean	21.03	19.90
Variance	26.33	6.10
Observations	17.00	10.00
Hypothesized Mean Difference	0.00	
df	24.00	
t Stat	0.77	
P(T<=t) one-tail	0.22	
t Critical one-tail	1.71	
P(T<=t) two-tail	0.45	
t Critical two-tail	2.06	

Table 13. Student's t-test Results for % Reduction of Area for Valve Castings and Test Blocks

%RA	*Valves*	*Test Blocks*
Mean	48.19	51.40
Variance	207.50	225.38
Observations	16.00	10.00
Hypothesized Mean Difference	0.00	
df	19.00	
t Stat	-0.54	
P(T<=t) one-tail	0.30	
t Critical one-tail	1.73	
P(T<=t) two-tail	0.60	
t Critical two-tail	2.09	

Table 14. Student's t-test for Comparison of the Charpy V-notch for Valves and Test Blocks

Impact Energy (ft-lb)	*Valves*	*Test Blocks*
Mean	37.25	39.79
Variance	4.92	102.16
Observations	4.00	18.00
Hypothesized Mean Difference	0.00	
df	20.00	
t Stat	-0.97	
P(T<=t) one-tail	0.17	
t Critical one-tail	1.72	
P(T<=t) two-tail	0.35	
t Critical two-tail	2.09	

6.3 Evaluation of Fracture surface

UAB preformed an analysis of the fracture surface of tensile bars as it relates to tensile strength and ductility. The surface of the fracture was analyzed in both the polished and non-polished state for the size of the single largest pore cluster. "Adjacent pores were counted as part of a single cluster if they are separated by no more than the largest ferret length of adjacent pores." [3] This was done because it has been found that "polished porosity measurements rarely correlate well with either reduction in area or elongation…the percent projected porosity on a fracture surface is almost always higher than the bulk porosity in a polished sample." [3] This is because much of the pore cluster is removed during the polishing process. Figure 15 and 16 show the fracture surface of ER and valve body tensile bars. The red line shows a pore cluster and the size of that pore cluster is shown on table 15 and 16. Figure 17 shows the correlation between fractured surface max pore size and yield strength/ UTS. Figure 18 shows the correlation between fractured surface max pore size and ductility. There is a much more noticeable correlation here. Figure 20 shows little to no correlation between polished surface max pore cluster and ductility.

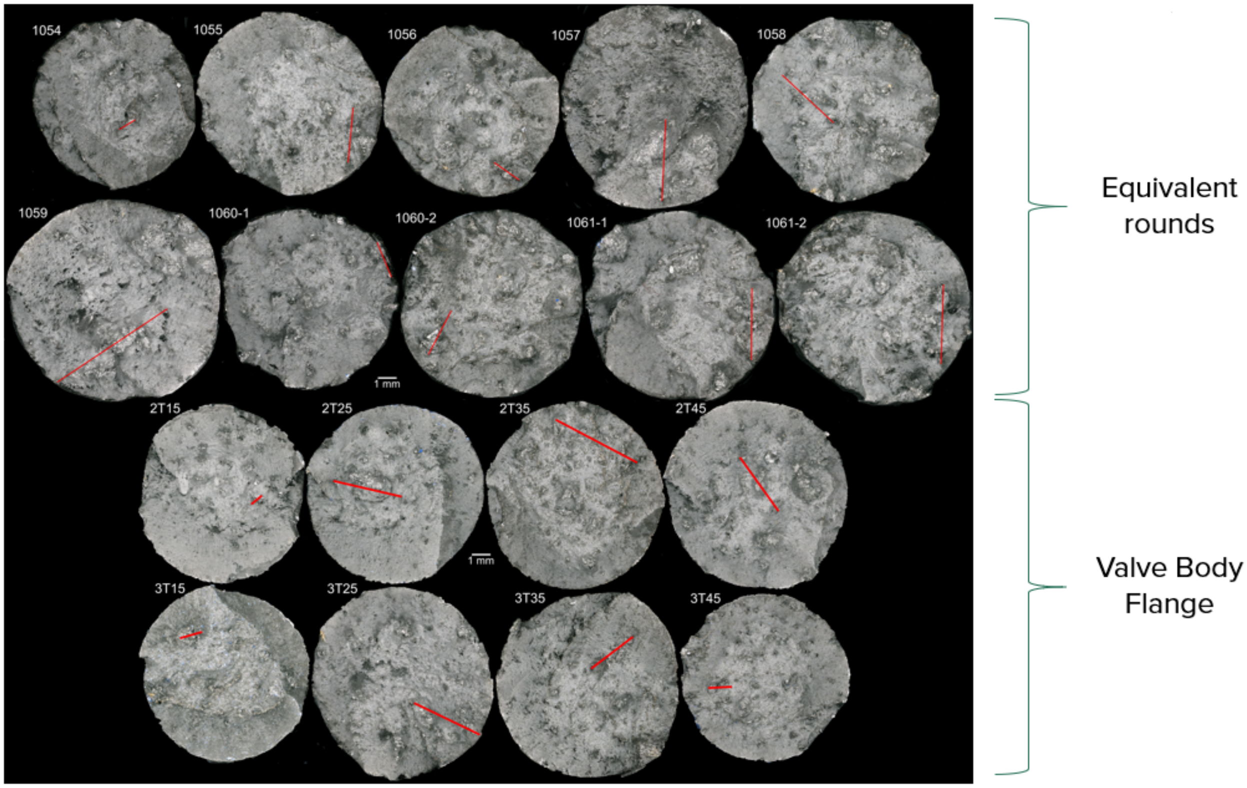


Figure 15 shows the fracture surfaces of .5" tensile bars from the valve body and the keel block. The pore cluster is marked in red.

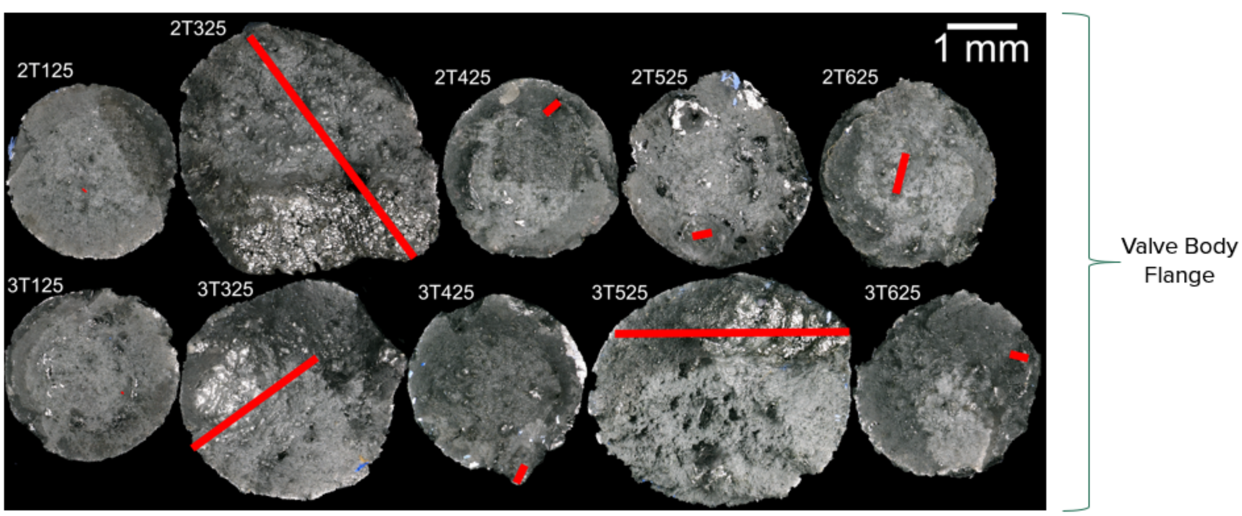


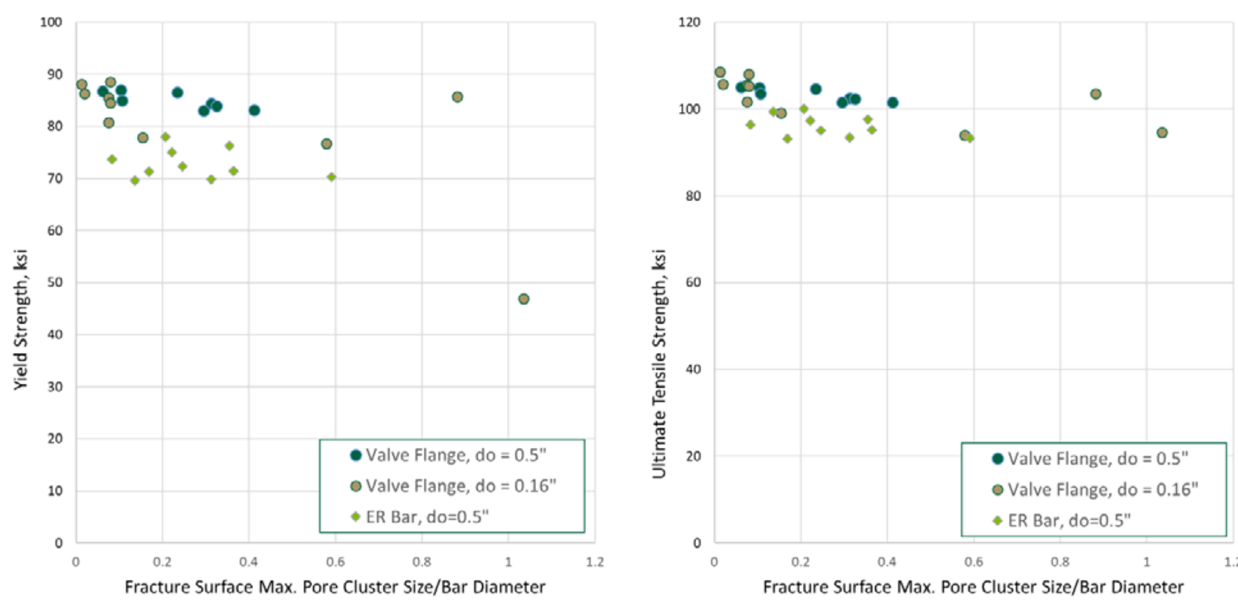
Figure 16 shows the fracture surface of .25" tensile bars. The pore cluster is marked in red

Table 15 shows the max flaw or pore cluster of each valve body tensile specimen. Note that the lab that machined the test bars machined the .25” bar to .16. This was an error on the part of the lab

Valve Body			
			Fracture Surface
Sample Code	Original Diameter, in	Original Diameter, mm	Max Flaw Cluster, mm
2T15	0.5	12.7	0.8
2T25	0.5	12.7	4.0
2T35	0.5	12.7	5.2
2T45	0.5	12.7	3.8
3T15	0.5	12.7	1.3
3T25	0.5	12.7	4.1
3T35	0.5	12.7	3.0
3T45	0.5	12.7	1.3
2T125	0.16	4.064	0.1
2T325	0.16	4.064	4.2
2T425	0.16	4.064	0.3
2T525	0.16	4.064	0.3
2T625	0.16	4.064	0.6
3T125	0.16	4.064	0.1
3T325	0.16	4.064	2.4
3T425	0.16	4.064	0.3
3T525	0.16	4.064	3.6
3T625	0.16	4.064	0.3

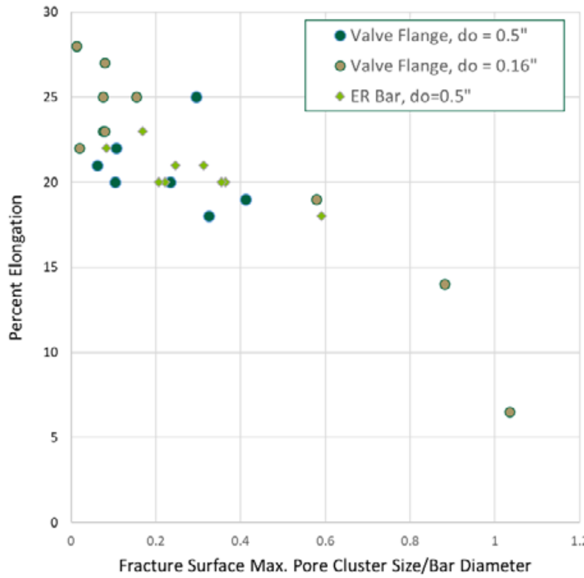
Table 16 shows the max flaw or pore cluster of each ER tensile specimen.

ER Bars			
			Fracture Surface
Sample	Original Diameter, In	Original Diameter, mm	Max Pore Cluster mm
1054	0.5	12.7	1.1
1055	0.5	12.7	3.1
1056	0.5	12.7	1.7
1057	0.5	12.7	4.6
1058	0.5	12.7	4.0
1059	0.5	12.7	7.5
1060-1	0.5	12.7	2.1
1060-2	0.5	12.7	2.8
1061-1	0.5	12.7	2.6
1061-2	0.5	12.7	4.5

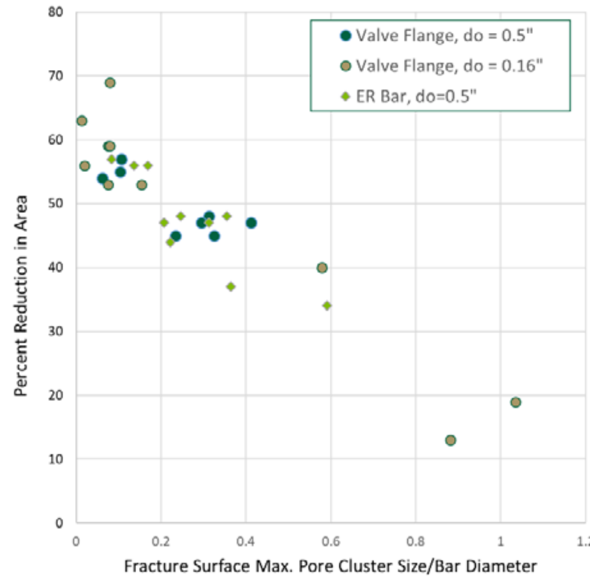


a b

Figure 17 shows the correlation between Fracture surface max pore size and yield strength/UTS. 17a shows the correlation to yield strength and 17 b shows the correlation to UTS.



a



b

Figure 18 shows the correlation between fracture surface max pore size and Elongation/reduction in area. 18a shows the correlation to percent elongation and 18b shows the correlation to percent reduction in area.

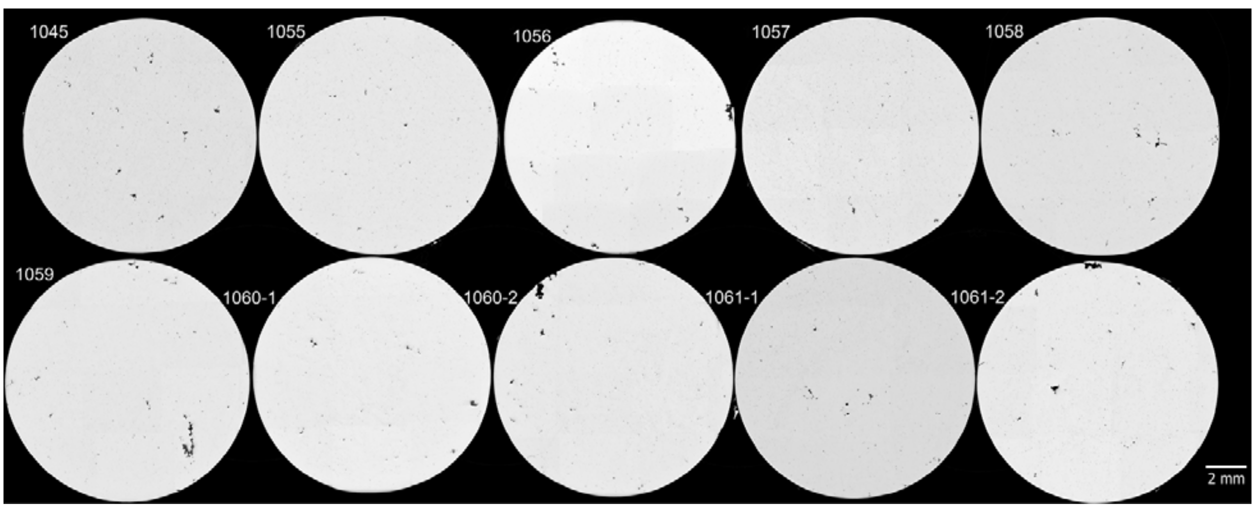
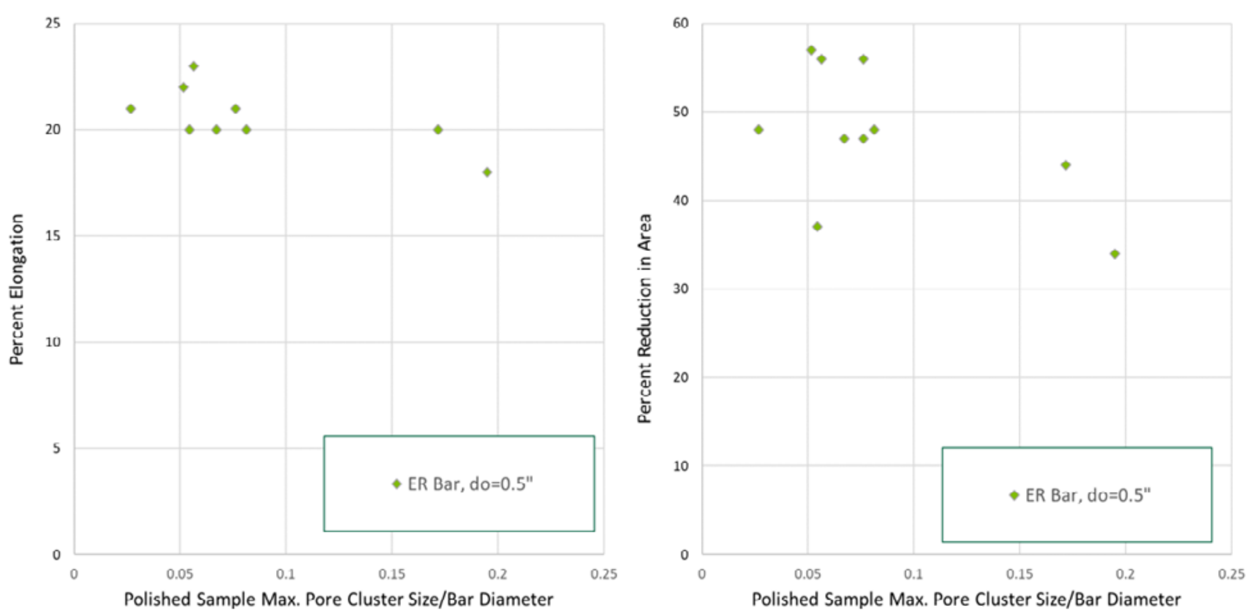


Figure 19 shows the polished fracture surface of the equivalent round test specimens. Max pore cluster size was obtained from these images.

Table 17 shows the max pore cluster of test specimens pulled from ER test bars. The max pore cluster is based off a polished sample.

ER Bars			
			Polished
Sample	Original Diameter, In	Original Diameter, mm	Max Pore Cluster, mm
1054	0.5	12.7	0.65
1055	0.5	12.7	0.34
1056	0.5	12.7	0.97
1057	0.5	12.7	0.69
1058	0.5	12.7	0.97
1059	0.5	12.7	2.48
1060-1	0.5	12.7	0.71
1060-2	0.5	12.7	2.18
1061-1	0.5	12.7	0.85
1061-2	0.5	12.7	1.03



a b

Figure 20 shows the correlation between polished surface max pore cluster size and elongation/reduction in area. 20a shows the correlation to percent elongation and 20b shows the correlation to percent reduction in area.

6.4 Cost Results

The factors that influence the cost of processing test bars include test bar weight and machine time. An indirect cost of test bars is that they take up material that could go into other castings. Table 18 shows the cost to cut and machine our various test bars using a shop rate of sixty dollars per hour. Table 19 show the cost of a test block based on 3$ per pound. Figure 21 Shows a comparison of the cost of processing our various test specimens

Table 18 Shows the cost to machine various test bars

Cost of processing test blocks into test specimens				
Bar	Time mins	hrs	price per hour	Total
Keel block Tenile	9	0.15	$ 60.00	$ 9.00
Keel Block Charpy	34	0.57	$ 60.00	$ 34.00
3" ER Charpy	196.5	3.28	$ 60.00	$ 196.50
4"ER Charpy	201.5	3.36	$ 60.00	$ 201.50
5" ER Charpy	206	3.43	$ 60.00	$ 206.00
3" ER Tensile	42.5	0.71	$ 60.00	$ 42.50
4" ER Tenile	46	0.77	$ 60.00	$ 46.00
5 " ER Tensile	48.5	0.81	$ 60.00	$ 48.50
3" MOD ER Tensile	34	0.57	$ 60.00	$ 34.00
4" Mod ER Tensile	70	1.17	$ 60.00	$ 70.00

Table 19 Shows the cost to create the test blocks needed to machine tensile and charpy specimens

Cost of test blocks used for making test specimens			
Bars	block weight LBS	Cost per pound	Toal cost
Keel block Tenile	5	$ 3.00	$ 15.00
Keel Block Charpy	7	$ 3.00	$ 21.00
3" ER Charpy	33.47	$ 3.00	$ 100.41
4"ER Charpy	56.98	$ 3.00	$ 170.94
5" ER Charpy	89.64	$ 3.00	$ 268.92
3" ER Tensile	22.96	$ 3.00	$ 68.88
4" ER Tenile	38.76	$ 3.00	$ 116.28
5 " ER Tensile	60.76	$ 3.00	$ 182.28
3" MOD ER Tensile	16.93	$ 3.00	$ 50.79
4" Mod ER Tensile	24.2	$ 3.00	$ 72.60

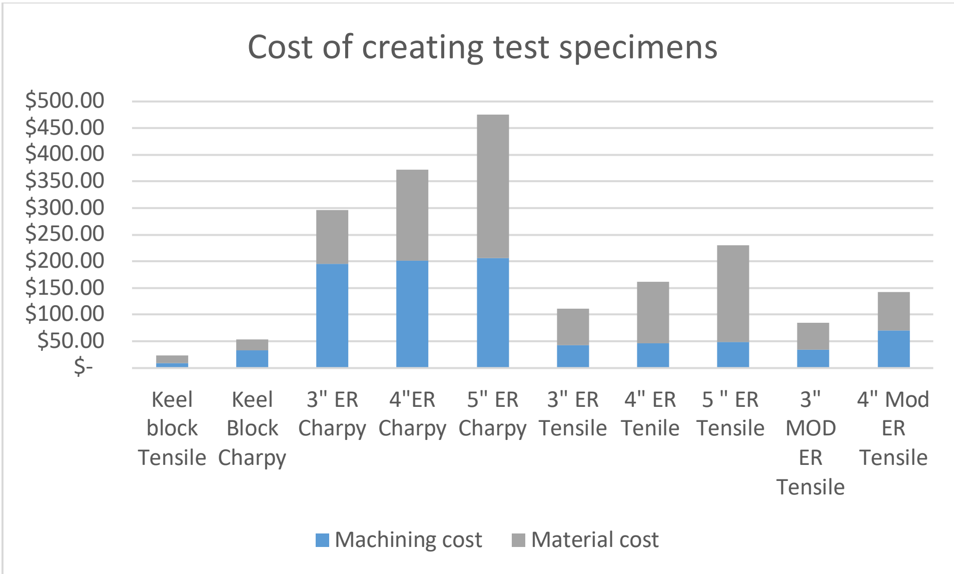


Figure 21 shows the cost of creating test specimens based on material cost and machining cost.

The Experimental Equivalent round test block did not save significant machine time that we had hoped. The time it takes to remove the material with a band saw was faster than we were able to remove material on the lathe. The Experimental E.R. did save material but not enough to make a large impact on the cost of processing.

6.5 Findings and Future work

The results from mechanical testing showed significant statistical differences in the casting and ER test bars. The differences in Mechanical properties needs to be correlated back to solidification simulation results as well as heat treat simulations. Testing of the keel block tensile and Charpy specimens still needs to be done. Similarly charpy no.2 and .25 " tensile no. 2 need to be tested and correlated. The Fracture surface evaluation showed correlation between max pore size and ductility. Max pore size needs to be correlated back to solidification simulation results.

The cost of producing large test bars is significantly both due to the machining time and weight of these large test bars. The modified ER is cheaper to produce, but mainly due to the cost of material. Other weight savings options will be explored to reduce the cost of making ER test bars.

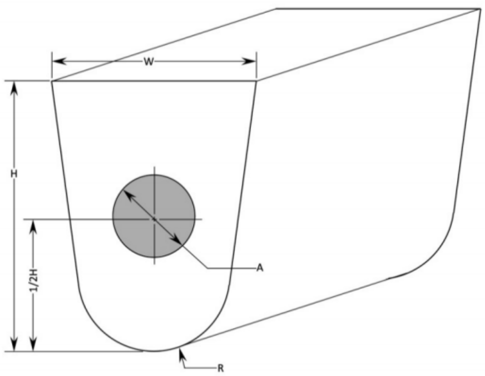
7.0 References

1. *MAGMAsoft*, version 5.4.0.4, MAGMA GmbH, Kackerstrasse 11, 52072 Aachen, Germany

2. Miettinen, J., Louhenkilpi, S., Kytönen, H. and Laine, J., “IDS: Thermodynamic–kinetic–empirical tool for modelling of solidification, microstructure and material properties,” *Math. Comp. Simul.*, vol. 80, pp. 1536-1550, 2010.

3. Foley, R.D, Griffin J.A and Monroe C.A. “Characterization of a Cast Low Alloy, Ultra- High Strength Martensitic Steel” Porosity Characterization

8.0 Appendix



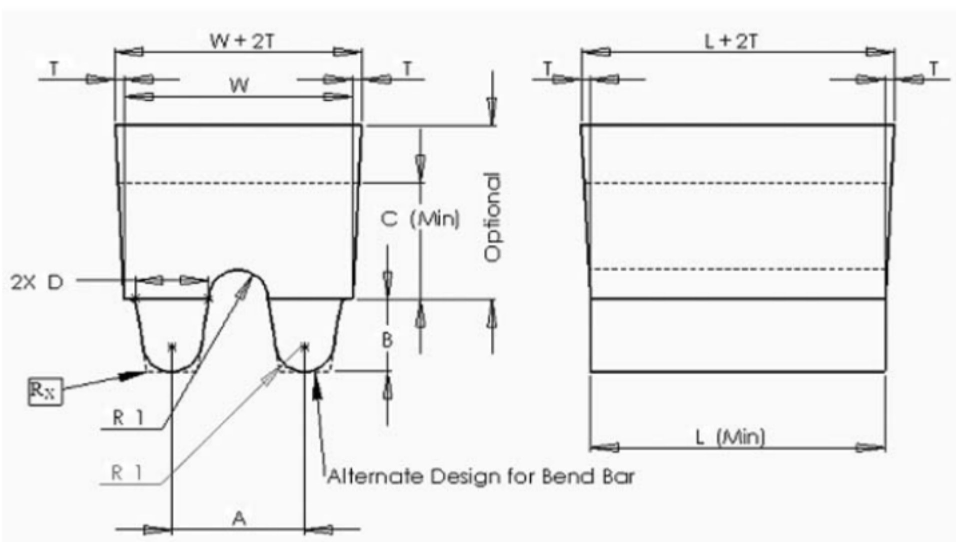
$$ER = 2.3R$$

Then

$$R = ER/2.3$$

1. Use the relationships shown in the figure at the right to construct Qualification Test Coupons configured as keel blocks.
2. Shaded area A is the 1/4T envelope for the qualification test coupon.
3. The length should suit the number and type of tests required.

Equivalent Round		W		H		1/2H		R		Diameter A	
Inches	mm	Inches	mm	Inches	mm	Inches	mm	Inches	mm	Inches	mm
1	25.4	1.1	27.9	1.5	38.1	0.8	20.3	0.4	10.2	0.5	12.7
2	50.8	2.2	55.9	3.0	77.2	1.5	38.1	0.9	22.9	1.0	25.4
3	76.2	3.3	83.8	4.6	116.8	2.3	58.4	1.3	33.0	1.4	35.6
4	101.6	4.3	109.2	6.1	154.9	3.0	76.2	1.7	43.2	1.9	48.3
5	127.0	5.4	137.0	7.6	193.0	3.8	96.5	2.2	55.9	2.4	61.0



Feature	4–leg design		2–leg design	
	in.	mm	in.	mm
A	2¼	60	2¼	60
B	1¼	35	1¼	35
C	2	50	2	50
D	1¼	35	1¼	35
E	Optional	Optional	Optional	Optional
W	8⅜	215	3⅞	100
T	*	*	*	*
L	5 min.	125 min.	5 min.	125 min.
R1	½	12.5	½	12.5
Rx	0 – 1⁄16	0 – 2	0 – 1⁄16	0 – 2

*Use of and size of taper is at the discretion of the foundry.

9.0 Acknowledgment

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