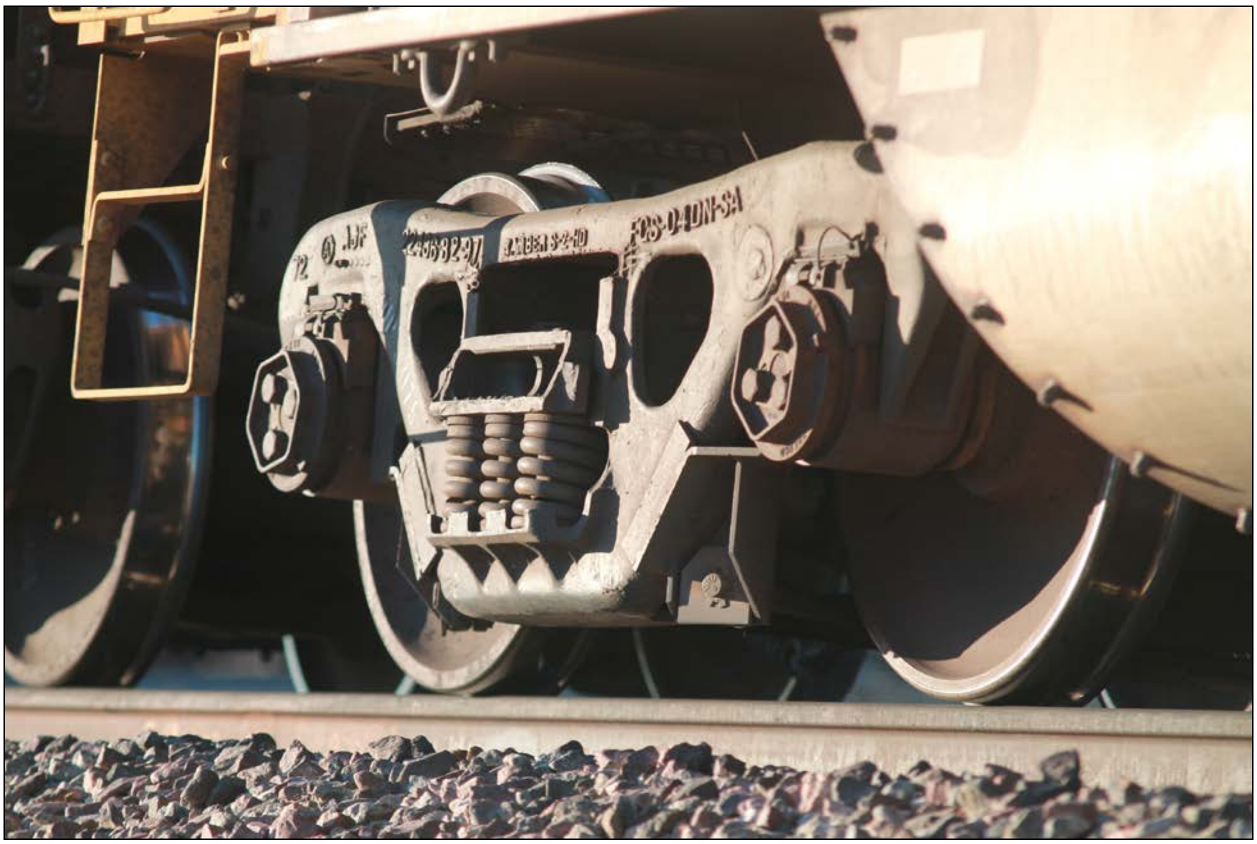
U.S. Department of Transportation

Federal Railroad Administration

Improved Quality Truck Castings

Office of Research, Development, and Technology
Washington, DC 20590



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13. ABSTRACT (Maximum 200 words)

A review of the car repair billing database shows that many bolsters and side frames are removed from service each year due to cracking or breaking. Derailment-related costs due to bolster and side frame failures total approximately $9 million per year. Although the number of removals may not be large in comparison to other components, the cost associated with these removals and failures is significant. To reduce the number of truck casting failures. Transportation Technology Center, Inc. (TTCI) investigated the material properties, material standards, foundry processes, nondestructive test procedures (NDT) and component design for truck castings, as well as reasons for removing castings from service, to determine possible areas for improvement. Mechanical testing was conducted on castings from seven foundries. After this testing, bolsters from three of these foundries were made with alternate chemistries and heat treatments for mechanical testing, and then TTCI determined whether these changes improved the toughness of the steel.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)		
1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)
AREA (APPROXIMATE)		
1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)
MASS - WEIGHT (APPROXIMATE)		
1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)
VOLUME (APPROXIMATE)		
1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)
TEMPERATURE (EXACT)		
[(x-32)(5/9)] °F	=	y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)		
1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)
AREA (APPROXIMATE)		
1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres
MASS - WEIGHT (APPROXIMATE)		
1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons
VOLUME (APPROXIMATE)		
1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)
TEMPERATURE (EXACT)		
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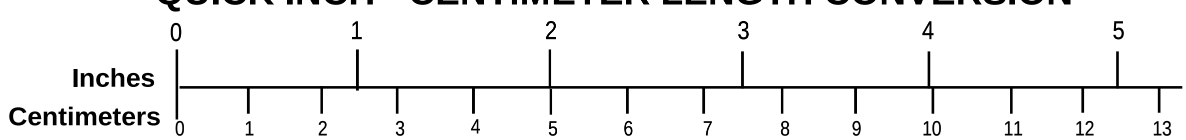

QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

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Executive Summary

When steel foundries produce truck castings, they perform various tests to ensure that the material used in the castings meets industry requirements, including the requirements in the Association of American Railroads (AAR) M-201 standard. The vast majority of the components perform well in service, but over time, small defects resulting from the manufacturing process or other defects that occur during service can grow and cause the component to fail.

Many bolsters and side frames are removed from service each year due to cracking or breaking. Derailment-related costs due to bolster and side frame failures total approximately $9 million per year; the cost of these removals and failures is significant. The removal and the derailment data indicate it is important to reduce the number of truck casting failures. Transportation Technology Center, Inc. (TTCI) investigated the following areas—material properties, material standards, foundry processes, nondestructive testing (NDT) procedures, and component designs of castings, as well as reasons for removing them from service—to determine possible areas for improvement.

Tension testing and Charpy impact testing were performed on bolster castings from seven foundries; these tests are required under the AAR M-201 standard, but are usually performed on special test blocks made with the castings.

Data analysis revealed limited examples of the mechanical properties did not meet all of the criteria. To improve the quality of these castings, alternate heat treatments were devised. These methods were changed without interfering with production or requiring the suppliers to reveal the details of their processes.

Bolsters from three of the original seven foundries were made using these alternate treatments to determine whether their properties improved. Their properties did not improve and in some cases decreased. All of the bolsters from a given manufacturer were poured from a single heat, so the chemistries would represent a snapshot rather than a comprehensive survey.

Computer simulation of the casting process was employed to optimize the way these castings are poured. Results were promising, but a larger effort in close cooperation with the manufacturers would be needed to achieve industrywide results.

NDT of the castings at the manufacturer or at a repair shop can also detect problems before they cause failures. These methods are used in some circumstances, but not all. Increased use of NDT could possibly reduce failure rates, but the process has not been demonstrated or justified.

Computer-aided engineering can be utilized to reduce the stresses in castings. Changing the design of a part reduced the highest stress on a component by 5–10 percent. Further reduction could be possible by working closely, but confidentially, with each of the suppliers.

A survey of manufacturers and repair shops was conducted to determine the main reasons truck castings are removed from service. This information, combined with the data gathered in the rest of this study, can be used to develop improvements that may increase the service life of these critical components.

1. Introduction

A review of the car repair billing database showed that many bolsters and side frames are removed from service each year due to cracking or breaking. Derailment-related costs due to bolster and side frame failures total approximately $9 million per year. Although the number of removals may not be large in comparison to other components, the cost associated with these removals and failures is significant. To better understand the nature of truck casting failures and identify possible areas for improvement, Transportation Technology Center, Inc. (TTCI) investigated the material properties, material standards, foundry processes, nondestructive testing (NDT) procedures, and the component design of castings, as well as the reasons for removing them service.

1.1 Background

Fatigue failures have historically resulted from multiple causes, such as foundry process issues and poor repair welding. The Association of American Railroads (AAR) utilizes fatigue testing for new and existing products to identify process and design shortcomings. The potential for fatigue failures still exists, so this task order looked into the wider use of NDT and reduction of maximum stresses as methods to further reduce the risk of fatigue.

Brittle failures can be attributed to marginal strength and poor impact resistance of the cast steel material. This failure mode is dangerous because it occurs instantaneously and under stresses that can be below the yield strength of the material. Figure 1 shows several eaxmples of brittle and fatigue failures.

Figure 1. Examples of Brittle and Fatigue Failure in Truck Castings

There have been no recent specification changes made to address brittle failures attributed solely to material properties. Since the mechanism is complex, the supporting research has not been completed, and recommended foundry changes will be extensive. It is generally believed that improving material properties is critical to reducing the occurrence of brittle failures of cast components.

In addition to reviewing the current state of the metallurgical properties of truck castings, TTCI performed radiography inspections to demonstrate the feasibility of this technology in the foundry environment. These inspections could aid in the determination of actual sizes and locations of internal and external defects present in high stress areas of the bolster.

1.2 Objectives

To assess the state of quality of the truck casting material, TTCI had the following objectives:

- Evaluate mechanical properties of truck castings from multiple manufacturers.
- Investigate alternate casting methods.
- Create new or propose changes to truck casting quality standards.
- Review current foundry NDT methods.
- Propose design changes in truck castings to reduce maximum stresses.
- Conduct an industry survey to determine why side frames and bolsters are removed from service.

1.3 Overall Approach

- Obtain bolsters from multiple foundries; perform chemical and mechanical testing on these bolsters and analyze data.
- Investigate alternate casting methods by working with suppliers and by using computer simulations.
- Propose changes to the AAR M-201 standard to improve casting quality.
- Evaluate the effectiveness of various NDT techniques for truck castings in production and in repair facilities. Evaluate feasibility of radiography as the sole NDT method for truck castings.
- Employ finite element analysis (FEA) to determine location and magnitude of maximum stress in a side frame or bolster, then attempt to reduce maximum stress by 20 percent by analyzing design changes.
- Take proposed AAR M-201 standard changes and other alternate parameters and apply them to bolsters obtained from a smaller set of foundries. Perform chemical and mechanical testing on these bolsters and compare to the results from the earlier testing.
- Conduct surveys of multiple railcar manufacturers and repair shops to determine why truck castings are removed from service.

1.4 Scope

TTCI conducted a comprehensive review of the quality of materials commonly used for bolster and side frame castings. The results from the material property analysis, NDT effectiveness evaluations, foundry process simulations, and suggested design changes will be used to improve the existing practices and standards for AAR M-201 Grade B+ bolsters and side frames.

1.5 Organization of the Report

The report is organized by the following sections:

- Section 2: Initial chemical and mechanical testing
- Section 3: Alternative casting methods

- Section 4: Proposed changes to AAR M-201 standard
- Section 5: NDT methods
- Section 6: Industry survey of reasons for removing components from service
- Section 7: FEA for reduction of maximum stress
- Section 8: Mechanical testing of bolsters produced using alternate parameters.
- Section 9: Conclusions

2. Truck Casting Material Requirements and Testing

Side frames and bolsters are produced from AAR M-201 Grade B+, a medium carbon cast steel. The AAR M-201 standard specifies chemical composition limits for several elements, but the manufacturers can add unspecified elements as long as all other properties are met [1]. Heat treatment and mechanical testing are also required. Other types of castings are produced from other grades of steel covered under this standard, with varying chemistries, heat treatments, and mechanical properties.

2.1 Material Requirements

2.1.1 Chemical Composition of Grade B+ Steel

Table 1 gives the chemical composition requirements for Grade B+ steel.

Table 1. Chemical Composition of Grade B+ Steel

Element	Weight Percent
Carbon, C	0.32 maximum
Manganese, Mn	0.90 maximum
Phosphorus, P	0.04 maximum
Sulfur, S	0.04 maximum
Silicon, Si	1.50 maximum

Elements not specifically mentioned above may be added as long as all other properties in the standard are met. Most foundries use optical emission spectroscopy (OES) to determine the chemical composition of the steel used for the castings.

2.1.2 Heat Treatment of Grade B+

All Grade B+ castings must undergo a normalizing heat treatment at a minimum [1]. A tempering step after normalizing is optional. The requirements for each heat treatment step are detailed in AAR M-201.

2.1.3 Mechanical Testing of Grade B+

Each heat or batch of steel must also undergo mechanical testing, consisting of tensile testing detailed in AAR M-201 and ASTM A370 [2]. Samples for this are usually taken from a keel block, which is a sample block poured with the castings and also heat treated with the castings to represent the manufacturer’s standard process. The purchaser has the option of using samples taken directly from the casting. In this case, the yield strength and ultimate tensile strength requirements are 80 percent of the values for samples from the keel blocks. All other mechanical testing requirements remain the same. Table 2 shows the tensile testing requirements. Retesting is permissible if minimum values are not met.

Table 2. Tensile Testing Requirements for Grade B+

Measurement	Minimum Keel Block Sample Requirement	Minimum Casting Sample Requirement
Ultimate Tensile Strength	80 ksi	64 ksi
Yield Strength	50 ksi	40 ksi
Elongation	24%	24%
Reduction of Area	36%	36%

2.1.4 Charpy Impact Testing of Grade B+ Steel

A minimum of once per week, Charpy V-notch impact testing must be performed. A test consists of the average absorbed energy of three impact specimens from the same heat [1]. For Grade B+, the average absorbed energy must be a minimum of 15 foot-pounds (ft-lbs) or 20 Newton-meters (N-m) at test temperature of 20 °F (-7 °C). Testing is performed per ASTM A370 and ASTM E23 [3].

2.2 Test Plan

Seven foundries that currently produce bolsters were selected as suppliers for this testing. Four bolsters were obtained from each of the seven foundries; three bolsters were used for the chemical and mechanical testing, and the remaining bolster was used as a spare if needed. Figure 1 shows the sample locations for the tensile and Charpy specimens. Five of the foundries supplied a keel block with their castings. One foundry supplied a keel block, but no castings.

Chemical testing was conducted by OES. All of the bolsters from a given manufacturer were poured from a single heat, so the chemistries would represent a snapshot rather than a comprehensive survey.

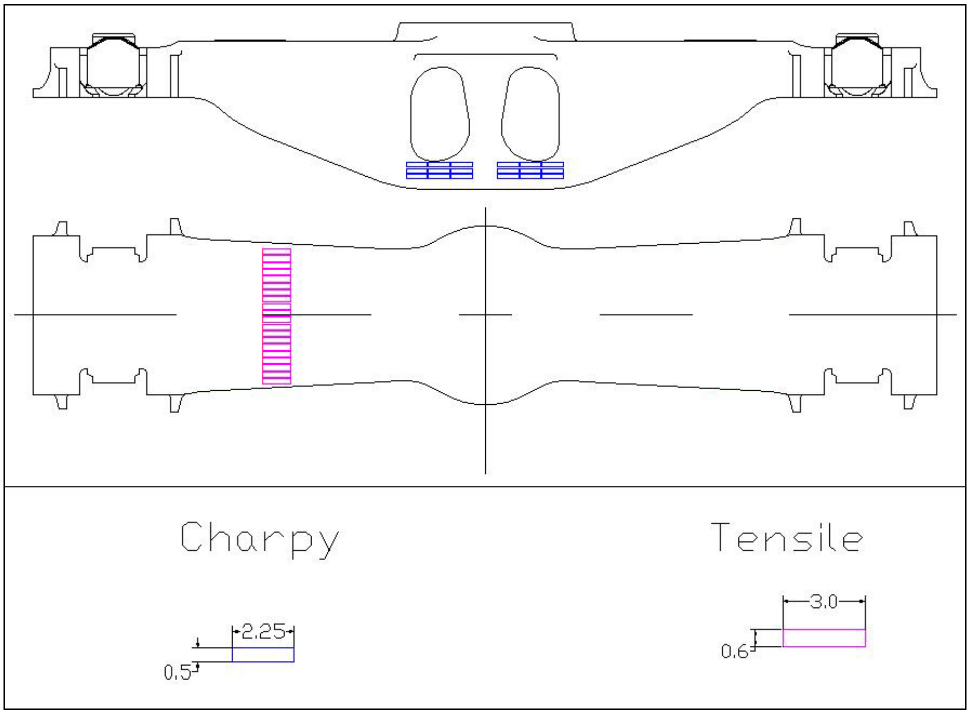

Figure 2. Tensile and Charpy Impact Test Locations

Number of samples:

3 bolsters per manufacturer x 18 Charpy samples per bolster = 54 samples per manufacturer

3 bolsters per manufacturer x 14 tensile specimens per bolster = 42 samples per manufacturer

All tensile tests were conducted at room temperature or 70–75 °F (21-24 °C). Charpy tests were performed at -40, -20, 0, 20, 40, 60, and 70–75 °F (-40, -29, -18, -7, 4, 16, and 21–24 °C).

2.3 Test Results

2.3.1 Tensile Test Results

Fourteen tensile specimens were tested from each bolster; for the foundries that provided keel blocks, four additional specimens were tested. A total of 313 tensile tests were performed. Ultimate tensile strength, 0.2 percent offset yield strength, elongation, and reduction of area were measured in each test. Figures 3 and 4 show summaries of the results.

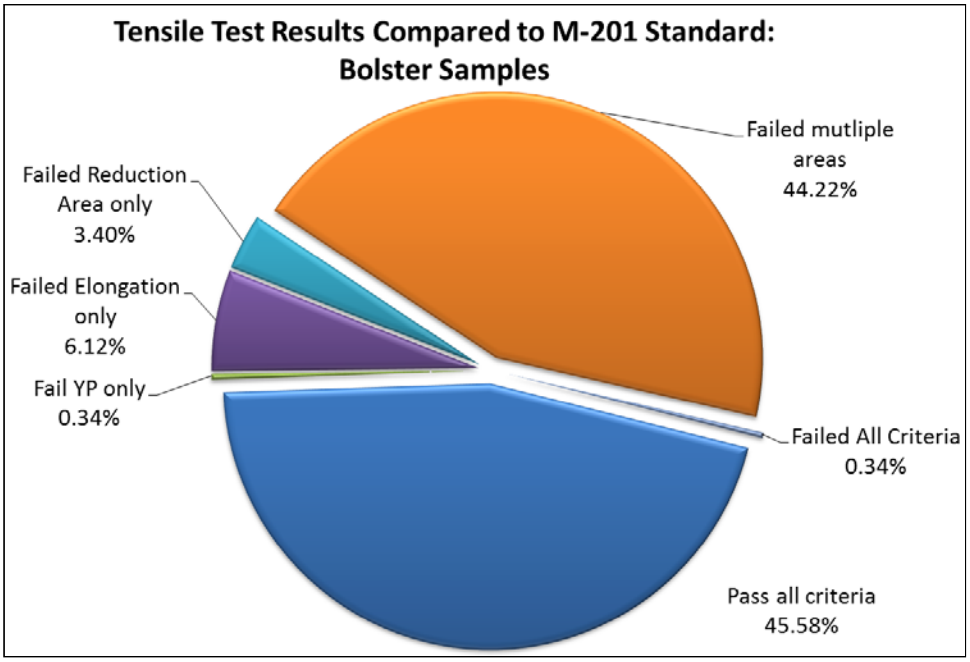

Figure 3. Tensile Tests Results from All Bolster Samples [4]

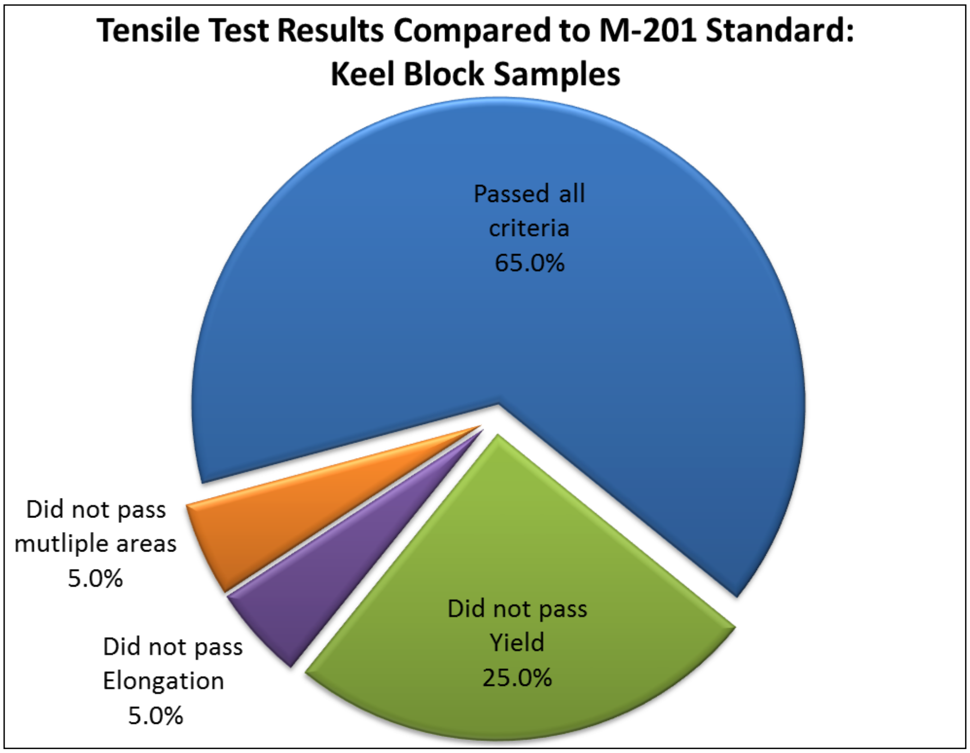

Figure 4. Tensile Test Results from Keel Block Samples [4]

As seen in Figures 3 and 4, a large number of specimens from the bolsters did not meet the minimum requirements. Of these, most were low on both elongation and reduction of area. The keel block specimens performed somewhat better, but there were still some that tested below the requirements. For the keel block samples, 25 percent of them did not pass the yield strength requirement. Some of the low performing samples were examined with low power optical microscopy; the fracture surfaces indicated very rough surfaces and porosity.

2.3.2 Charpy Impact Test Results

Fourteen Charpy impact samples were tested from each bolster. There were seven test temperatures, and two samples per test temperature per bolster were tested. For the foundries that supplied keel blocks, four additional Charpy samples were tested. The keel block data is not presented here due to the small sample size. Figures 5 and 6 show the test results for the bolster samples.

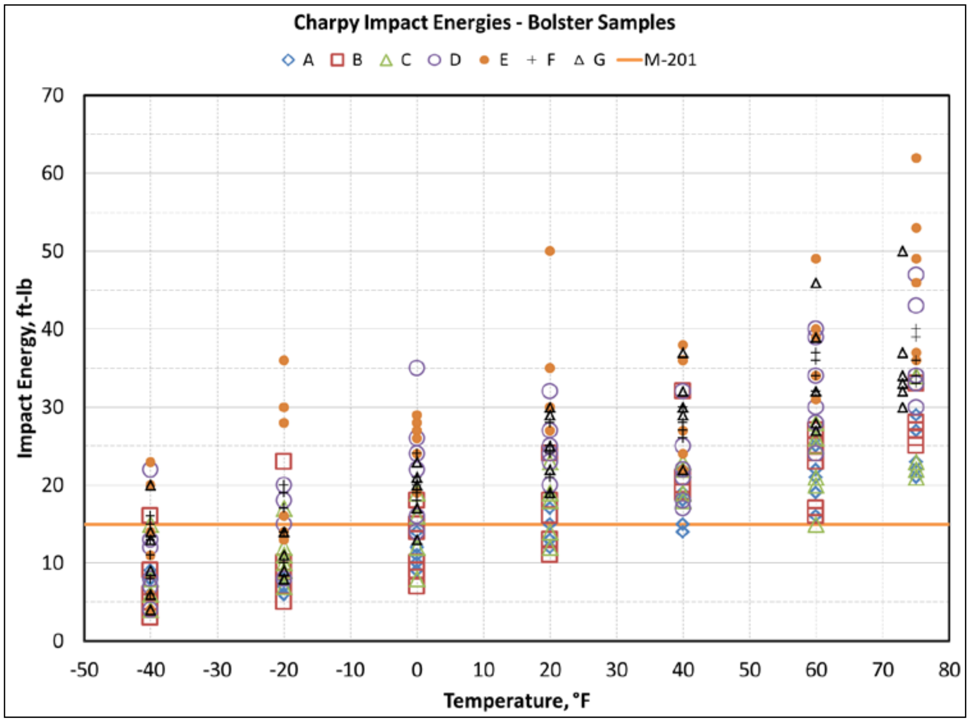

Figure 5. Charpy Impact Test Results from All Bolster Samples

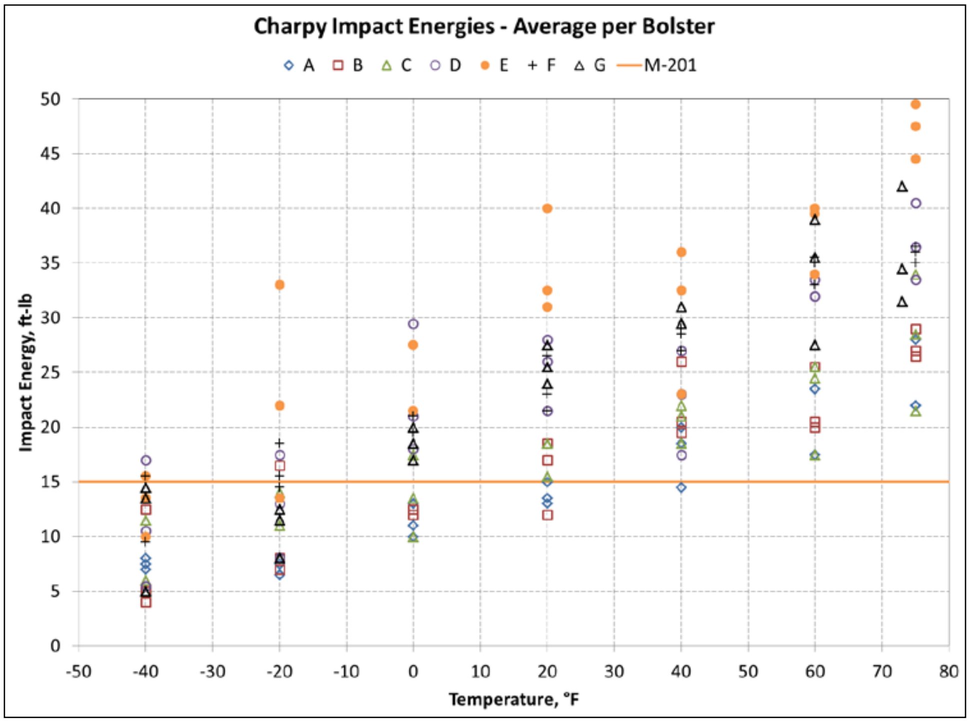

Figure 6. Average Charpy Impact Test Results per Bolster

The testing was conducted over a wide range of temperatures, but the critical test temperature per the AAR M-201 standard is 20 °F (-7 °C). Foundries A and B had samples that did not meet the minimum requirement of 15 ft-lbs (20 N-m) at the critical temperature [5]. These two suppliers also had the largest number of tensile samples that did not meet the elongation and reduction of area requirements.

Impact energies from each supplier were proportional with temperature, as expected. Variation of the data also increased with temperature. Suppliers generally retained their relative positions with the other suppliers. Some were consistently low across the temperature range, and some were consistently high.

To further investigate the causes of the low impact energies, the fracture surfaces of 11 of the lowest performing Charpy impact samples were analyzed with a scanning electron microscope (SEM) [6]. All of the samples in this group showed some degree of shrinkage porosity on the fracture surface. As expected, most of the samples tested at relatively warm temperatures exhibited at least partially ductile fracture surfaces, while the samples tested below 0 °F (-18 °C) were entirely brittle. Figure 7 shows a SEM of the sample with the lowest absorbed energy of the 11 samples [6]. This feature is inside a large pore. The black oxide material on the dendrites indicates this porosity was likely caused by gas; the large pore was likely a major reason for the low absorbed energy of this sample. Shrinkage porosity can be controlled by modifying the gating and risering system, and by monitoring the melt temperature. Gas porosity has two sources: core gases and dissolved gases in the metal.

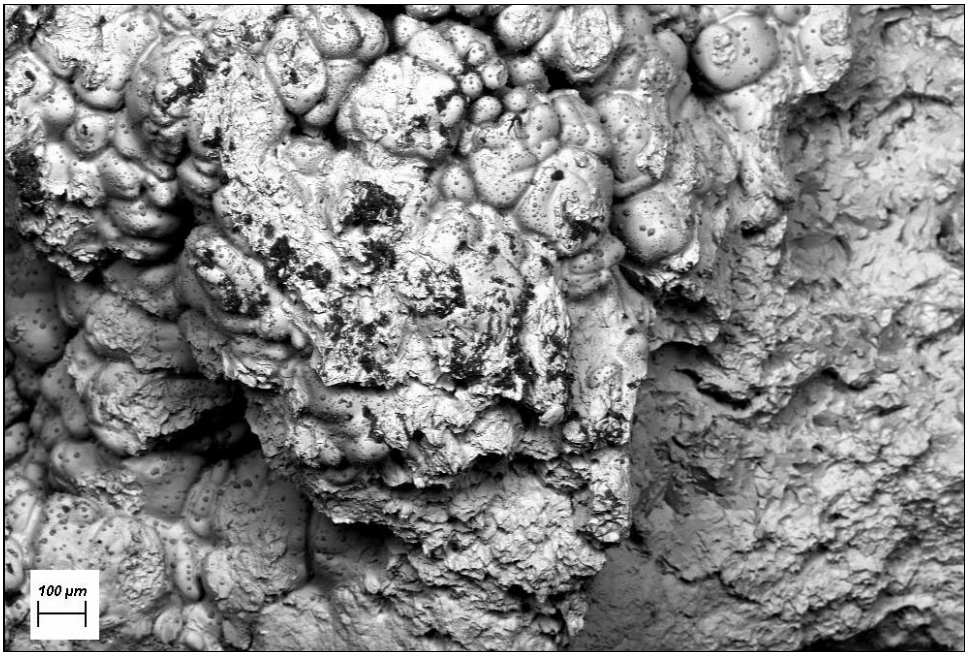

Figure 7. Gas Porosity in a Low Performing Charpy Impact Specimen

Also, inclusions can greatly reduce the strength or impact energy; these are frequently present as oxides or sulfides. The oxygen and sulfur atoms typically combine with a metal atom, forming a hard inclusion. These inclusions form discontinuities in the material and cause lower mechanical properties. Figure 8 shows an inclusion that energy dispersive spectroscopy revealed to be a manganese sulfide (MnS) particle in a pore of a Charpy impact fracture surface [6]. Inclusions occur because of residual elements in the scrap steel used for melt material, oxygen entrained during melting and pouring, or sand from the mold. Control of scrap sources, gate modification, and improved molding techniques can reduce these inclusions.

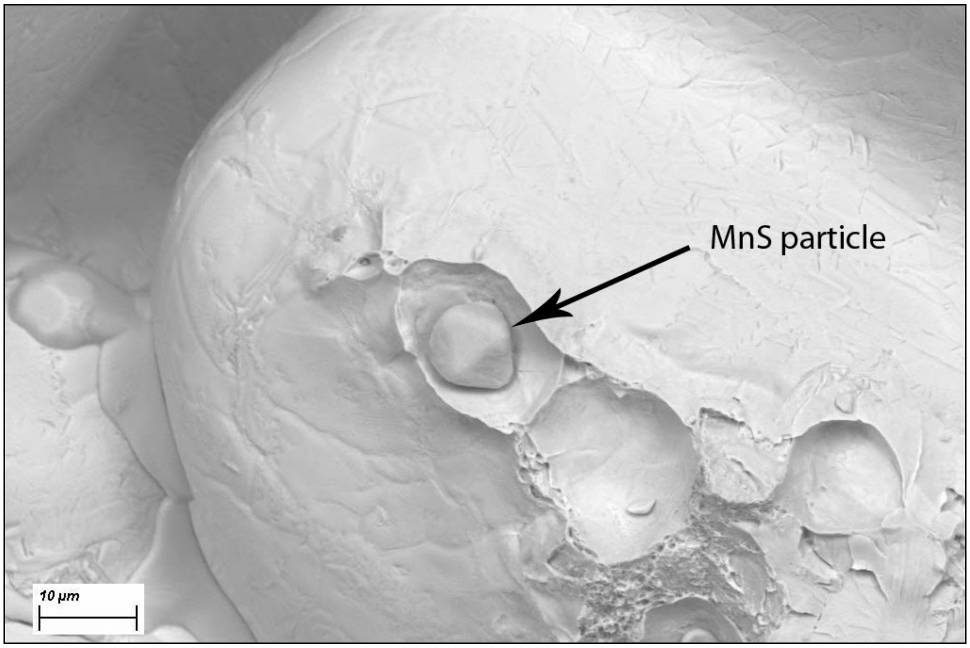

Figure 8. Manganese Sulfide Particle in Charpy Specimen

2.3.3 Chemical Test Results

The chemical tests were performed on samples cut from bolsters; a minimum of two samples were tested for each bolster. All samples conformed to the AAR M-201 standard requirements. Figure 9 shows the average chemistries of the bolsters from each of the foundries for carbon (C), manganese (Mn), phosphorus (P), sulfur (S), silicon (Si), nickel (Ni), chromium (Cr), molybdenum (Mo), copper (Cu), vanadium (V), and antimony (Sb).

	Element, weight percent										
Foundry	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	V	Sb
A	0.248	0.737	0.019	0.019	0.395	0.091	0.589	0.038	0.128	0.003	0.0022
B	0.273	0.729	0.012	0.020	0.414	0.061	0.517	0.014	0.098	0.001	0.0063
C	0.239	0.974	0.010	0.013	0.443	0.105	0.313	0.083	0.211	0.085	0.0021
D	0.229	0.863	0.011	0.008	0.493	0.154	0.354	0.017	0.070	0.046	0.0018
E	0.246	0.899	0.013	0.008	0.438	0.207	0.361	0.010	0.027	0.021	0.0014
F	0.281	1.071	0.014	0.007	0.470	0.083	0.078	0.016	0.103	0.028	0.0020
G	0.283	0.820	0.013	0.006	0.401	0.276	0.389	0.007	0.036	0.007	0.0006

Figure 9. Chemistries of Bolsters from Each of the Seven Foundries

Phosphorus and sulfur, two elements that can reduce toughness, were well within the maximum allowable value of 0.04 weight percent. Almost all values for these two elements were below 0.02 weight percent. The three remaining elements detailed in the AAR M-201 standard, carbon, manganese, and silicon were well within their composition limits.

Some ASTM standards for cast steels limit the permissible levels of residual elements such as chromium, molybdenum, copper, and vanadium. The AAR M-201 standard does not directly limit these elements, but does control their amount through a carbon equivalent calculation; for Grade B+ steel, the maximum is 0.72. All readings were below this maximum. Most of these residual elements are not easily removed by furnace or ladle treatment; control of scrap sources can reduce or eliminate them. Some suppliers add chromium, molybdenum, and vanadium to boost mechanical strength. Molybdenum reduces steel’s susceptibility to temper embrittlement [7] and also increases hardenability and mechanical properties.

Antimony was present in samples from each supplier in amounts from approximately 0.0005–0.002 weight percent. However, one supplier had antimony readings of about 0.006 weight percent, which is a concern, because antimony is known to cause embrittlement in steels [8].

Proposed limits on elements are listed in later sections.

2.4 Metallographic Analysis of Bolster Samples

On the basis of the chemistry and heat treatment requirements for the Grade B+ material, the microstructure was expected to be mostly ferritic, with small amounts of pearlite possible. The samples were examined by optical light microscopy, and all microstructures were ferritic. Samples were examined from some of the best and worst performing mechanical test samples to determine if there were obvious differences in microstructure, porosity, etc.

Figures 10–12 are photomicrographs of samples from three bolster mechanical test samples; each sample is from a different supplier. These photomicrographs are representative of the samples observed. The mechanical test results did not always correspond to the amount of porosity. No inclusions were found in these samples, but high amounts of porosity were found in most samples.

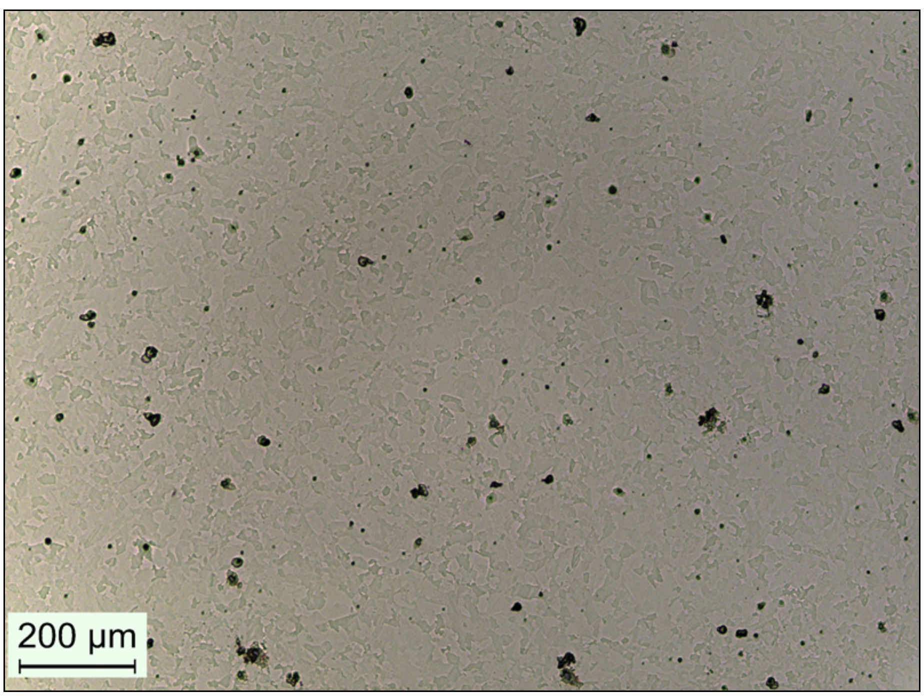

Figure 10. Ferritic Microstructure of a Bolster Mechanical Test Sample (2% Nital Etch)

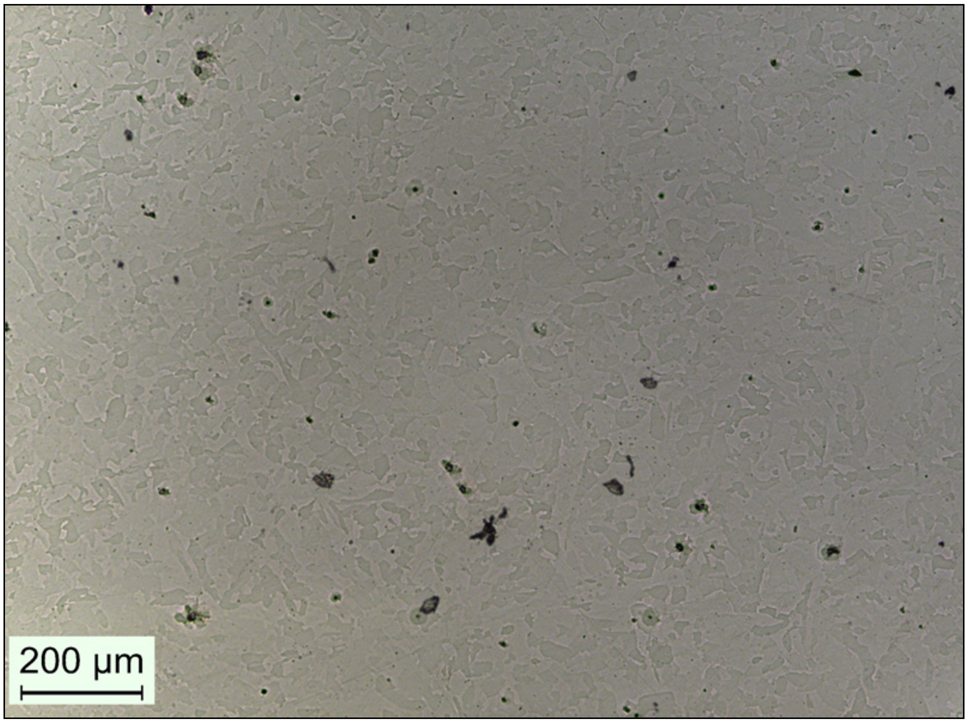

Figure 11. Ferritic Microstructure of a Bolster Mechanical Test Sample (2% Nital Etch)

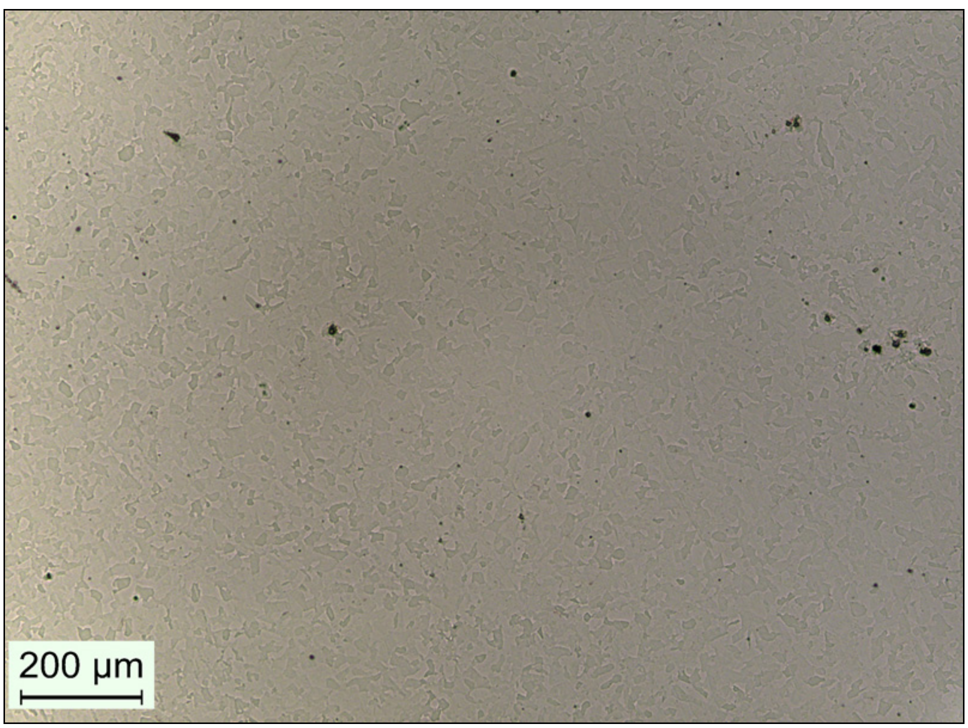

Figure 12. Ferritic Microstructure of a Bolster Mechanical Test Sample (2% Nital Etch)

3. Alternate Casting Methods

3.1 Background and Objective

Truck castings must be of good quality, both in appearance and structure. Since these castings receive little or no machining before being placed into service, the surface finish is important. Also, identifying information such as manufacturing date, pattern number, and manufacturer identification must remain legible throughout the service life of the component.

In addition to cosmetic issues, the castings must be structurally sound. Some common casting defects that can drastically affect casting performance include shrinkage porosity, gas porosity, inclusions, and hot tears. A nearly perfect casting can be made, but usually at a greater expense than the industry can support. The challenge is to create sound castings within cost constraints. Each foundry has its own process to maximize the quality of its castings and this information is guarded closely.

TTCI's goal was to devise general improvements that could be applied to virtually any supplier's process without disclosing confidential process details.

3.2 Method

TTCI used Flow-3D, a computational flow dynamics software package which has a special module for castings, to simulate the casting process for bolsters. Using this software, metal flow, solidification, temperatures, residual stresses, air entrainment, likelihood of inclusions, and many other parameters can be calculated.

A generic bolster with a simple sprue and basic feeding system was used for all of the simulations. The parameters or feeding system components were not modeled after any specific supplier's process. Three parameters were varied to form a designed experiment, using the mold tilt angle, the sprue angle, and the initial velocity as variables. This was not designed as a full Taguchi designed experiment, but to show a starting point for actual trials in the foundry. Table 3 shows the experiment array and parameter levels.

Table 3. Parameters and Levels for Experiment

Run	Mold Angle, degrees	Sprue Angle, degrees	Initial Velocity, m/s
1	0	0	0.60
2	0	10	0.85
3	0	20	1.00
4	10	0	0.85
5	10	10	1.00
6	10	20	0.60
7	20	0	1.00
8	20	10	0.60
9	20	20	0.85

The simulation's output was particles that represent sand in the mold. The particle sizes ranged from 0.15 to 0.40 millimeters (mm), but were enlarged on the output screen for visibility. Relatively few particles were generated in the simulations, as a large number would cause too much clutter on the display. The particles were given the density of silica sand, which was approximately 30 percent that of the liquid steel.

A very long sprue was used for each of the simulations; this kept the simulation volume the same for all situations and reduced the need to perform extensive rework for each simulation. The mold filling was simulated to complete filling. Solidification was not part of this study.

3.3 Results

Figures 13–18 show the particle locations at the end of filling for each set of parameters.

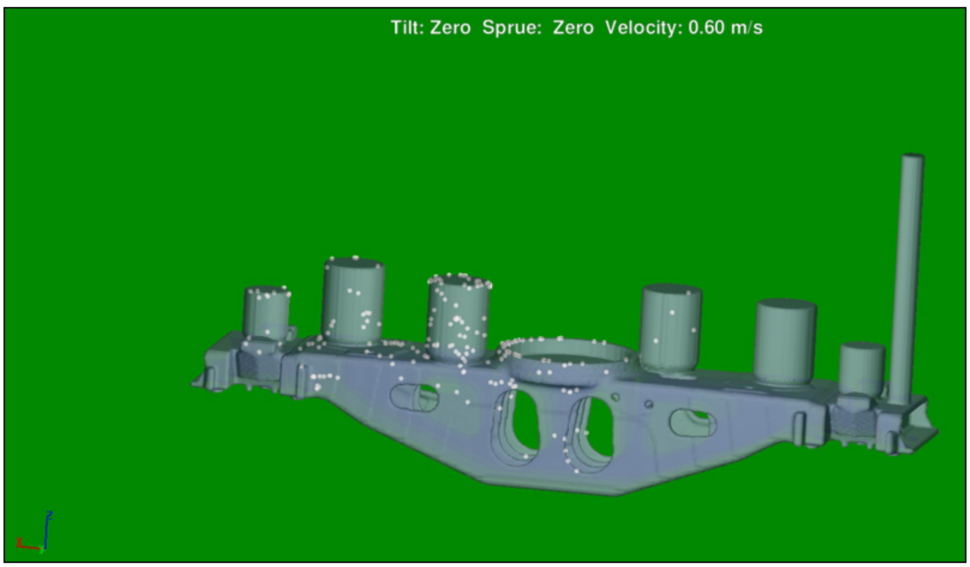

Figure 13. Mold Angle: 0° Sprue Angle: 0° Initial Velocity: 0.60 m/s

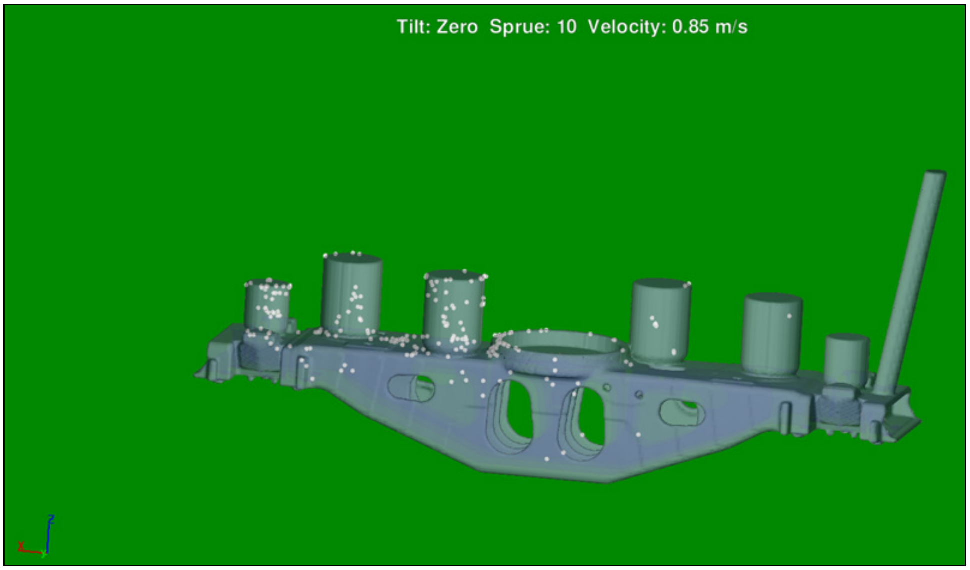

Figure 14. Mold Angle: 0° Sprue Angle: 10° Initial Velocity: 0.85 m/s

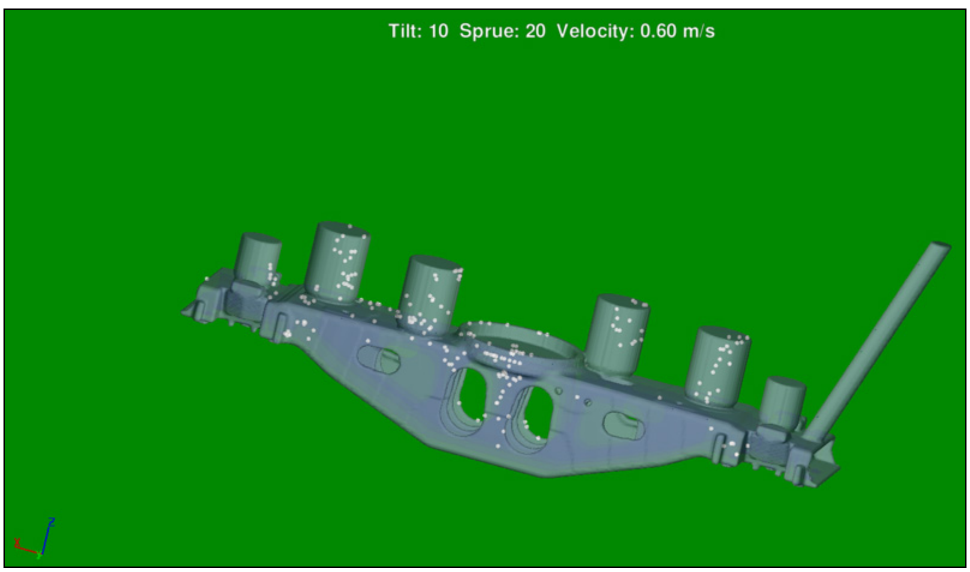

Figure 15. Mold Angle: 10° Sprue Angle: 20° Initial Velocity: 0.60 m/s

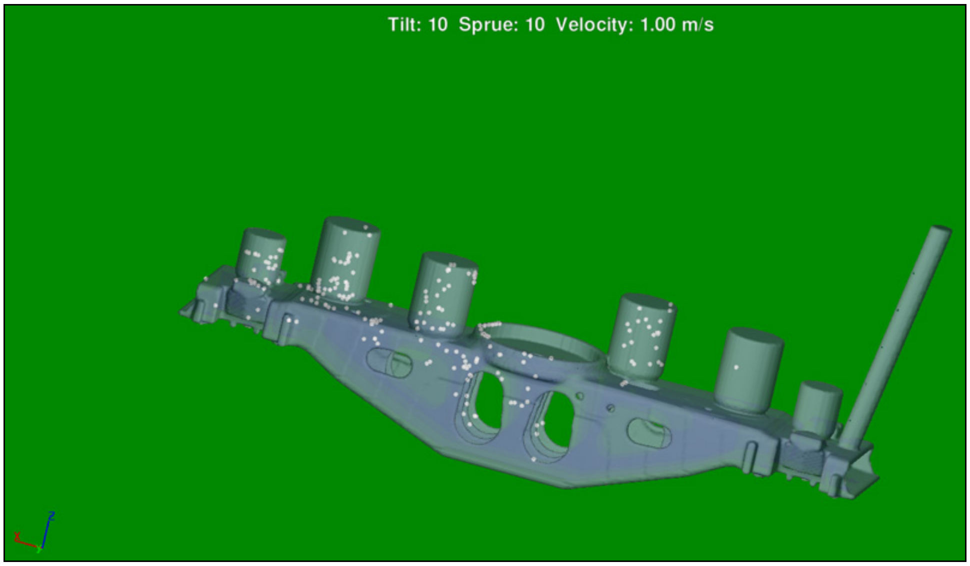

Figure 16. Mold Angle: 10° Sprue Angle: 10° Initial Velocity: 1.00 m/s

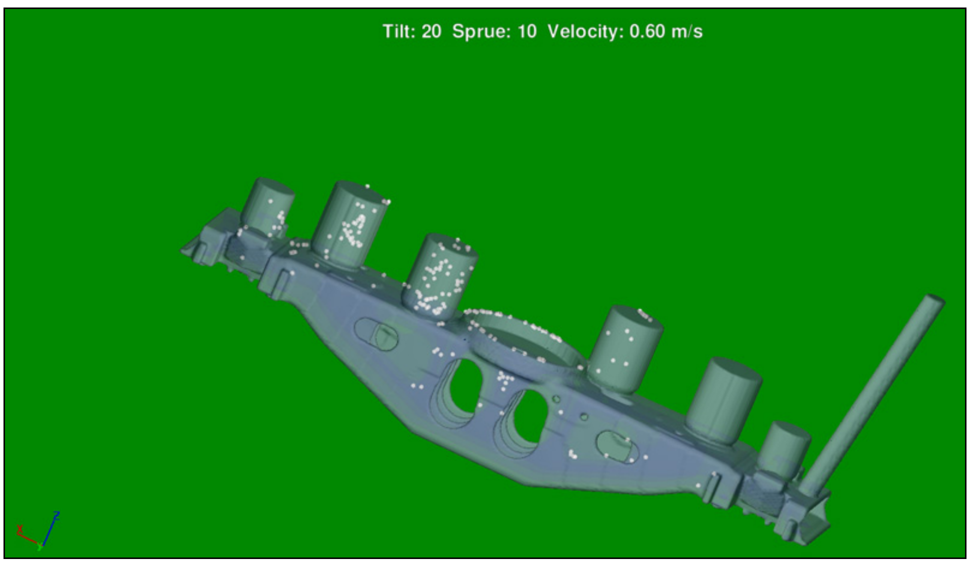

Figure 17. Mold Angle: 20° Sprue Angle: 10° Initial Velocity: 0.60 m/s

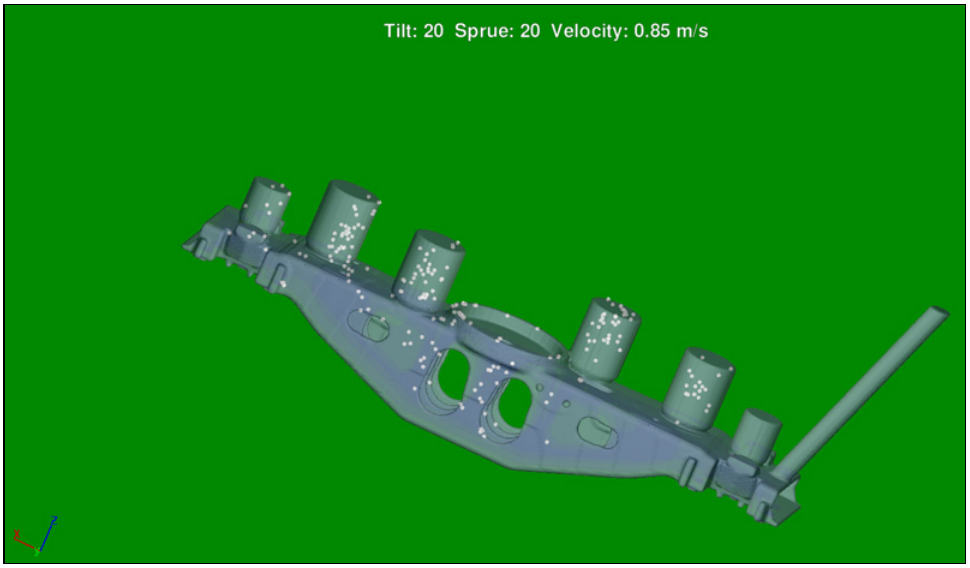

Figure 18. Mold Angle: 20° Sprue Angle: 20° Initial Velocity: 0.85 m/s

Table 4 shows the particle count at the brake rod hole and at the bowl for each experiment run. The particles were included if they intersected the given feature.

Table 4. Particles Found in Brake Rod Holes and Bowl

Run	Mold Angle	Sprue Angle	Initial Velocity	Particles in Brake Rod Hole	Particles in Bowl
1	0	0	0.60	12	32
2	0	10	0.85	6	36
3	0	20	1.00	10	22
4	10	0	0.85	9	31
5	10	10	1.00	13	18
6	10	20	0.60	9	25
7	20	0	1.00	7	27
8	20	10	0.60	3	34
9	20	20	0.85	12	21

Simulation Run 9 had with the fewest particles at the surface of the brake rod openings, followed by Run 2. Both of these runs had a sprue angle of 10 degrees. Run 5, which also had a sprue angle of 10 degrees, had a much higher number of particles in the critical area.

Many of the particles ended up in the bowl area of the bolster, because particles could not easily leave the rim area, which would be a problem area in any configuration with the bowl on top.

The initial velocity was that of the metal entering the top of the sprue. The maximum in these simulations was 1.00 meters per second (m/s), which is frequently used as the maximum that the fluid should travel in the mold. The long sprue used in these runs caused some of the velocities well above 1.0 m/s, which could alter the flow path of the particles and give different results in foundry trials.

A mold or sprue tilted up to 20 degrees may provide a solution to sand or other inclusions in the brake rod openings. An in-depth analysis, combined with foundry trials, would be necessary to prove this technique. Obtaining the cooperation of suppliers may make a test difficult, especially if the foundry's process information would become available to competitors.

3.4 Conclusions

Simulating the casting process with computer software allows researchers to try new processes or parameters without building costly prototypes or pouring excess metal. A wide variety of parameters can be adjusted and tested before pouring any metal, reducing the lead time of new tooling, gating systems, and component design.

The simulations conducted for this project used mold tilt angle, sprue angle, and initial fluid velocity as variables. The number of particles at the brake rod openings and the bowl area were counted as output. Of the nine simulations, the two with the best results used sprues tilted at 10 degrees to the vertical and had varying degrees of tilt on the mold.

If a foundry could conduct trials that duplicate the parameters of these two simulations, it would be interesting to see whether these simulation results translate to the foundry process.

Other studies could be performed using the Flow-3D software on different types of castings or on the original simulated castings while measuring air entrainment, porosity, and other parameters.

4. Proposed Changes to AAR M-201 Standard and Alternate Parameters

4.1 Proposed Changes

In the AAR M-201 standard, the maximum phosphorus and sulfur levels are 0.04 weight percent. On the basis of the chemical test results of the bolster samples, the suppliers were all well below these levels [9]. In early 2013, the chemical and mechanical testing results were given to the foundries; each supplier received all of the data, but the other suppliers were not identified. The A, B, C, D, E, F, and G designations were used. In August 2013, it was proposed to the AAR Coupling Systems and Truck Castings Committee (CSTCC) that the phosphorus and sulfur levels be reduced to 0.02 weight percent. The AAR CSTCC was also informed that further research may look at the effect of reducing residual elements.

4.2 Alternate Parameters

To test the effects of modified chemistry and heat treatments, two foundries were to use their standard chemistry, but heat treat the castings by normalizing and tempering. Another foundry would use the chemistry shown in Table 6 and would also heat treat the parts by normalizing and tempering.

If mechanical properties improved because of these alternate parameters, these changes could be proposed for the AAR M-201 standard. Section 8 gives results of the testing.

5. Nondestructive Testing (NDT) Methods for Truck Castings

5.1 Background

Nondestructive testing (NDT) consists of many methods to inspect truck casting components. These inspection methods show varying degrees of detection sensitivity. Some have been automated, whereas others can only be operated manually.

The primary goal of NDT is to reveal a defect without inflicting damage to the component. It can be accomplished by chemical, magnetic, electromagnetic or electromechanical means and is sometimes enhanced or controlled by computers.

5.2 Objectives

The objective of this research was to investigate the applicability of various NDT techniques for bolsters, side frames, and knuckles.

It was also important to determine what methods are most suitable for each environment, because a foundry might have different inspection constraints than a car shop or other railroad environment.

5.3 Methods

The following methods were evaluated: dry magnetic particle, wet fluorescent magnetic particle, liquid penetrant, alcohol wipe, visual, ultrasonic, ultrasonic phased array, and radiography.

All of the methods used in this survey have been widely used in the industry for many years.

The dry magnetic particle, wet magnetic particle, visual, and liquid penetrant testing were performed on 50 side frames and 50 bolsters at two repair facilities. Figure 19 shows a crack detected by magnetic particle testing.

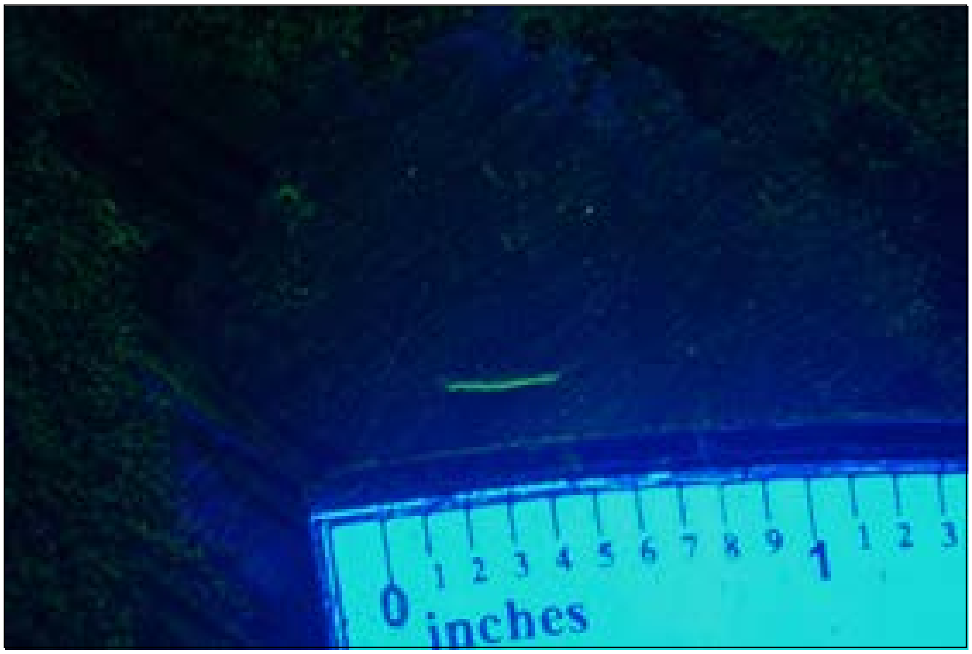

Figure 19. Crack Detected by Magnetic Particle Testing

TTCI performed ultrasonic, phased array ultrasonic, alcohol wipe, visual, and radiographic testing on five side frames and five bolsters at the Transportation Technology Center (TTC).

For the ultrasonic method, the rough surface finish of some of the critical areas prevented good coupling between the transducer and the inspection surface. This limitation also applied to the phased array ultrasonic method.

Two methods were used for radiography. In the first method, film was used. Computed radiography was used as the second method. Radiographic film is an older technology but is still widely used in industry.

In a separate test at TTC, seven bolsters and five side frames were gathered for radiographic testing. Each component was new from the foundry and had not been put into service.

General Electric provided and operated a CRx Flex scanner, which included the computer, the software, and imaging plates. Technicians from Intermountain Testing provided the iridium 192 source and ensured that radiography safety precautions were in place.

5.4 Results

Some of the testing methods were successful at detecting defects in all three types of castings, whereas some had limitations due to the geometries of the parts.

The dry magnetic particle method could inspect the side frame and knuckle in all critical areas. However, only the outside critical areas of the bolster could be inspected. The ribs inside the brake rod holes were not accessible.

The wet fluorescent magnetic particle, visible liquid penetrant, and alcohol wipe methods were able to inspect the side frame, knuckle, and bolster castings in all the critical areas [10].

All of the critical areas of the side frame, knuckle, and bolster castings could be inspected with the visual inspection method.

The ultrasonic inspection method could only partially inspect the critical areas of the side frame, knuckle, and bolster. The surfaces of the castings were very rough and did not provide good coupling between the transducer and the inspection surface. Successful inspection of the bolster using this method was limited to the transition radius from the diagonal tension member and the spring seat. Successful inspection of the side frame was limited to the side of the pedestal radius.

The ultrasonic phased array method could only partially inspect the critical areas of the bolster and the knuckle. It had the same limitations as the ultrasonic method concerning the surface finish of the castings. The bolster could only be successfully inspected in the same area as with the ultrasonic method.

Radiographic inspection was able to evaluate all of the critical areas of the bolster castings. TTCI had less success with side frames, because the shape of the part limited the placement of the imaging plate for critical areas [11]. Knuckles were not evaluated. Figure 20 shows a radiograph displaying casting defects in a bolster. This test showed that the time required to acquire a clear image of critical areas can be less than 25 minutes, even with thicker wall sections and double wall exposures. Computed radiography was very convenient, because of its quick development and reusability. However, many in the NDT industry maintain that traditional film should be used if the main goal is to find cracks.

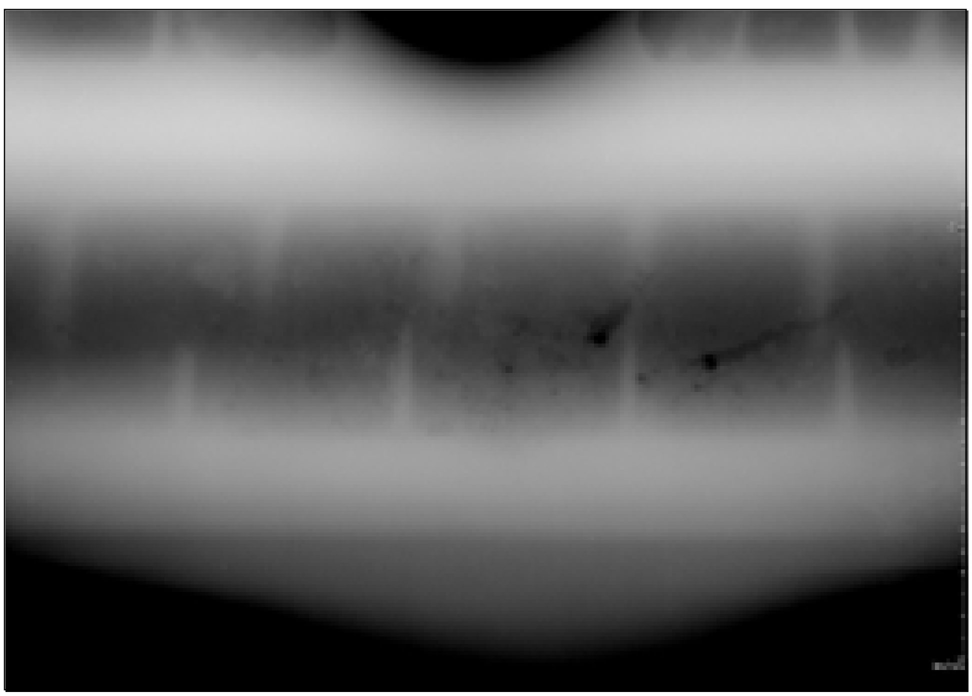

Figure 20. Defects in Bolster Shown by Radiography [11]

5.5 Conclusions

A variety of NDT methods can be utilized on side frames, bolsters, and knuckles to detect defects.

Due to the geometries of the parts, some methods have limited applications.

In car shops and railroad environments, bolsters are best examined by a combination of dry magnetic particle and liquid penetrant techniques. Side frames and pulling faces of knuckles should be examined by dry magnetic particle methods.

In manufacturing environments such as foundries, wet fluorescent magnetic particle testing is recommended for inspection of bolsters, side frames, and knuckles. Radiography can be used for critical areas of bolsters, but it is difficult to position the imaging plate to capture critical areas of side frames.

6. Industry Survey to Determine Reasons for Removal from Service

6.1 Background and Objectives

Industry perception is that most side frame and bolster failures can be attributed to fatigue or brittle fracture. These conditions can result from poor welding, heat treatment, or casting process control.

To determine if fatigue and brittle fractures are the main contributing causes of side frame and bolster failure, the AAR CSTCC proposed a survey. TTCI personnel would conduct the survey by gathering scrapped side frame and bolster casting data from three to five car shops or repair facilities. This survey would be quantitative and as much casting information as possible would be recorded to create the foundation for a database.

Additional information such as manufacturer, production date, design, and type of service could also be recorded in the database. More data could be added in the future.

The data provided an accurate representation of the causes for which these components are removed from service.

6.2 Methods

Parts from four shops were examined for this survey: Havelock in Lincoln, NE; Norfolk Southern's shop in Decatur, IL; Comet Industries in Kansas City, MO; and Union Pacific's car shop in De Soto, MO.

The defective parts at each shop were, at a minimum, inspected visually. The defects and their locations were then recorded on a defect sheet. It was noted that some of the parts exhibited multiple defects. Photographs were taken of all specific defect types.

Approximately 70 bolsters and 55 side frames were examined for this survey. In a few cases, multiple defects occurred on one casting.

6.3 Results

For the bolsters, 12 specific defects were recorded during the survey; 9 defects were found on the side frames. Figure 21 shows the top six occurring defects for bolsters, which accounted for 83 percent of the total bolsters examined during this survey [9].

The majority of the bolster defects were cracked pockets and worn pockets. Old castings, rail burns, cracked webs, and cracked bowls were the other leading defect causes in bolsters.

The remaining causes of scrapped bolsters were bowls not machined correctly, oversize pinholes, gouges around bowls, worn bowls, cracked liners, and bent castings.

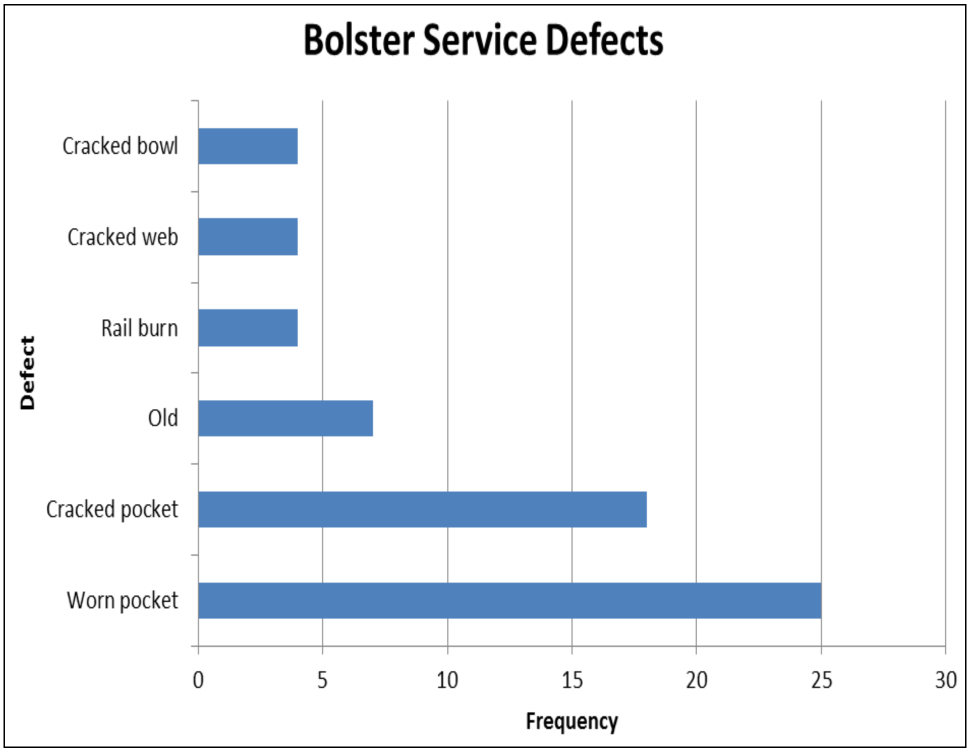

Figure 21. Common Bolster Defects Seen during Survey [9]

Figure 22 shows the top six side frame defects, which represent 93 percent of the defective side frames examined.

The side frames had cracked pedestal jaws and bent pedestals that accounted for almost 40 percent of the defects. The pedestal jaws usually experience the highest loads during service.

Worn columns were also a significant problem, occurring in 19 percent of the side frames. Rail burns, old castings, and cracked spring seats completed the top six defects in side frames.

The remaining defects were cracks below the wear plate, bent spring seats, and cracks on lightening holes.

Some components were probably scrapped in the field instead of being sent back to car shops or repair facilities, which may have skewed the results of the survey.

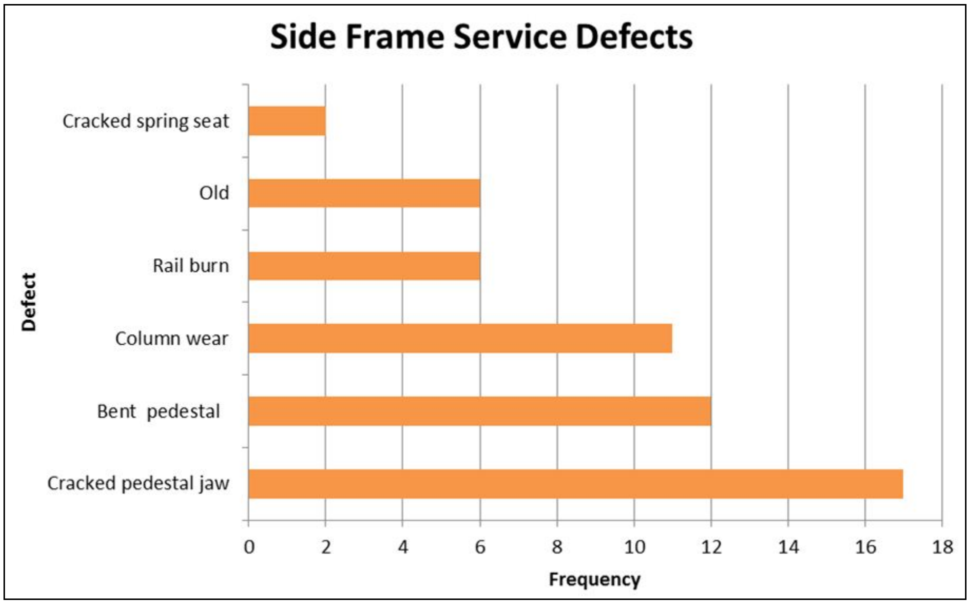

Figure 22. Common Side Frame Defects Seen during Survey [9]

6.4 Conclusions

The pedestal jaw is a critical area for side frames. During the survey, defects in this area caused nearly 40 percent of removals from service. Reducing the stress on the pedestal jaw and/or modifying its design might extend the service life of the components.

Cracked or worn pockets were the main cause of bolsters being removed from service, at least in this survey. Additional surveys can provide more information about service life and reasons for removal.

7. Finite Element Analysis (FEA) for Reduction of Maximum Stress

7.1 Objective and Background

Finite element analysis (FEA) was used to determine the location and magnitude of maximum stress in a side frame. The maximum stress in the component was reduced by using iterative design change and analysis, which should lead to longer service life.

7.2 Method

To compute the stresses, a solid model of a Barber S-2-HD side frame was used. An unmodified model was used as a baseline for the stress calculation. The stiffness of vertical supports was designed to allow approximately the same vertical deflection at the center of the casting as shown in Table 4.3 of the AAR M-203 standard [12], which is 0.051 inch (1.30 mm). Due to meshing difficulties, a symmetrical model using one half of the side frame was used, as Figure 23 shows. The critical areas examined were the pedestal jaw and the tension member hole. The tension member hole allows access to some internal parts of the casting for removal of sand and can be an escape path for core gases.

To produce the most realistic analysis, a combination of vertical and lateral loading was used. The vertical load was 164,000 pounds, and a transverse load of 21,300 pounds was used at the side frame-to-bolster interface.

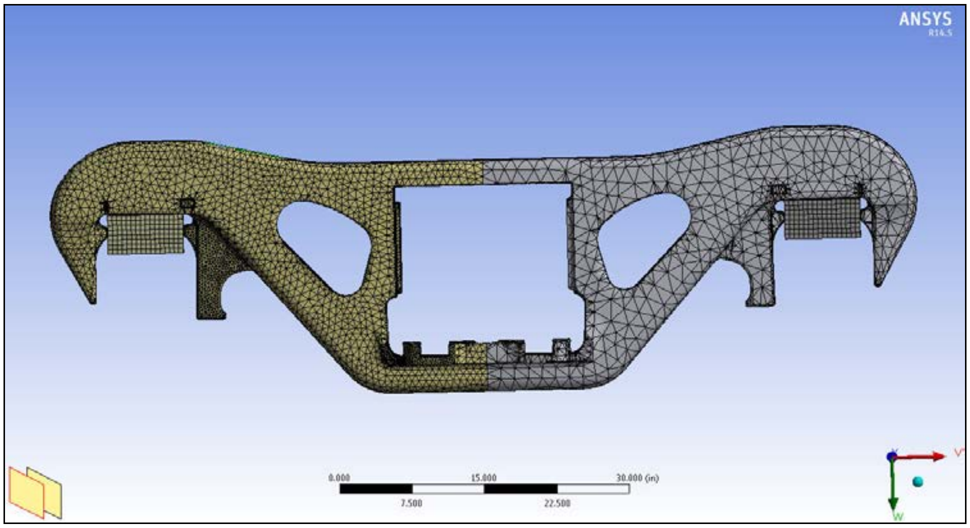

Figure 23. Symmetrical Mesh Used for the Stress Analysis

7.3 Results

After the baseline was computed, design changes were introduced. The pedestal jaw radius was increased by almost 90 percent, and the wall thickness of the tension member was increased by about 30 percent.

Table 5 shows the maximum principal stresses at the two areas before and after modification. Figures 24 and 25 are stress maps of these two areas under load.

Table 5. Stresses after Design Change

Load	Bearing Support Radius	Percent Decrease	Tension Member Hole	Percent Decrease
Original Configuration				
Vertical Load Only	37,230		22,060	
Vertical + Lateral Load	41,200		34,850	
Modified Casting				
Vertical Load Only	35,570	4.5	19,550	11.4
Vertical + Lateral Load	39,020	5.3	31,600	9.3

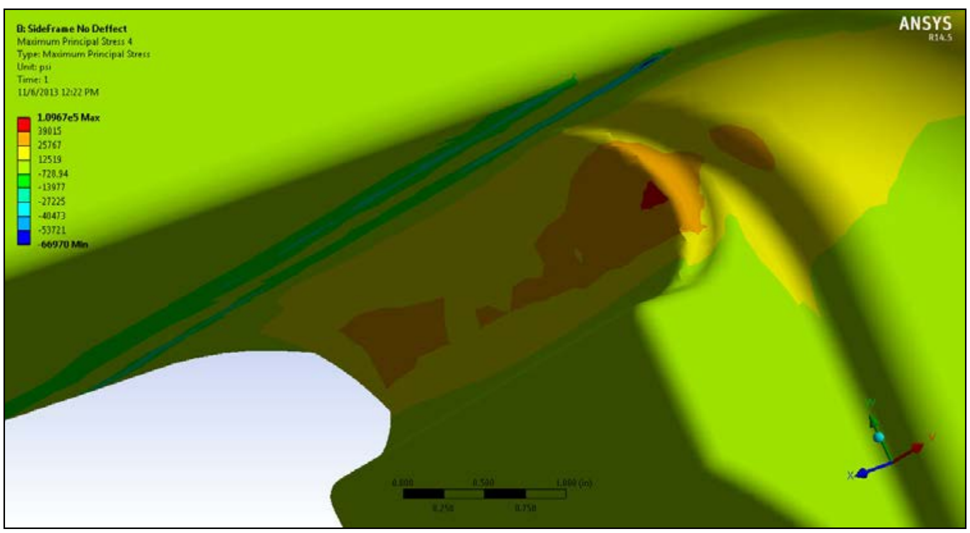

Figure 24. Stress Map of Pedestal Radius after Modification

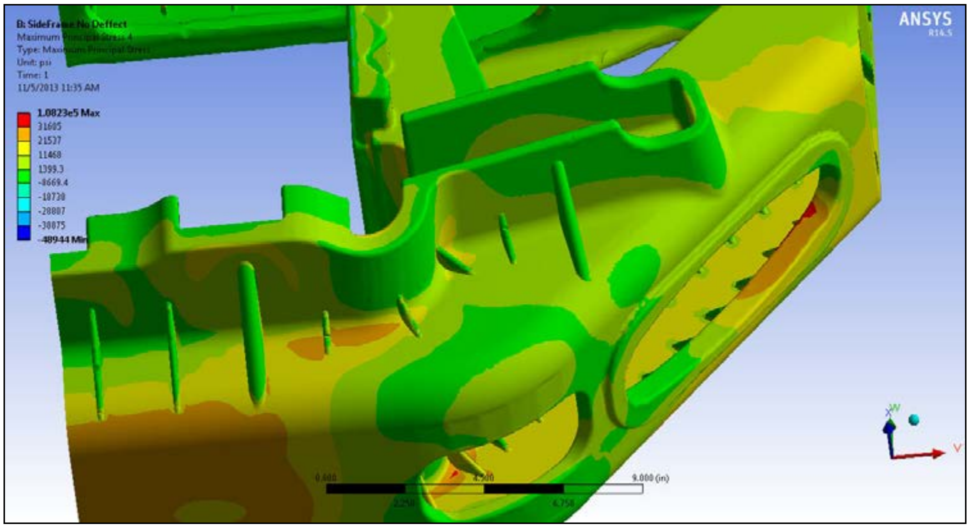

Figure 25. Stress Map of Tension Member Hole after Modification

7.4 Conclusions

Modest stress decreases were accomplished by lengthening the pedestal radius (5.3 percent) and thickening the wall of the tension member (9.3 percent). Though these decreases were less than the goal of 20 percent, this could still make significant improvements to the service life of side frames. It is not known whether any manufacturers have ever made these changes before. Any design changes would need to be evaluated for fit with other components and potential cost changes. Discussion and cooperation with manufacturers could yield more results.

8. Mechanical Testing of Bolsters Manufactured to Alternate Parameters

8.1 Alternate Parameters

To maximize the potential mechanical properties of bolsters without changing proprietary molding or pouring processes, TTCI decided to obtain and test a small number of bolsters that would be produced with a modified chemistry and/or heat treatments. Table 6 shows the alternate chemistry.

Table 6. Alternate Chemistry

	Weight Percent	
Element	**Existing**	**Alternate**
Carbon, C	0.32 maximum	No change
Manganese, Mn	0.90 maximum	No change
Silicon, Si	1.50 maximum	No change
Phosphorus, P	0.04 maximum	0.02 maximum
Sulfur, S	0.04 maximum	0.02 maximum
Copper, Cu	---	0.15 maximum
Antimony, Sb	---	0.004 maximum
Molybdenum, Mo	---	0.05–0.15

The alternate heat treatment was normalizing and tempering, complying with the AAR M-201 standard requirements for each step. Currently, the tempering step has been optional.

Foundries B, C, and E were selected for the testing with alternate parameters. Foundries B and C used their normal process chemistry, but received the alternate heat treatment. Foundry E used both the alternate chemistry and the alternate heat treatment, as Table 7 shows.

Table 7. Parameters for the Second Set of Mechanical Tests

Foundry	Parameters for Second Set of Mechanical Tests
B	Standard chemistry, normalizing and tempering
C	Standard chemistry, normalizing and tempering
E	Alternate chemistry, normalizing and tempering

Three bolsters from each supplier were tested, though it was not required that the all parts were cast from the same heat. Eighteen Charpy samples were tested from each bolster, and a smaller temperature range was used, because the previous testing showed small foundry-to-foundry variations at low temperatures. Three samples for each bolster were tested at -20 °F (-29 °C), 0

°F (-18 °C), 20 °F (-7 °C), 40 °F (4 °C), 60 °F (16 °C), and 70 °F (21 °C). Fourteen room temperature tensile tests were conducted for each bolster, the same as in the first set of tests.

8.2 Charpy Impact Test Results

In the graphs below, the ‘i’ or ‘init’ designation stands for initial and ‘m’ or ‘mod’ stands for modified. Figure 26 compares the average impact energy for each foundry for both initial and modified processes. Figures 27–35 plot the values for the individual foundries.

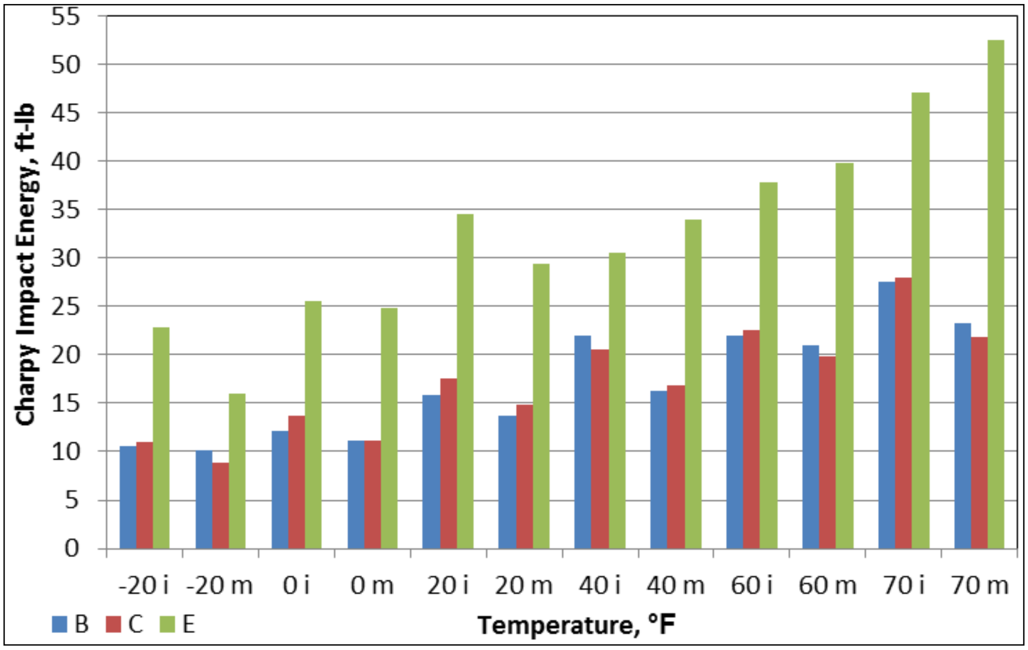

Figure 26. Comparison of Average Charpy Impact Values for Foundries B, C, and E

The modified bolsters from Foundries B and C did not show an improvement of the average energy; at each test temperature, the average impact energy values decreased. Foundry E showed improvement at 40 °F and above. More detailed analysis occurs in the following sections.

The remaining graphs plot for each foundry, in order, the impact energies and the standard deviations. The final graph for each foundry is a box and whisker plot showing mean, median, and range of the results.

8.2.1 Foundry B Charpy Impact Results

Figures 27–29 show different representations of the Charpy impact test results for both sets of Foundry B tests. Samples tested at 75 °F (24 °C) in the initial round were tested at 70 °F (21 °C) during the second round of testing. Though there was little, if any, statistical difference in the impact energies, the mean impact energies decreased for the modified samples. This was not expected. However, the ranges and standard deviations showed definite decreases.

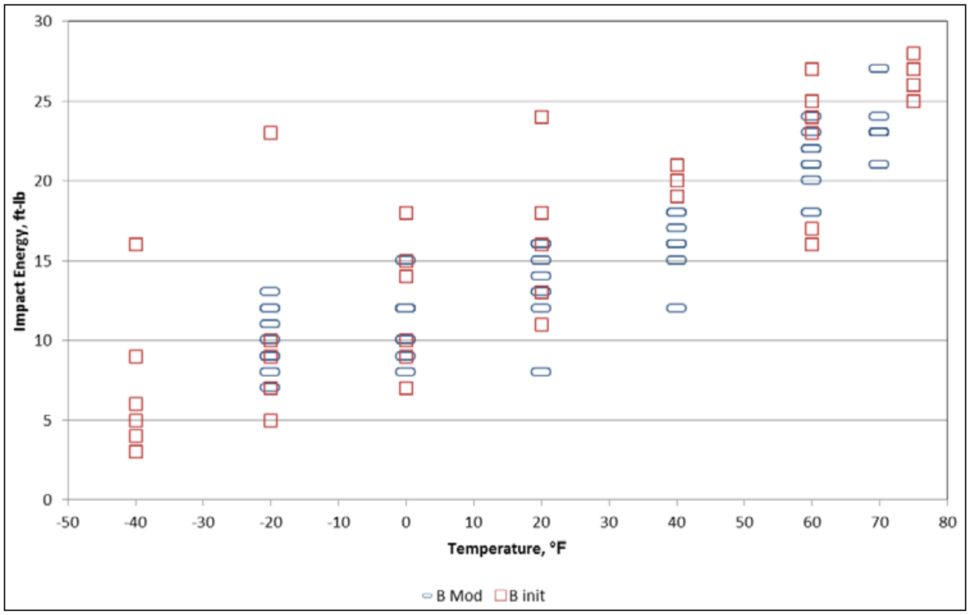

Figure 27. Charpy Impact Test Results from Standard and Alternate Parameters for Foundry B

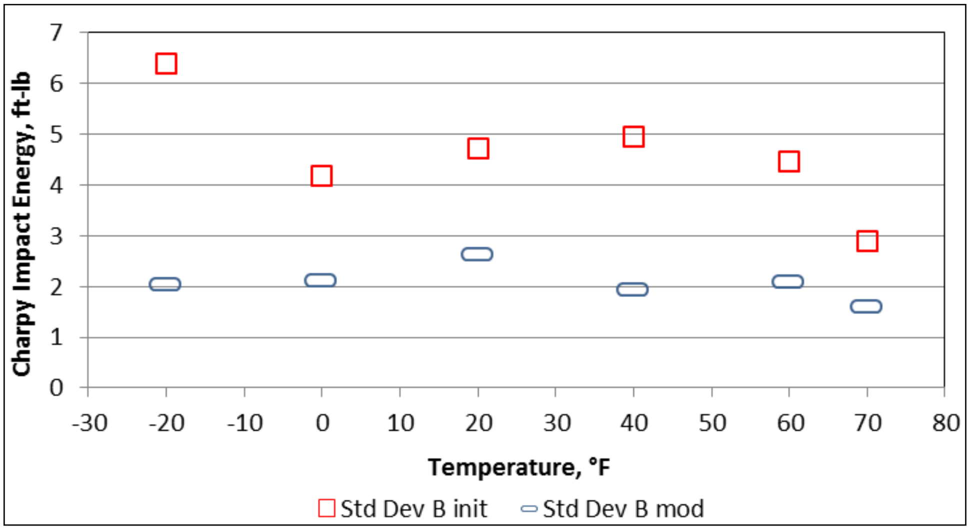

Figure 28. Standard Deviation of Foundry B Charpy Impact Samples

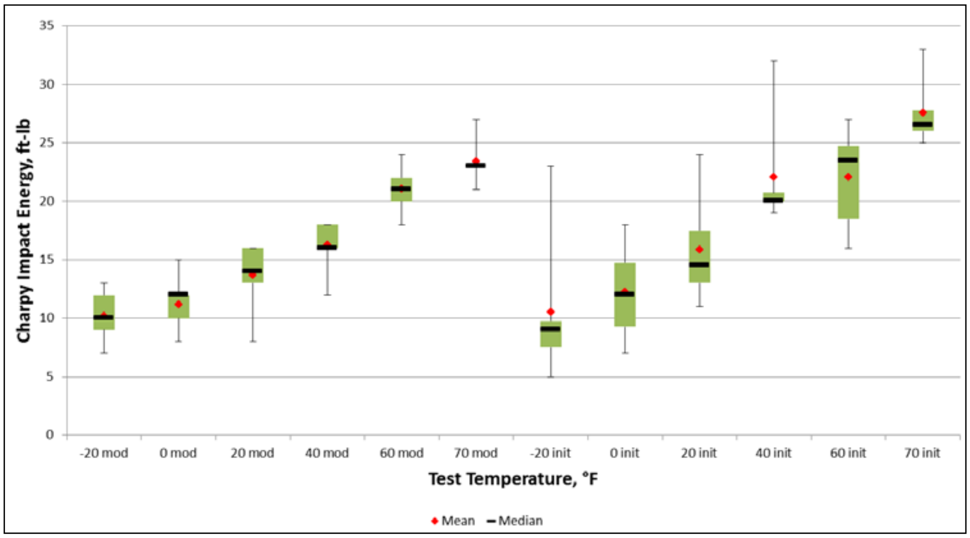

Figure 29. Box and Whisker Plot of Foundry B Charpy Results

8.2.2 Foundry C Charpy Impact Results

Figures 30–32 show different representations of the Charpy impact test results for both sets of Foundry C tests. Samples tested at 75 °F (24 °C) in the initial round were tested at 70 °F (21 °C) during the second round of testing. As with the results from Foundry B, there was little statistical difference in the impact energies; again, the mean impact energies decreased for the modified samples. The ranges and standard deviations decreased as most test temperatures decreased.

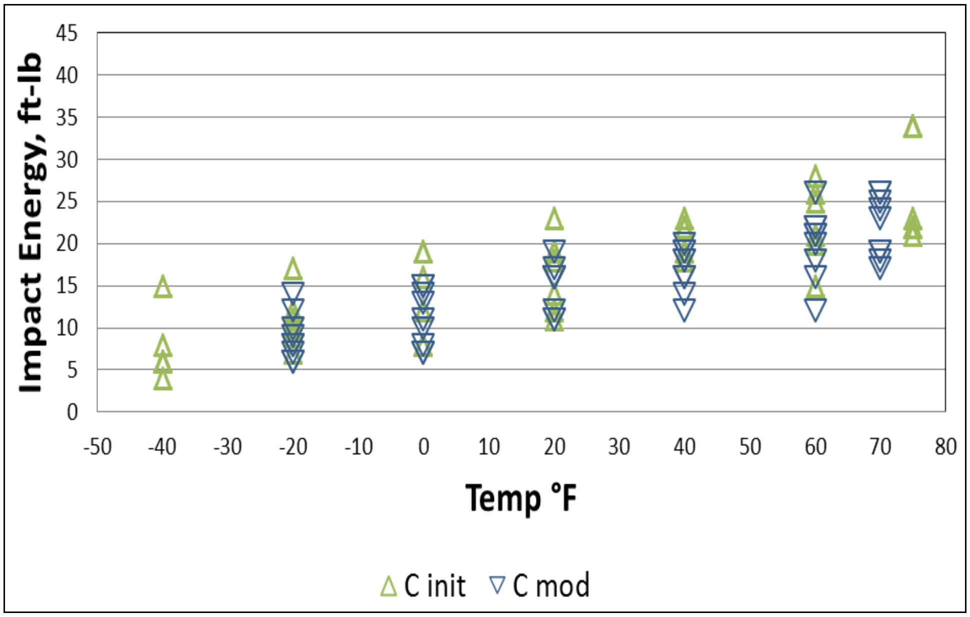

Figure 30. Charpy Impact Test Results from Standard and Alternate Parameters for Foundry C

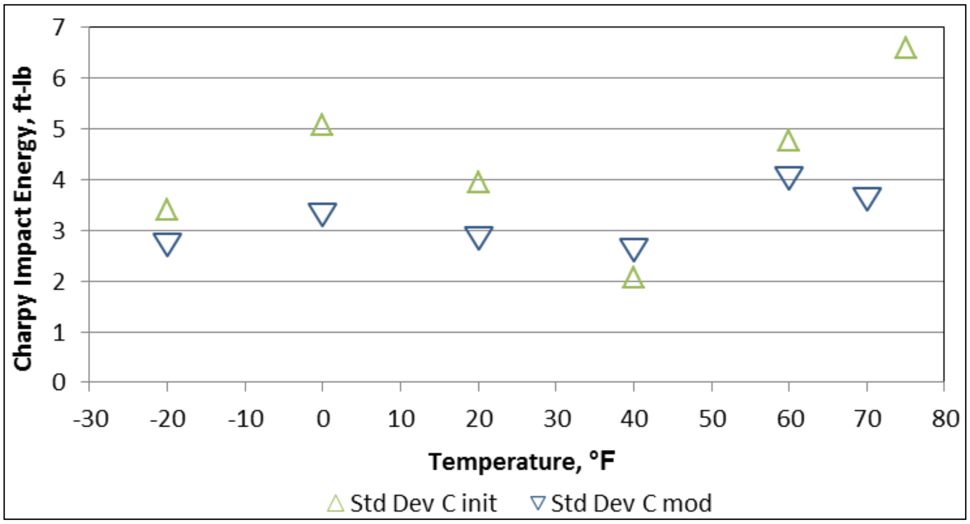

Figure 31. Standard Deviation of Foundry C Charpy Impact Samples

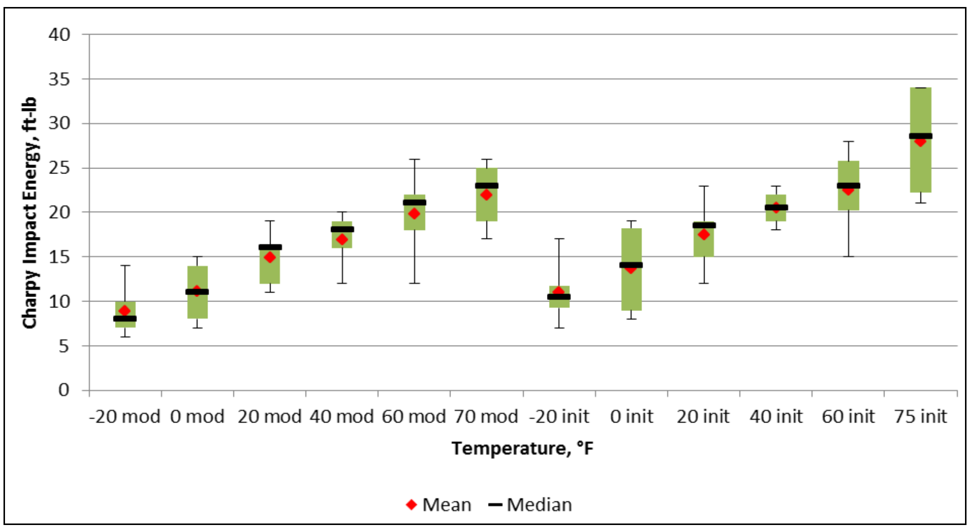

Figure 32. Box and Whisker Plot of Foundry C Charpy Results

8.2.3 Foundry E Charpy Impact Results

Figures 33–35 show different representations of the Charpy impact test results for both sets of Foundry E tests. There was no statistical difference in the impact energies; at 40 °F (4 °C) and above, the mean impact energies increased for the modified samples. The mean energies for both the initial tests were much higher than those of Foundries B and C. The standard deviations decreased for most test temperatures, but were higher than Foundries B and C. There was an overall range decrease for the modified samples.

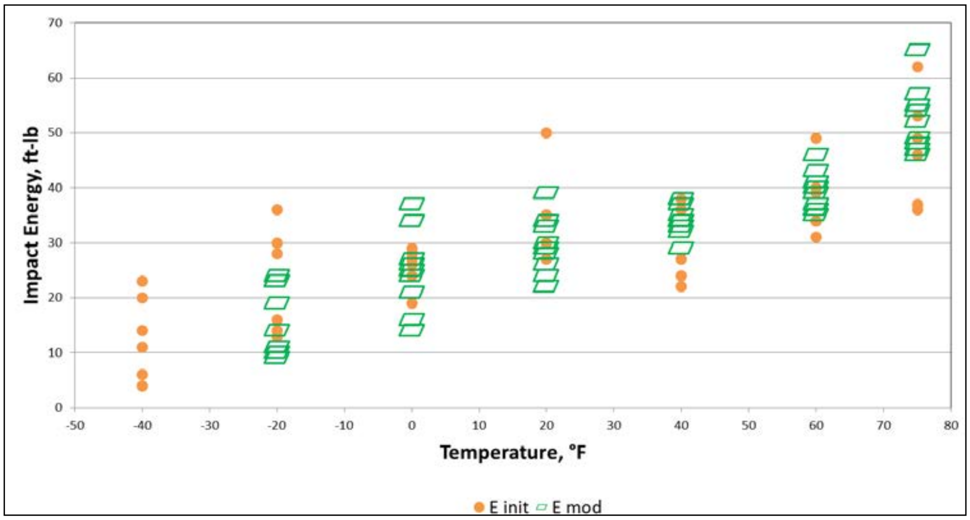

Figure 33. Charpy Impact Test Results from Standard and Alternate Parameters for Foundry E

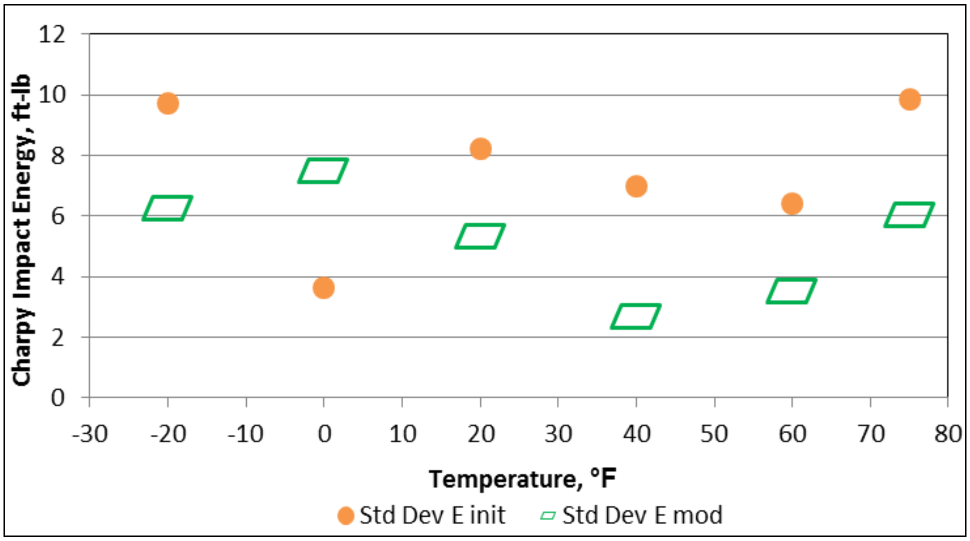

Figure 34. Standard Deviation of Foundry E Charpy Impact Samples

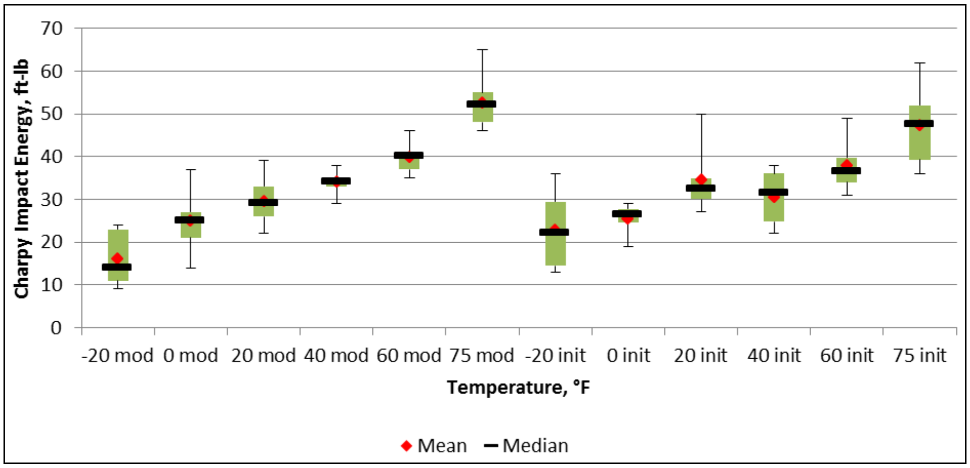

Figure 35. Box and Whisker Plot of Foundry E Charpy Results

8.3 Tensile Test Results

The second round of tensile testing for Foundries B, C, and E were performed at room temperature, as were the first sets. Between 39 and 42 specimens were tested for each supplier.

The mean values of tensile strength and yield strength showed small to moderate variations. Though there were some individual values below the requirements of AAR M-201 standard, the mean of all three foundries in both sets of tests were above the required values.

Figure 36 shows the elongation and reduction of area values for the three foundries; both of these properties are measures of ductility. All of the foundries had mean elongation values below the required 24 percent, though some were well above this. Two suppliers had reduction of area values above the required 36 percent for the initial set of tests. For the second set of tests, the mean value for all foundries was below the requirement. The results for each supplier are detailed in the following sections. In Figure 36, the “init” designation stands for initial and or “mod” stands for modified.

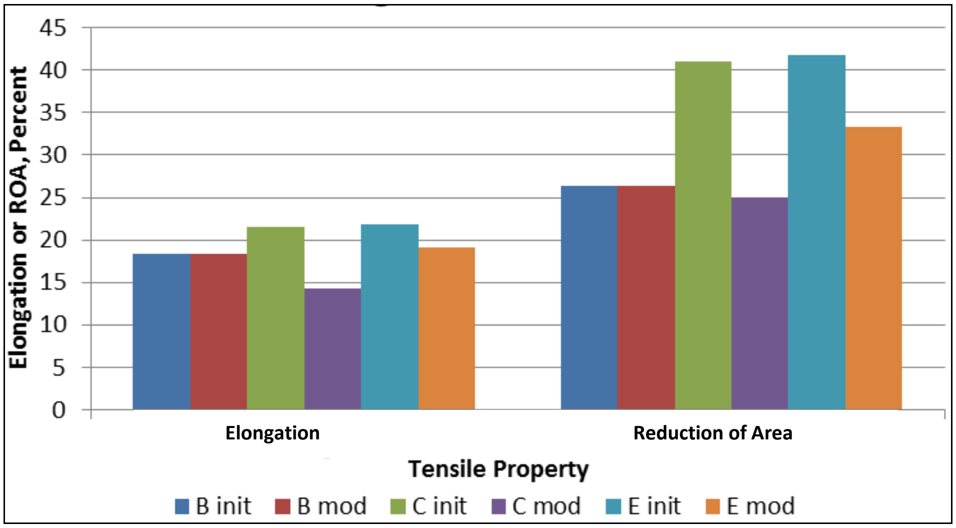

Figure 36. Mean Elongation and Reduction of Area Changes for Foundries B, C, and E

8.3.1 Foundry B Tensile Test Results

As Table 8 shows, the average values for elongation and reduction of area increased slightly with the alternate parameters, but the number of samples not passing elongation and reduction of area requirements increased from 27 to 32. The average values for tensile and yield strengths also decreased.

Table 8. Tensile Test Results for Original Testing from Foundry B

		Tensile Strength	Yield Strength	Elongation	Reduction of Area
Mean	B initial	81.7	46.7	17.2	25.7
	B modified	77.4	42.0	18.3	26.4
	Change	-5.3%	-10.0%	6.0%	2.6%
Standard Deviation	B initial	2.66	1.25	4.58	8.16
	B modified	6.47	2.09	6.39	10.48
Range	B initial	15.7	5.3	20	39
	B modified	33.3	13.5	23.0	44.5

8.3.2 Foundry C Tensile Test Results

Table 9 shows the tensile results for the original tests and for the alternate parameter test.

Tensile and yield strengths increased, but elongation and reduction of area values fell drastically. The number of samples not passing elongation and reduction of area requirements decreased from 36 to 12.

Table 9. Tensile Test Results for Alternate Parameters from Foundry C

		Tensile Strength	Yield Strength	Elongation	Reduction of Area
Mean	C initial	80.1	49.5	21.6	41.1
	C modified	84.5	55.7	14.3	25.0
	Change	5.4%	12.4%	-50.7%	-39.1%
Standard Deviation	C initial	5.52	2.59	7.12	14.35
	C modified	6.27	2.01	4.90	8.82
Range	C initial	29.5	10.4	29	52
	C modified	27.2	8.3	21	35

8.3.3 Foundry E Tensile Test Results

Table 10 shows the tensile results for the original tests and for the alternate parameter test.

Table 10. Tensile Test Results for Alternate Parameters from Foundry E

		Tensile Strength	Yield Strength	Elongation	Reduction of Area
Mean	E initial	81.7	48.1	21.9	41.8
	E modified	77.3	45.7	19.1	33.4
	Change	-5.4%	-5.0%	-14.7%	-20.2%
Standard. Deviation	E initial	6.53	1.82	7.76	15.50
	E modified	6.17	2.18	6.67	14.39
Range	E initial	30.7	10.1	27	50
	E modified	36.3	10.0	24	49

8.4 Conclusions

Neither the additional tempering nor the chemistry changes resulted in the expected improvement in the mechanical properties of castings. The standard deviation of Charpy impact energies for most, but not all, samples decreased for the tempered castings, but did not lead to an increase in the impact values themselves. As in the first set of tests, Foundry E was visibly and statistically higher than Foundries B and C.

The tensile properties of the modified castings showed varied results, but most values decreased. Each supplier experienced at least two decreased tensile properties. The most significant decreases occurred in elongation and reduction of area values. Optical microscopy revealed very rough fracture surfaces, and metallographic analysis showed that large amounts of porosity were still present.

Because these parameters did not improve the castings' mechanical properties, other parameters should be investigated. These are discussed in Section 9.7.

9. Conclusions

9.1 State of Quality of Grade B+ Steel

Grade B+ steel is an unalloyed, medium carbon steel. The required tensile and Charpy impact testing give it adequate strength and basic toughness for truck castings; however, there is always room for improvement.

It is not a requirement for every sample taken from the casting to meet the mechanical property values specified in AAR M-201. The intent is for a solid sample (one with little or no porosity) to meet those values, and solid samples are not always readily available in castings. Nonetheless, the elongation and reduction of area measurements were the most difficult to achieve consistently. Optical examination of fracture surfaces of poorly performing tensile specimens showed very rough areas and porosity.

Charpy impact testing was performed on bolster samples over a range of temperatures. Under AAR M-201, the Charpy samples are required to absorb a minimum of 15 ft-lb (20 N-m) at 20 °F (-7 °C). Even though the specification does not require it, the average energy of samples from most foundries exceeded this. There was a large spread in results for many of the foundries and between the foundries. SEM analysis of fracture surfaces of low energy Charpy samples showed shrinkage porosity, gas porosity, and inclusions. These defects can greatly decrease mechanical properties.

Chemistry testing of the samples revealed that all samples complied with the requirements of AAR M-201. Some of the suppliers had relatively small amounts of some residual elements, either as intentional additions for mechanical properties or elements in scrap metal.

Metallographic analysis revealed a ferritic microstructure on the 14 samples evaluated. These samples involved all seven foundries with varying mechanical properties. All samples contained porosity; many, even ones with high mechanical properties, contained large amounts of porosity. Reducing the amount of porosity would substantially increase toughness of the material.

9.2 Alternate Casting Methods

Flow-3D was employed to examine possible casting process changes that could be used in most foundries. This study looked at tilting the mold by up to 20 degrees, as well as tilting the sprue by up to 20 degrees. A matrix of nine simulations was tested and the distribution of particles, representing sand grains, was used as the output. The simulations revealed that the fewest particles in the critical area occurred at a sprue angle of 10 degrees when the mold was tilted to either 0 degrees or 20 degrees.

9.3 Changes to AAR M-201 Standard

After careful analysis of the mechanical test results and chemistry results from seven different foundries, a reduction of the maximum phosphorus and sulfur levels was proposed to the AAR CSTCC. Alternate parameters, such as maximum limits on some residual elements and modified heat treatment are possible future changes to the AAR M-201 standard.

9.4 Nondestructive Testing (NDT)

Manufacturers and repair shops use NDT to find defects before they can cause component failure. Multiple methods are employed, but most do not rely on a single method. Dry magnetic particle testing is the most widely used method in car repair shops to detect surface defects, particularly for side frames and pulling faces of knuckles. Also, repair shops use dry magnetic particle testing and liquid penetrant methods for NDT of bolsters. Manufacturers use wet fluorescent magnetic particle testing for NDT of bolsters, side frames, and knuckles. Radiography is used to find porosity and other defects within castings. Film radiography is preferred over computed radiography for the detection of cracks. Radiography has the capability to be the sole method for the complete NDT of bolsters, but it is not preferred for testing side frames, because it is difficult to position the imaging plate for side frame critical areas.

9.5 Industry Survey of Reasons for Removal from Service

The survey of four manufacturers and repair shops assessed reasons why side frames and bolsters were removed from service. In bolsters, cracked or worn pockets were the leading reasons these components were taken out of service. For side frames, cracked pedestal jaws or bent pedestals were the leading reasons. Additional surveys will add to this initial database.

9.6 Improved Designs

FEA was used to determine the location and magnitude of the maximum stress in a generic side frame. The two highest stress areas were the pedestal jaw radius and the tension member hole. By enlarging this radius and increasing the wall thickness around the tension member hole, modest reductions in the maximum stress levels were achieved. Even a small reduction in stress could increase the service life of a side frame. By working closely with manufacturers, larger reductions could be achieved.

9.7 Mechanical Testing of Bolsters Produced to Alternate Parameters

Based on the first round of mechanical and chemistry testing, three of the seven original suppliers were selected for a second round of testing. The same test plan was used: three bolsters were obtained from each supplier, and tensile test and Charpy impact samples were cut from each. Bolsters from Foundries B and C were poured to standard chemistry, but a tempering step was added to the heat treatment. Foundry E poured to the modified chemistry and also tempered the castings after normalizing.

The average impact energies for Foundry B and Foundry C decreased; the energies for Foundry E increased at 40 °F (4 °C) and above. There was little, if any, statistical difference between the first and second sets of Charpy results, but the standard deviation and range of values decreased in general.

The tensile test results were also mixed. Among the average tensile and yield strengths that decreased, they were still above the AAR M-201 standard requirements. The elongation and reduction of area showed slight improvement for Foundry B, but drastic decreases for Foundries C and E. The average elongations for B, C, and E were below the AAR M-201 standard limit for both rounds of testing. For reduction of area, only the initial tensile tests of C and E had values above the 36 percent minimum. The standard deviations for the second round of tensile testing were also mixed.

The additional step of tempering during heat treatment did not appear to increase mechanical properties. The slight chemistry modification for Foundry E also did not cause much difference in the results. These two sets of testing only looked at brief snapshots that were 2 to 3 years apart, not long-term trends. The differences could be due to natural variations.

Because the parameters used did not improve the material properties, investigation should continue to determine what parameters would improve the mechanical properties. Additional areas for investigation are the following:

1. Add nickel as an alloying element. A nickel addition will increase toughness, without compromising strength. An estimated 1–2 percent nickel addition should significantly increase toughness, especially at lower temperatures. Because of the higher cost, nickel-alloyed steel components may only be feasible for low temperature service.
2. Verify computer simulation results with foundry trials. Based on the simulations described in Section 3, several combinations of mold tilt and sprue tilt showed fewer particles in critical areas compared to the standard untilted configuration. Collaborate with one or more suppliers to reproduce simulation results, and then improve casting quality by simulating further improvements and verifying the results in the foundry. Based on the optical microscopy performed in this research, reducing shrinkage porosity and gas porosity would improve casting quality.

Many process changes and requirements can be considered, and most would increase production cost. They would only be feasible if they provided increased service life and the industry could support increased component cost.

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Abbreviations and Acronyms

AAR	Association of American Railroads
CSTCC	Coupling Systems and Truck Castings Committee
FEA	finite element analysis
NDT	nondestructive testing
OES	optical emission spectroscopy
SEM	scanning electron microscope
TTCI	Transportation Technology Center, Inc.