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Fracture Surface Analysis of Grade B+ Material over a Range of Temperatures

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Summary

In an effort to improve the safety, quality, and performance of Grade B+ bolsters and side frames, Transportation Technology Center, Inc. (TTCI) under the direction of the Federal Railroad Administration and the Association of American Railroads (AAR) began a joint research program to reduce the number of castings failures occurring in service. To assist with this effort, TTCI has performed tests and analyses to improve the life of Grade B+ castings. This *Technology Digest* is an intermediate report summarizing the analysis of the fracture surface of Charpy samples using scanning electron microscopy. Future reports will include the results of the remaining mechanical testing.

Eleven Charpy samples were selected to study the fracture surface for porosity, chemical inclusions, and failure mode. All samples analyzed exhibited significant levels of porosity (as large as 0.098 in. (2.5 mm) in some cases), chemical inclusions, and low resistance to impact at lower temperatures. It is unclear if chemical inclusions or the regions of dense porosity are more detrimental to the fracture toughness of the material, but the results of the analysis indicated that any discontinuity in the structure will negatively impact the performance of the material.

Results of the fracture surface analysis, in combination with mechanical test results, will be used to propose improved standards to the AAR's Coupling Systems and Truck Castings Committee. The results from this analysis show that temperature effects should be considered in material specifications for castings because of the influence of temperature changes on the fracture surface of the material. Results also indicate that chemical composition improvements and casting mold redesign have the potential to reduce the inclusion density and improve the overall performance of Grade B+ castings. Both of these areas are likely to be included in the proposed modifications to current specifications.

Future work under consideration is an analysis of the fracture surface of Grade B+ castings that have failed in service over a range of temperatures. This analysis has the potential to confirm the relationship between brittle failures and colder temperatures.



INTRODUCTION

This digest is an intermediate report on the testing and results of an effort to improve the life of Grade B+ castings. The results of Charpy and scanning electron microscopy are discussed. Future digests will be completed to report the results of other tests currently being completed.

BACKGROUND

Between 2000 and 2008, the AAR car repair billing database showed an average of 1,700 bolsters and side frames removed from service per year due to either initial cracking or critical failure, which accounted for over \$2.6 million per year loss in revenue.

This information prompted the Federal Railroad Administration (FRA) and the AAR to do a comprehensive survey of the major railroad casting manufacturers around the world. Similar data has not been collected in approximately 30 years.

To gather the appropriate information, TTCI developed a program that focuses on three main areas to improve the performance of Grade B+ castings:

1. Increase component life
2. Inspection and defect detection
3. Interchangeability and dimensional tolerances

Each one of these areas encompasses many aspects of the design and quality of cast components. Other available Technology Digests summarize the activities and test results relating to component life and inspection and defect detection.^{1,2}

Data from this ongoing survey will be used to make recommendations to the AAR’s Coupling Systems and Truck Castings Committee in an effort to improve quality and performance standards of current Grade B+ by updating Grade B+ material performance specifications.

The M-201 specifications include optional Charpy testing where the bolster coupon, which is prepared from a keel block, must have a fracture toughness value at or above 15 ft-lbs when tested at 20°F.³ To test the completeness of this standard, TTCI directed Charpy testing of 252 samples to determine the susceptibility of Grade B+ castings to brittle failure over a range of temperatures, using fracture toughness to measure the materials resistance to brittle fracture.

Charpy Test Objectives and Procedures

Brittle failures can be attributed to marginal strength and poor impact resistance of cast steel materials. This failure mode is problematic because it occurs instantaneously and under stresses that can be below the yield strength of the material. Charpy mechanical testing is a relatively inexpensive test that provides useful information about material performance as a function of temperature and amount of entrained defects in the cast structure.

Test samples were collected from the foundries of several major manufacturers of bolsters and side frames. All test

samples were removed from critical stress areas of the bolster to determine the brittle characteristics of the casting in areas susceptible to brittle failures.⁴ Figure 1 shows the locations where the Charpy samples were extracted.

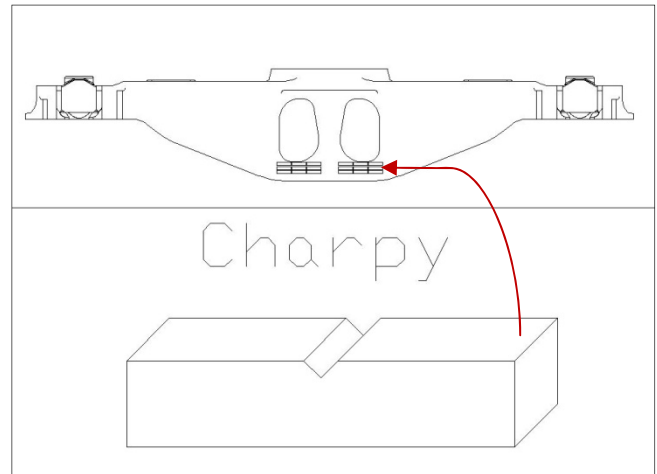


Figure 1. Charpy Sample Location

Fourteen samples were extracted from each foundry’s casting to ensure repeatability of the results. Two test samples were used at each temperature. Test temperatures ranged from -40°F to approximately 75°F. All tests were conducted under the ASTM A370 test specification using test procedures ASTM E23.^{5,6}

Figure 2 shows the energy absorption of the Charpy samples over the range of temperatures tested. A linear fit was used to show the general trend of the samples. In general, the trend line tends to follow the median of each temperature grouping and shows a positive correlation. Results from this portion of the analysis show that the test temperature has a significant influence on the energy absorption of the test samples and Grade B+ material.

These test results suggest that bolster performance could be reduced in colder temperatures.

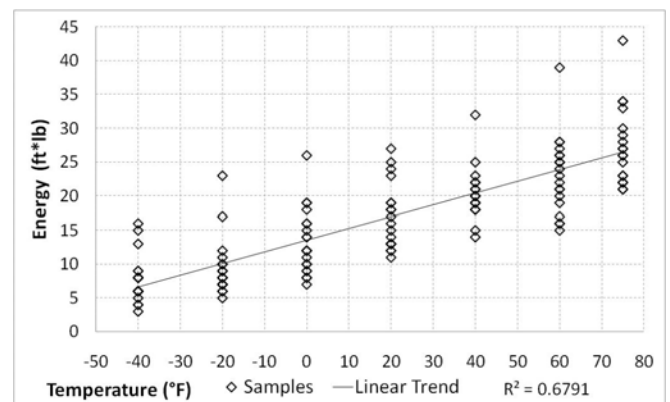


Figure 2. Energy Absorption of Samples at Various Temperatures

**Scanning Electron Microscopy
Analysis Description**

A scanning electron microscopy (SEM) analysis was conducted on 11 Charpy samples to:

- Characterize fracture surfaces of the Charpy samples
- Determine the effect of temperature on the mode of failure
- Document similarities and/or differences between various foundry steels
- Determine if discontinuities on the fracture surface influenced Charpy results (e.g., entrained gas bubbles, shrink porosity, oxide films)

The SEM analysis was conducted under the guidance and funding of the AAR’s Strategic Research Initiatives Program using test samples from the mechanical testing funded by the FRA.

Fracture Surface of Charpy Samples

Because of the nature of the test and samples, both ductile shear and brittle cleavage were exhibited in the samples tested. Ductile behavior is desired to increase energy absorption in the material and increase the material toughness.

At the specified temperature range, presence of both shear and cleavage fractures can be expected.⁷ An example of differences in fracture surface can be seen in three of the samples tested at different temperatures (Figure 3) and on a microscopic scale in Figure 4.



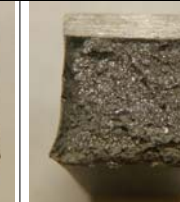
Brittle	Ductile and Brittle	Ductile
		
Energy = 15 ft*lb	Energy = 18 ft*lb	Energy = 32 ft*lb
% Shear = 0	% Shear = 10	% Shear = 20
T = -40 °F	T = 0 °F	T = 40 °F

Figure 3. Ductile and Brittle Nature of Charpy Samples

A ductile fracture surface, shown in Figure 4, is characterized by a cup-and-cone fracture surface. This fracture method accommodates greater plastic deformation and therefore greater energy absorption. Conversely, the brittle fracture zone shows a cleavage fracture surface and is accompanied by very little deformation and little energy absorption.

Ductile fracture occurred on the edges of the sample, evenly distributed around the sample perimeter. Ductile behavior was more common in the samples tested at higher temperatures. At lower temperatures, the fracture surface showed more evidence of brittle failure. As shown in Figure 2, at higher temperatures, approximately 40°F, the observed percentage of shear was around 20 percent and had an absorbed energy value of 32 ft-lbs.

The opposite was true for the lower test temperature, -40°F, where the energy absorption was only 15 ft-lbs and the fracture surface was entirely brittle in nature.

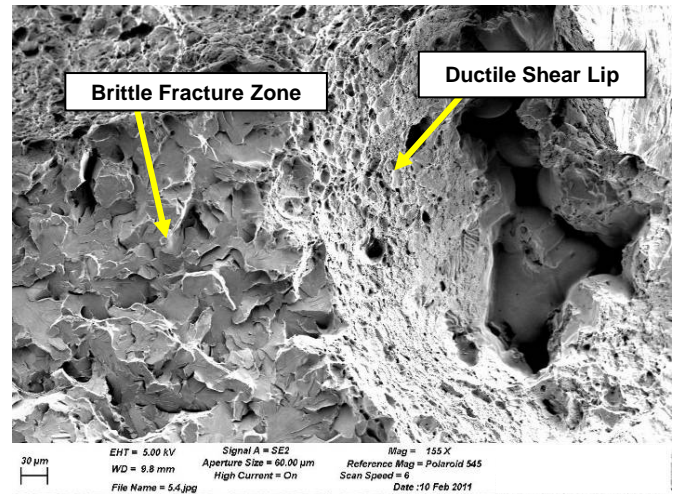


Figure 4. SEM Micrograph Excerpt from Figure 3 Showing the Ductile Shear Lip and the Brittle Fracture Zone at the Edge of the Sample

Effect of Discontinuities on Fracture Surfaces

All of the samples in the population had some shrink porosity on the fracture surface. Some of the shrinkage cavities were relatively small in size, but some contained areas of shrink as large as 0.098 inch (2.5 millimeters). In general, the presence of these pores weakens the load bearing capacity of the surface, which causes the specimen to shear at an absorbed energy level lower than expected. In addition, these shrink pores locally increase the stress concentration that can promote the tri-axial state of stress (depending on orientation) and lead to brittle cleavage.

Small amounts of black film deposited on the dendrites outlining the pore, as Figure 5 shows, are indicative of a combination of gas and porosity. Comparing the SEM analysis with the Charpy test data revealed that this sample had the lowest energy absorption values of all of the 11 samples that were analyzed using this technique. It is likely that the large pore was a major contributor to premature fracture initiation and poor Charpy performance.

Chemical inclusions were also found on the fracture surface of this sample. These discontinuities may have also contributed to the poor toughness of the material. The yellow highlighted areas in Figure 6 show the aluminum oxide (Al₂O₃) inclusions found in various samples. Similar inclusions of manganese sulfide (MnS) were also found in various samples. Presence of chemical inclusions directly influences the ability of the material to absorb energy. As more chemical inclusions are present, the fracture toughness decreases. Reducing the amount of porosity and indigenous inclusions has the potential to extend the life of Grade B+ castings.

