

"Metallurgical Design and Development of NASA Crawler/Transporter Tread Belt Shoe Castings"

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The NASA Crawler/Transporters (CT-1 and CT-2) used to transport the Space Shuttle are one of the largest tracked vehicles in existence today. Two of these machines have been used to move space flight vehicles at Kennedy Space Center since the Apollo missions of the 1960's and relatively few modifications have been made to keep them operational. In September of 2003 during normal Crawler/Transporter operations cracks were observed along the roller pad surfaces of several tread belt shoes. Further examination showed 20 cracked shoes on CT-1 and 40 cracked shoes on CT-2 and a formal failure analysis investigation was undertaken while the cracked shoes were replaced. Six shoes were cross-sectioned with the fracture surfaces exposed and it was determined that the cracks were due to fatigue that initiated on the internal casting web channels at pre-existing surface defects and propagated through thickness both transgranularly and intergranularly between internal shrinkage cavities, porosity, and along austenitic and ferritic grain boundaries. The original shoes were cast during the 1960's using a modified 86B30 steel with slightly higher levels of chromium, nickel and molybdenum followed by heat treatment to achieve a minimum tensile strength of 110ksi. Subsequent metallurgical analysis of the tread belt shoes after multiple failures showed excessive internal defects, alloy segregation, a non-uniform ferritic/ bainitic/martensitic microstructure, and low average tensile properties indicative of poor casting and poor heat-treatment. As a result, NASA funded an initiative to replace all of the tread belt shoes on both crawler/transporters along with a redesign of the alloy, manufacturing, and heat-treatment to create a homogeneous cast structure with uniform mechanical and metallurgical properties. ME Global, a wholly owned subsidiary of ME Elecmetal based in Minnesota was selected as manufacturing and design partner to develop the new shoes and this paper describes the research, development, and manufacturing that resulted in the successful delivery of 1044 new Crawler/Transporter tread belt shoes all meeting rigid metallurgical and mechanical design criteria derived from finite element modeling of the stress loads required for safe space shuttle transport.

Metallurgical Design and Development of NASA Crawler/Transporter Tread Belt Shoe Castings

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ABSTRACT: The NASA Crawler/Transporters (CT-1 and CT-2) used to transport the Space Shuttles are one of the largest tracked vehicles in existence today. Two of these machines have been used to move space flight vehicles at Kennedy Space Center since the Apollo missions of the 1960's and relatively few modifications have been made to keep them operational. In September of 2003 during normal Crawler/Transporter operations cracks were observed along the roller pad surfaces of several tread belt shoes. Further examination showed 20 cracked shoes on CT-1 and 40 cracked shoes on CT-2 and a formal failure analysis investigation was undertaken while the cracked shoes were replaced. Six shoes were cross-sectioned with the fracture surfaces exposed and it was determined that the cracks were due to fatigue that initiated on the internal casting web channels at pre-existing casting defects and propagated through thickness both transgranularly and intergranularly between internal shrinkage cavities, porosity, and along austenitic and ferritic grain boundaries. The original shoes were cast during the 1960's using a modified 86B30 steel with slightly higher levels of chromium, nickel and molybdenum followed by heat treatment to achieve a minimum tensile strength of 110ksi. Subsequent metallurgical analysis of the tread belt shoes after multiple failures showed excessive internal defects, alloy segregation, a non-uniform ferritic/ bainitic/martensitic microstructure, and low average tensile properties indicative of poor casting and poor heat-treatment. As a result, NASA funded an initiative to replace all of the tread belt shoes on both crawler/transporters along with a redesign of the alloy, manufacturing, and heat-treatment to create a homogeneous cast structure with uniform mechanical and metallurgical properties. ME Global, a wholly owned subsidiary of ME Elecmetal based in Minneapolis, MN was selected as manufacturing and design partner to develop the new shoes and this paper describes the research, development, and manufacturing that resulted in the successful delivery of 1044 new Crawler/Transporter tread belt shoes all meeting rigid metallurgical and mechanical design criteria derived from finite element modeling of the stress loads required for safe space shuttle transport.

1 INTRODUCTION

The crawler transporter (CT) is a tracked vehicle used at the Kennedy Space Center (KSC) to carry launch vehicles. Originally designed and used for Apollo missions, the two CT's are now used by NASA to carry space shuttles from the Vehicle Assembly Building (VAB) to the launch pads. The CT's weigh six million pounds and are designed to carry a twelve million-pound payload. Each CT travels on eight belts of shoes. These tracked belts each consist of a string of 57 shoes, for a total of 456 shoes on each crawler transporter. Each shoe is 90 inches long, 25 inches wide and weighs approximately 2,100 lbs. Marion Power Shovel originally supplied the tread belt shoes in 1965 during the original manufacture of both crawler transporters for NASA. Until the

early 1980's, tread belt shoes were considered consumable items and failed shoes were routinely replaced. Once the original supply became depleted, a spares program was initiated and shoes were purchased from both Kobe Steel, Kobe, Japan and Bay City Castings, Bay City, Michigan. A subsequent program was initiated in the latter 1980's for the refurbishment of CT shoes which involved a weld repair of damaged roller pad surfaces. This procedure only postponed the inevitability of failure and resulted in downtime associated with exchange of shoes awaiting repair.

2 SHOE FAILURES

The potential for catastrophic failure of CT shoes was first noted in 1986 when long cracks were found along the roller path between two pin lugs on a Kobe shoe during rollout of a mobile launch platform (MLP). The incident was deemed isolated and the shoe was replaced. In 1990, two Bay City Casting shoes suffered a catastrophic failure on transition up the hill to Launch Complex 39, Pad B. Cracks extended across the roller path to the pin lugs resulting in complete separation of the lugs and near disengagement of the tread belt. A technician on the ground noticed the failure, called for an emergency stop, and the crawler transporter was backed down the hill to exchange a shoe. Subsequent metallurgical failure analysis showed an extensive fatigue crack that had originated at subsurface casting flaws and propagated through thickness between the two pin lugs. All Bay City Casting shoes were then examined by non destructive inspection techniques and showed a high percentage of crack shoes. All Bay City Casting shoes were then removed from service and replaced with Marion or Kobe shoes. In October 2003, a routine inspection noted a cracked shoe that displayed similar characteristics to the previous Bay City Casting shoes and an extensive visual borescope inspection of the internal channels and non destructive manetic particle inspection of the roller pads was ordered. Forty cracked shoes on CT-2 were found and subsequent inspection of CT-1 found an additional twenty shoes that were cracked. All fractured and cracked shoes were replaced and in November 2003 a Rollout Fatigue Test was done on CT-2 with strain gage instrumentation installed on several random shoes. During this test, CT-2 traveled approximately five miles to simulate movement from the VAB to the launch pads. Inspection of the CT-2 shoes after this test revealed forty-three additional shoes had cracked during this Rollout Fatigue Test. Risk Assessment was undertaken and in February 2004 and concluded that CT operations were now to be limited to level surfaces at a maximum of 0.3 mph. Additionally, CT movement was minimized to avoid depleting the inventory of useable spare shoes. The NASA/KSC Materials Failure Analysis Laboratory completed their investigation and released their findings indicating that the failures experienced were due to fatigue that initiated at casting defects on the internal web surfaces and propagated both transgranular and intergranular through a segregated, non-uniform microstructure to the roller pad surface. Based on these results, determination was made that the CT shoes in service may be at or near their life limit. Factors that contributed to the failures included surface defects, improper microstructure, shrinkage cavities, and porosity in the originally supplied CT shoes. Two conclusions were made following testing. First, the non-destructive examination methods used to inspect the CT shoes could not conclusively identify serviceable shoes. Second, the available spare CT shoes in inventory also could be depleted with two additional CT moves. As a result of these failures and the limitation of CT movement, the decision was made to replace the CT shoes. A Statement of Work was written and a Request for Proposal was initiated for the supply of 1,044 shoes to replace all shoes on both CT's and have 132 spares. This

proposal required the production of CT shoes to strict quality requirements with specific cross-section microstructure and uniform mechanical properties within a specified range of hardness and tensile strength to outfit both Crawler Transporters within a sixteen week production schedule.

3 DEVELOPMENT

ME Global of Minneapolis, MN was selected as the sole supplier for the CT Shoe Replacement Project. Of the eight suppliers in the process, ME Global was selected as the only domestic supplier with the ability to produce the required number of shoes, meeting the quality requirement, and the required delivery schedule for Return to Flight operations. The initial prototypes were cast using a V-Process molding using silica sand without a binder that is vacuum formed into the mold shape. Internal cores were made using zircon sand to enhance dimensional control and improve surface finish along the internal channels. The alloy selected was a modified 4320 alloy, replacing the original modified 86B30 alloy designated in 1962 by Marion Power Shovel. The modified 86B30 alloy had increased chromium, molybdenum, and nickel to enhance hardenability but the alloy as cast was severely segregated with large internal casting defects and the microstructure contained extensive ferrite along internal casting channels with a cross-section combination of bainite and widmanstatten ferrite with a predominantly bainitic structure beneath the roller pad surface indicating a low through thickness undercooling rate on quenching. Modeling of the new tread belt shoes using MAGMA software confirmed the location of potential internal shrink defects and significant modifications to the riser size and location were made along with geometric changes to the internal channels of the shoe to increase feeding to suspect locations from the gates. Heat treatment involved normalizing at 1600° F for 4 hours followed by a water quench with medium to high agitation for 25 minutes followed by tempering at 1100° F for 4 hours followed by air cooling. The prototype shoes were then sectioned in 4 locations along the roller pad to examine the cross-section microstructure and verify the through thickness hardness. The structure was predominantly bainitic with finely dispersed acicular ferrite and the cross-section hardness ranged from 307 HB in the core to 317 HB near the surface. Tensile specimens were cut from the shoes directly above the internal channels for verification of mechanical properties and averaged 137 ksi UTS and 120 ksi YS, above the specified minimum of 130 ksi UTS, and 110 ksi YS. Examination of the area under the roller pad confirmed the shrinkage cavities and large porosity found on the old shoes that had failed was eliminated. A sound casting without shrink or porosity could now be produced in this redesigned casting.

4 PRODUCTION

During the prototype phase the critical production elements were defined and statistical process controls were developed to track material performance. Inspection procedures were outlined and included strict surface finish requirements, chemical analysis of furnace charge for each pour, 26 as-cast brinell pads for surface hardness measurement, time and temperature data for each heat-treatment lot, magnetic particle inspection of 100%, radiographic examination of a random 10%, ultrasonic inspection of an additional 10%, and destructive testing of 20 random "First Article" shoes from production lots. The first article testing included cross-section metallography, hardness, and tensile testing of specimens cut from directly above the internal casting channels.

5 RESULTS AND DISCUSSION

The primary verification of process control was through continuous monitoring of shoe surface hardness data that was downloaded daily from the foundry. Two key criteria were monitored throughout the production phase for indication of loss of process control: average surface hardness and surface hardness variation within each shoe. The following charts, shown in Figure 1, display the average and range for the process with the vertical line showing the point at which the tempering temperature was increased from 1100° F to 1125° F to reverse trending towards a non-compliant process.

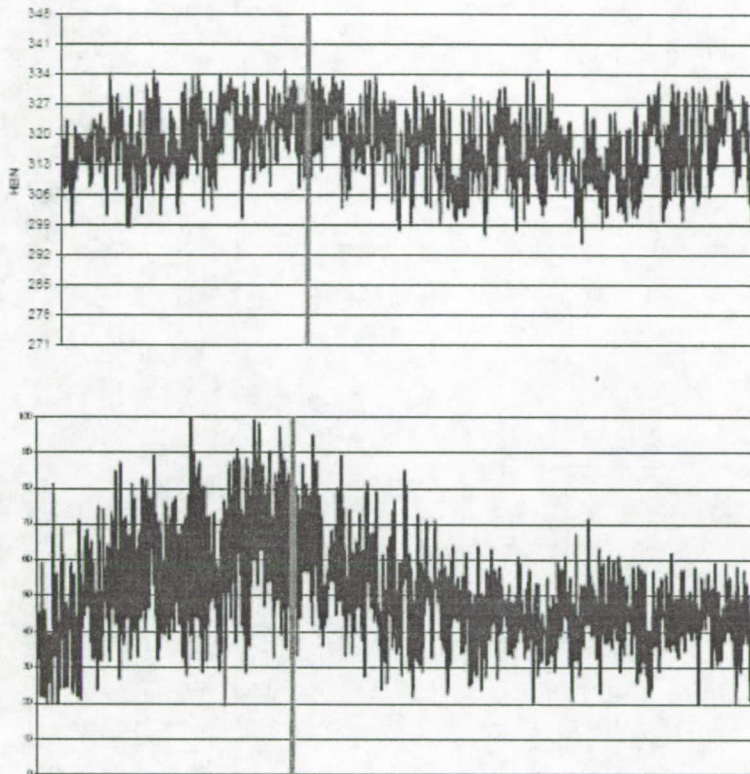


Figure 1: Top - Average surface hardness, Bottom - Range of surface hardness measurements

Prior to production, the process capability was evaluated and the specification limits for the individual surface hardness measurements was set at the range 271-371 HB and the average hardness measurements were specified by zone. When final compilation of productions shoe hardness measurements are compared to the requirements, 100% of the measurements conformed. The graph in Figure 2 shows the compilation of individual surface hardness measurements.

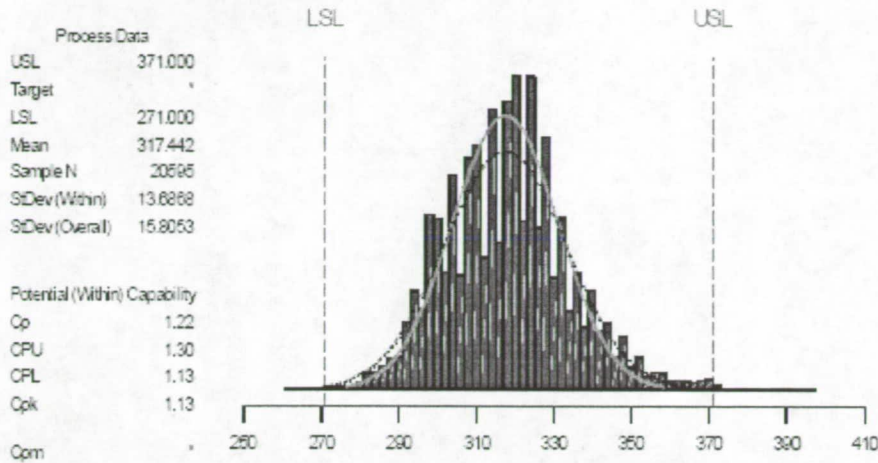


Figure 2: Process capability analysis

Internal mechanical property data is shown in Table 1. Linear regression analysis of the data gathered from destructively tested shoes provided a relationship between the external and internal hardness values as follows:

$$\text{HB (internal)} = 0.952 \times \text{HB (surface)}. \quad (1)$$

Similarly, a relationship between surface hardness and tensile strength was determined as follows:

$$\text{Internal (UTS)} = 62181.1 + 238.425 \times \text{HB (surface)} \quad (2)$$

$$\text{Internal (Yield)} = 28127.9 + 292.899 \times \text{HB (surface)} \quad (3)$$

	Number of Measurements per Value	Average Value	Std. Dev	Min Value	Max Value*	Spec
Through Hardness, HBN	5	307	8	294	326	271 min
Internal Tensile, ksi	2	137	4.2	131	148	130 **
Internal Yield, ksi	2	119	6.4	109	130	110 **

Table 1: Summary of internal mechanical property data

From the linear regression analysis, internal mechanical properties can now be estimated with a certain degree of confidence and Figure 3 shows the empirical relationship developed between hardness and tensile strength.

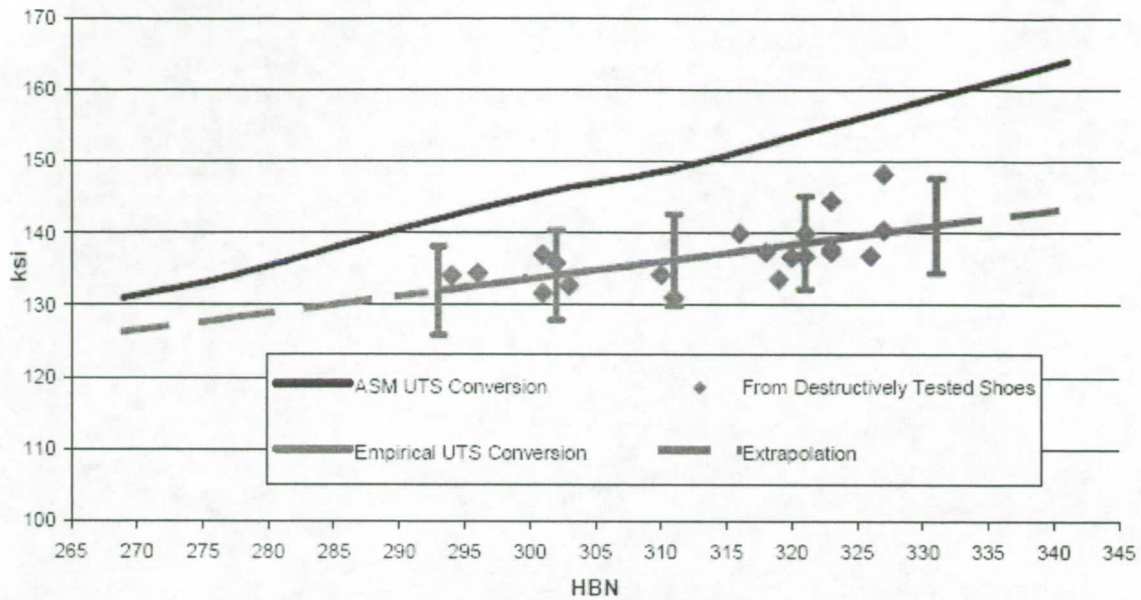


Figure 3: Relationship between measured hardness data and tensile strength

6 SUMMARY

In the fall of 2004, the crawler transporters began being outfitted with the new tread belt shoes as shipments arrived during the course of the project. Final delivery of the CT shoes was completed in January 2005 and the initial rollout testing of the CT vehicles began on schedule in support of the Return to Flight of STS-114 in February 2005. Rollout of Space Shuttle Discovery to Launch Complex 39B occurred on April 6, 2005 in anticipation of launch to the International Space Station during the May 15 to June 7 time frame. Failures of shoes used by the crawler transporter at Kennedy Space Center led to the decision by NASA to replace shoes that had been in service from the 1960's. ME Global's proactive role in the research and development in partnership with NASA mechanical and metallurgical engineering groups resulted in the development of a CT shoe that met or exceeded the new design requirements and is anticipated to perform throughout the life of the Space Shuttle program and onto service the next generation space flight vehicle. ME Global manufactured over 1050 CT shoes under stringent quality specifications and delivered on time to meet NASA's stringent Return to Flight schedule requirements.