A Design Study in Steel Castings

Track Shoe on the NASA Crawler Transporter

Design Study Outline

NASA Shuttle on Crawler Transporter

(NASA Photo)

Key Words *= metal casting, steel, ME Elecmetal, ME Global, V-process, AISI 4320*

Start the Design Study !

Acknowledgment --

The metalcasting design studies are a joint effort of the Steel Founders' Society of America and the American Foundry Society. Project funding was provided by the American Metalcasting Consortium Project, which is sponsored by the Defense Logistics Agency, Attn: DLSC-T, Ft. Belvoir, VA, 22060-6221

Return to SFSA Home Page

Address comments to: blairr@sfsa.org

Last Modified:July, 2006 by STG

In cooperation with ME Elecmetal

Crawler Track Shoe -- Application

The crawler transporter is a very large, heavy duty tracked vehicle used at the Kennedy Space Center (KSC) to move launch vehicles from the Vehicle Assembly Building to the launch pads.

- Originally designed and used for the original Apollo missions, two crawler transporters (CT) are now used by NASA to carry the Space Shuttle vehicles.
- The CT's weigh six million pounds each and are designed to carry a twelve million pound payload.
- Traveling at one mph, the CT's are driven by electric motors powered by diesel engines. The engines consume one gallon of fuel every fifty feet of travel.
- Including the Apollo years, the transporters have racked up 2,526 miles, about the same distance as a one-way trip from KSC to Los Angeles by interstate highway or a round trip between KSC and New York City.

NASA Crawler Transporter with Space Shuttle ***(NASA Photo)***

Back Next

Return to SFSA Home Page

Address comments to: blairr@sfsa.org
Last Modified:July, 2006 by STG

Page 1

In cooperation with ME Elecmetal

Crawler Track Shoe -- Application

Crawler Drive Unit *(NASA Photo)*

Each crawler transporter travels on four crawler drive units, with one unit on each corner of the transporter.

- **The drive units are like a bulldozer. Each drive unit has two tracks consisting of a string of 57 crawler shoes linked together.**
- **The full length of an individual track is over 120 feet.**

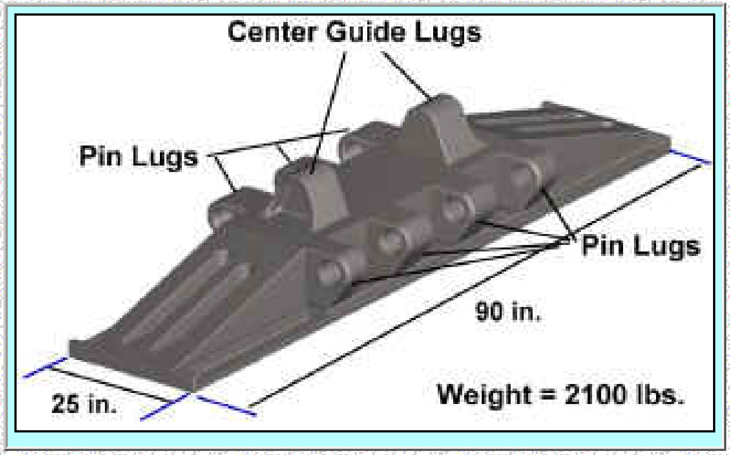
With a total of eight tracks for the four drive units, each crawler transporter uses a total of 456 shoes.

Address comments to: blairr@sfsa.org
Last Modified:July, 2006 by STG

In cooperation with ME Elecmetal

Track Shoe -- Description

Each crawler shoe is 90 inches long, 25 inches wide and weighs approximately 2,100 lbs. The shoes are made of steel for strength and durability. The center section of each shoe has a hollow box structure to save weight without loss of strength or stiffness.



The top of each shoe has two center lugs which act as guides for the rollers on the crawler unit.

Both sides of each shoe have multiple pin lugs to link with adjacent shoes and form the complete track.

The center guide lugs and pin lugs are integral features in the design and are critical elements for strength and durability.

The outer wings of the shoe are tapered. The maximum wall thickness in the casting is 6.5 inches; the thinnest wall section is 1.0 inch.

Address comments to: blairr@sfsa.org
Last Modified:July, 2006 by STG

In cooperation with ME Elecmetal

Track Shoe -- History

The original 1000+ track shoes for the two crawler transporters were produced for NASA in 1965 for the Apollo moon missions.

The first failure of CT shoes was noted in 1986 when long cracks were found along the roller path on one shoe. In 1990, two shoes suffered catastrophic failure during a Shuttle move, with cracks extended across the roller path to the pin lugs; the lugs broke off and the track belt separated.

- In 2003, multiple inspections and tests revealed a growing fracture problem with almost 100 cracked track shoes that had to be replaced.
- In a follow-up test in March 2004, CT-1 traveled approximately 1.5 miles with its shoes instrumented to record fatigue data. Inspection of the shoes showed that another ten shoes had cracked and had to be replaced.

Close Up of Track Shoes

A detailed failure analysis by the NASA/KSC Materials Failure Analysis Laboratory showed that the track shoe failures were due to fatigue. The fatigue failure initiated at internal casting defects and propagated to the outer surface through a segregated, non-uniform microstructure.

Address comments to: blairr@sfsa.org
Last Modified:July, 2006 by STG

In cooperation with ME Elecmetal

Analysis and Conclusions

NASA engineers made four conclusions following the 2004 performance testing and failure analysis.

1. The available non-destructive examination methods used to inspect the CT shoes could not conclusively identify serviceable shoes.

2. Refurbishing the defective shoes was not cost effective.

3. The available spare CT shoes in inventory would be depleted with two additional CT moves.

4. The CT shoes in service were likely at or near their life limit.

Front View of Crawler Unit *(NASA Photo)*

NASA decided that new CT shoes were needed for the transporters.

Address comments to: blairr@sfsa.org
Last Modified:July, 2006 by STG

In cooperation with ME Elecmetal

Production Requirements and Schedule

In spring 2004 NASA put out an RFP for the production and delivery of 1,044 shoes to replace all the shoes on both CT's and have 132 spares.

****

This proposal required the production of track shoes to strict quality requirements in a demanding three phase schedule.

Crawler Track *(NASA Photo)*

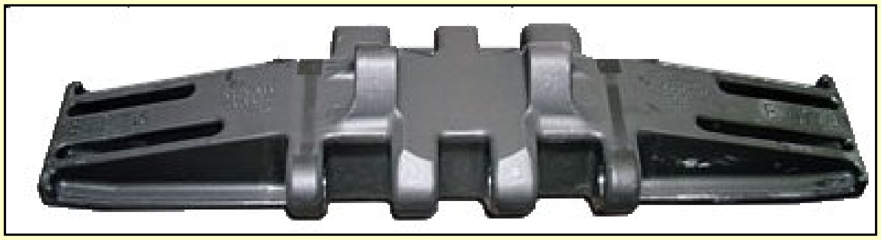
Phase 1 included the development and qualification of the casting design and the casting process definition to produce two prototype shoes that met the design requirements.
Phase 1 started in May 2004 and concluded with a production decision in Aug 2004.

Phases 2 and 3 specified the production of 1,044 shoes in two sets to outfit both Crawler Transporters within a sixteen week production schedule.
Phases 2 and 3 began in Aug 2004 and had to be completed with final delivery in January 2005.

In cooperation with ME Elecmetal

Track Shoe Requirements

NASA specified detailed performance and production requirements for the track shoe.



Track Shoe Casting

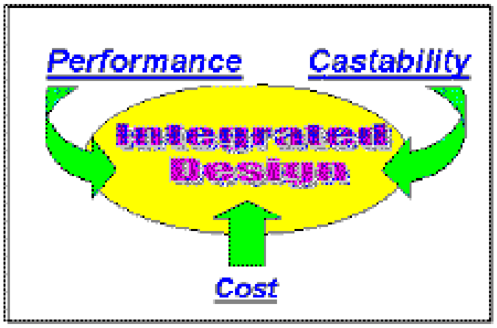
- **The mechanical strength requirements were-**
  - Ultimate tensile strength --130 ksi
  - Yield strength -- 110 ksi
- **Hardness requirements were specified for 21 critical locations on the casting separated into three zones.**
  - Hardness range requirements for the center lugs and roller path zones were 294 to 327 Brinell hardness (BHN).
  - The pin lug zone hardness range was specified as 286 to 344 BHN.
  - The microstructure in the casting had to be controlled for phase content to produce the desired hardness in the different regions. This required precise control of the heat treatment (heat-quench-temper).
- **The quality assurance requirements were also extensive, covering both casting process parameters and comprehensive inspection, testing, and non-destructive and destructive evaluation of castings.**

Address comments to: blairr@sfsa.org
Last Modified:July, 2006 by STG

In cooperation with ME Elecmetal

The Casting Design Issues

NASA selected the ME Elecmetal Company of Duluth, MN to produce the castings.



The casting design team *(the ME Elecmetal casting engineers and the NASA design engineers)* focused on three imperatives.

-- ***Design for Performance***
-- ***Design for Production/Castability***
-- ***Design for Cost***

Critical Casting Design Issues **--The requirements for performance, casting production, and cost are closely interconnected. Three casting design issues played a major role in meeting the three design imperatives.**

- **Select a *steel alloy* that meets the mechanical requirements and produces this heavy casting in a sound condition.**
- **Select a *molding method* that produces the required surface finish and dimensional tolerances in a cost-effective manner.**
- **Develop a *casting and mold design* that produces flaw-free shoes at the best cost.**

In cooperation with ME Elecmetal

Steel Alloy Selection

NASA engineers originally specified a heat-treated AISI 8640 or equivalent steel alloy as having sufficient mechanical properties for long life.

AISI 8640 is a high strength, high hardenability oil quench steel alloy.

(The 8640 composition is 0.38-0.43C, 0.75-1.00 Mn, 0.15-0.30 Si, 040-0.60Cr, 0.40-0.70 Ni. 0.15-0.25 Mo.)

With the heavy cross-section of the shoe, a rapid water quench was required for the 8640 alloy to produce the required strength and hardness. But during water quench of the first prototype, the AISI 8640 alloy shoe cracked severely in areas that could not be repaired.

Hot Track Shoe Ready to Quench

An alternate alloy had to be found that would give the required strength, microstructure, and hardness with a suitable heat-treatment, but could also be water quenched without cracking in the heavy cross-sections.

Address comments to: blairr@sfsa.org
Last Modified:July, 2006 by STG

In cooperation with ME Elecmetal

Steel Alloy Selection

ME Elecmetal engineers considered two alternate Cr-Ni-Mo steel alloys

AISI 8630 (0.27-0.33C, 0.60-0.95 Mn, 0.15-0.30 Si, 0.35-0.65Cr, 0.35-0.75 Ni, 0.15-0.25 Mo)

AISI 4320 (0.17-0.23C, 0.40-0.70 Mn, 0.15-0.30 Si, 0.35-0.65Cr, 1.55-2.00 Ni, 0.20-0.30 Mo)

Tests on these standard alloys showed that they did not meet the mechanical property requirements. But they were close enough, that the alloys could be modified with the addition of alloying elements to increase the strength and hardenability to meet the property requirements in this large casting.

Casting and heat-treat tests and mechanical tests gave the following properties for the two modified steel alloys.

	Performance Requirement	Choose AISI 8630 Modified	Choose AISI 4320 Modified
Minimum Ultimate Tensile Strength	**130 ksi**	**<130 ksi**	**>130 ksi**
Minimum Yield Strength	**110 ksi**	**<110 ksi**	**>110 ksi**
Acceptable Hardness Range	**280-320 BHN**	**240-320 BHN**	**280-320 BHN**
Water Quench	**Crack Free**	**Yes**	**Yes**

Given the mechanical property requirements for the track shoe,

Choose the alloy that best meets the performance requirements.

Back

Choose an alloy above

Return to SFSA Home Page

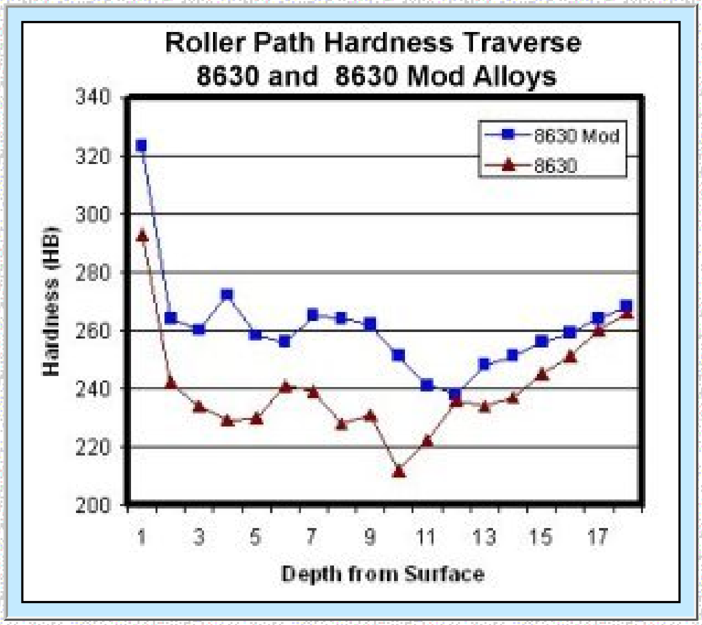
Address comments to: blairr@sfsa.org
Last Modified:July, 2006 by STG

Page 1

In cooperation with ME Elecmetal

AISI 8630 Modified Steel Alloy

When a test casting was made with heat-treated standard AISI 8630 alloy, the casting was water-quenched without cracking, but it did not meet the strength and hardness requirements.



The 8630 alloy chemistry was modified with additional proprietary alloying elements to improve the strength and hardenability.

- **The hardness plot to the left shows the Brinell hardness values through the cross-section of the prototype shoe. The modified 8630 does not meet the hardness range required (280-320 HB).**

The heat-treated, quenched, and tempered test casting with the modified AISI 8630 chemistry was crack free, but it did not have sufficient hardness and strength in the thicker sections of the casting.

The AISI 8630 Modified does not have the high hardenability needed to develop the required strength and hardness through the thickness of the track shoe.

The AISI 8630 Modified is not the best choice.

Go Back for Another Alloy!

Back

Return to SFSA Home Page

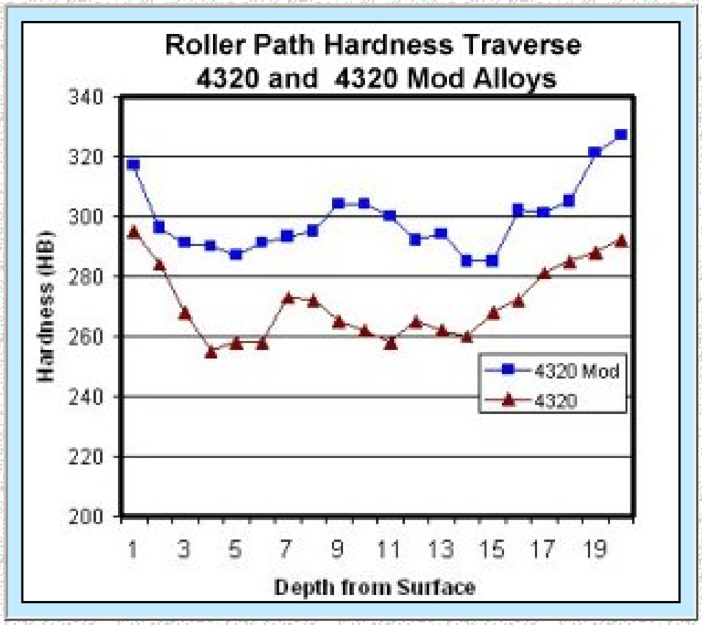
Address comments to: blairr@sfsa.org
Last Modified:July, 2006 by STG

Page 1

In cooperation with ME Elecmetal

AISI 4320 Modified Steel Alloy

When a test casting was made with the heat-treated standard AISI 4320 alloy, the casting was water-quenched without cracking, but it did not meet the strength and hardness requirements in the thicker sections of the casting.



The 4320 alloy chemistry was modified with additional proprietary alloying elements to improve the hardenability.

- **The hardness plot to the left shows the Brinell hardness values through the cross-section of the prototype shoe. The modified 4320 does meet the hardness range required (280-320 HB).**

The heat-treated, quenched, and tempered test casting with the modified AISI 4320 chemistry was crack free, and it met the hardness and strength requirements in all sections of the casting.

The heat-treated modified 4320 alloy had a uniform martensite-bainite microstructure in all the critical sections and met the requirements for tensile strength, yield strength, and hardness.

The AISI 4320 modified is the best choice.

Go on to the next casting design issue.

Back Next

Return to SFSA Home Page

Address comments to: blairr@sfsa.org
Last Modified:July, 2006 by STG

Page 1

In cooperation with ME Elecmetal

Mold Production with the V-Process

ME Elecmetal uses a vacuum forming process (the V-process) to form sand molds with high dimensional accuracy, excellent surface finish, zero draft angle, and unlimited tool life.

V-Process Molding

- The V-Process uses a strong vacuum applied to free-flowing, dry, unbonded sand around patterns in airtight flasks.
- The process uses a specially designed, strong, highly flexible polymer film to seal the open ends of the sand mold and form the mold cavity.
- The vacuum inside the mold results in a net pressure pushing in, holding the sand rigidly in the shape of the pattern, even after the pattern is removed.

Stripping the Cope Mold off the Pattern

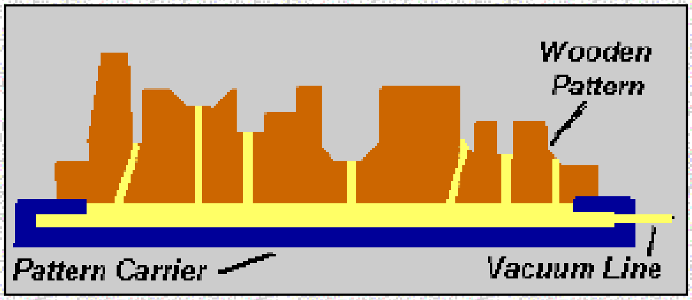
The V-Process can be used on almost all metal types and for all sizes and shapes of castings.

Address comments to: blairr@sfsa.org
Last Modified:July, 2006 by STG

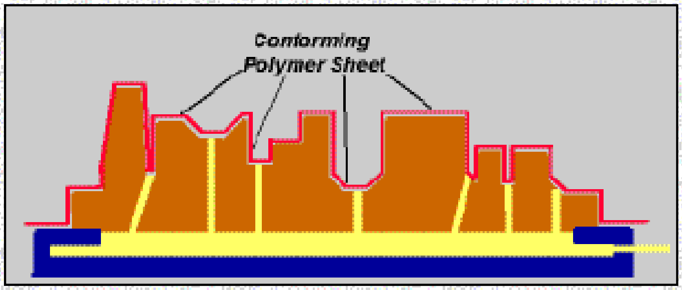
In cooperation with ***ME Elecmetal***

V-Process Molding

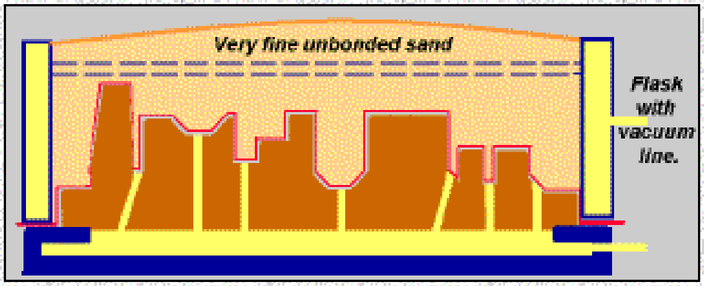
The V-process consists of seven steps. The first four steps are:



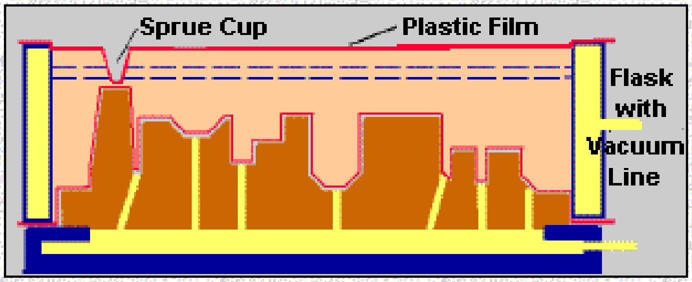
1. A precision pattern with vent lines is positioned on a pattern carrier with a vacuum line.



2. A heat-softened polymer sheet is positioned on the pattern and the vacuum draws the sheet down to form a conforming polymer film on the pattern.



3. A flask with vacuum lines is placed over the film covered pattern. The flask is filled with very fine, dry, unbonded sand. The flask is vibrated to settle the sand into all the pattern features.



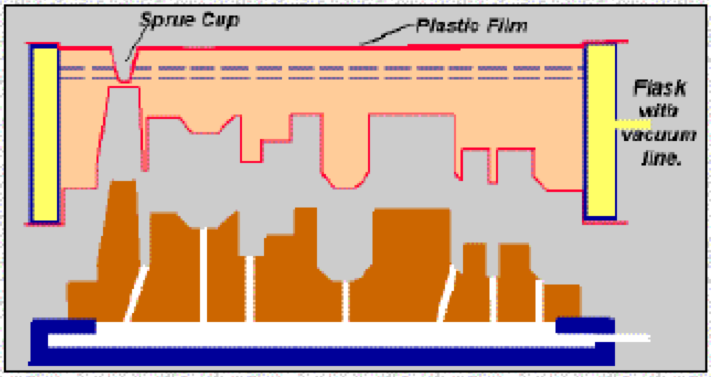
4. The sand is leveled and a sprue cup is formed in the mold. A plastic film is placed on top of the mold to form a vacuum tight seal. A vacuum is drawn on the flask to rigidize the sand in the mold.

Address comments to: blairr@sfsa.org
Last Modified:July, 2006 by STG

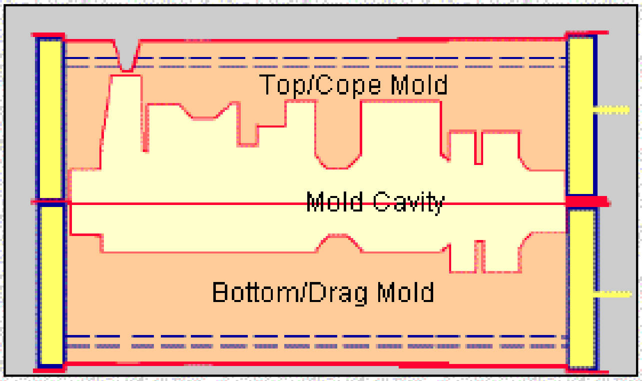
In cooperation with ME Elecmetal

V-Process Molding

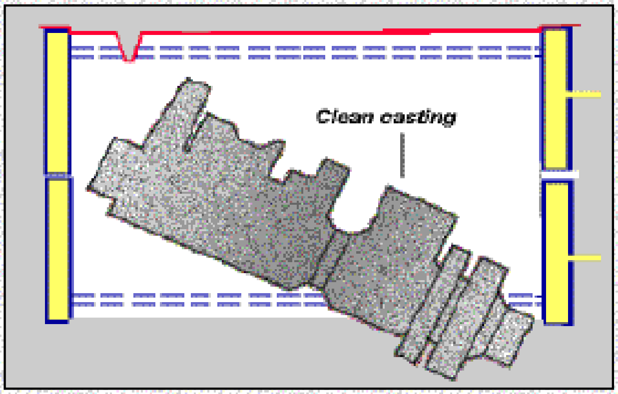
The next three steps in the V-process are:



5. The vacuum is released from the pattern carrier and the vacuum-constrained mold is stripped off the pattern.



6. The two mold halves (cope and drag) are joined together to form the completed plastic lined mold cavity. The vacuum is maintained in the flasks during molten metal pouring.



7. After metal pouring and cooling, the vacuum on the mold is released.

The unbonded sand drops away, leaving a clean casting with zero draft and a 125-150 RMS surface finish.

Address comments to: blairr@sfsa.org
Last Modified:July, 2006 by STG

In cooperation with ME Elecmetal

Solidification Control in Castings

The failure analysis of the original failed track shoes showed that there was solidification shrinkage and porosity deep in the body of the track shoe in the center web section.

- **This is the heaviest and most remote section of the casting.**

Solidification modeling by ME Elecmetal confirmed the potential for shrinkage in this area. When the first prototype casting was produced in the original design and then inspected, the prototype had the same shrinkage problem in the center web section.

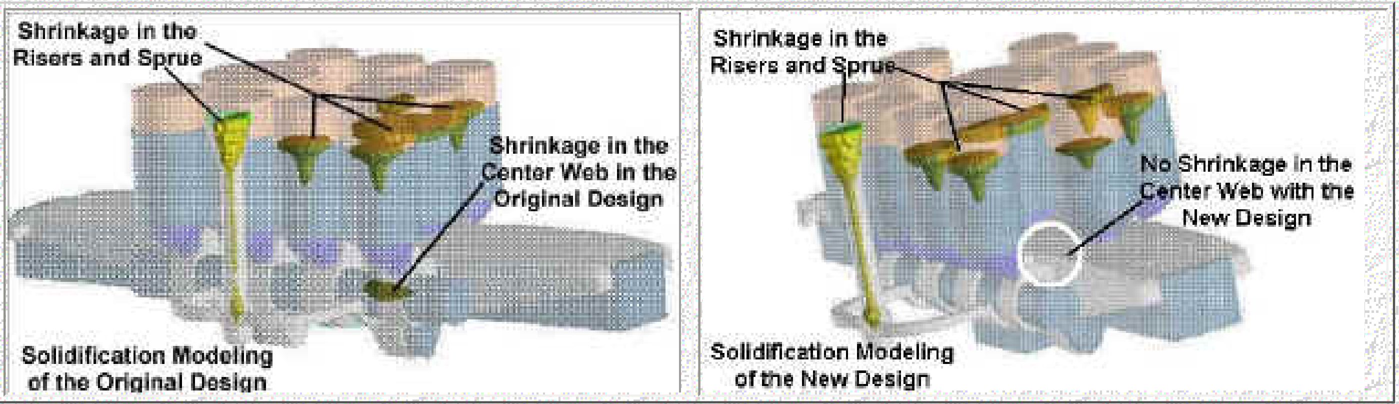
Address comments to: blairr@sfsa.org
Last Modified:July, 2006 by STG

In cooperation with ME Elecmetal

Solidification Modeling

Solidification modeling is a computer analysis tool used in the casting industry to predict the temperature, phase condition, porosity, and microstructure in different sections of a casting as a function of process time.

Solidification modeling is an important tool in designing the geometry of castings to produce a casting that is sound and free of flaws.



The ME Elecmetal engineers redesigned the casting with a tapered center web to aid in feeding and solidification of the track shoe. Solidification modeling predicted that the geometry change would eliminate the solidification shrinkage.

When the new design was cast in prototype, inspection and sectioning showed that the center web was solid and free of porosity.

In cooperation with ***ME Elecmetal***

Net Shape Features

One of the advantages of casting is that fine features can be produced in a near-net shape configuration in the casting process. This capability can reduce or even eliminate expensive machining steps.

- **In the track shoe, each pin lug has a 3.308 inch diameter hole for pin placement. The size and location of these holes are held to precise tolerances.**
- **The 3.308" holes are formed directly in the seven pin lugs by positioning sand cores in the mold.**
- **With the holes produced by the sand cores, a simple two-step finish drill takes the holes to final dimensions and tolerances.**

Using cores in the casting eliminates an expensive, heavy boring operation on the seven pin lugs.

Back Next

Return to SFSA Home Page

Address comments to: blairr@sfsa.org
Last Modified:July, 2006 by STG

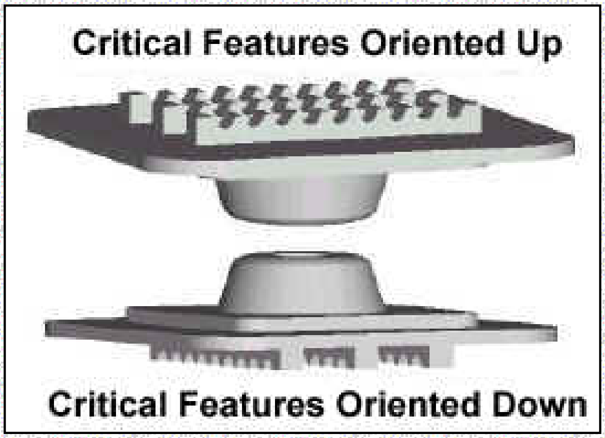
Page 1

In cooperation with ME Elecmetal

Orientation in the Mold

In mold design for castings, the orientation of the part in the mold is an important factor in producing a sound casting.

- **Casting defects (porosity, inclusions), when they occur, tend to rise and segregate in the upper/cope mold section of the casting.**
- **The casting should be oriented so that machined surfaces and critical features are molded in the drag or the lower section of the casting.**



Back Next

Return to SFSA Home Page

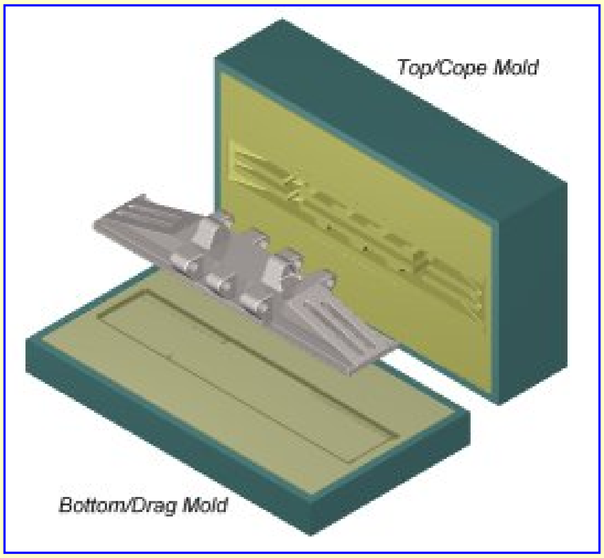
Address comments to: blairr@sfsa.org
Last Modified:July, 2006 by STG

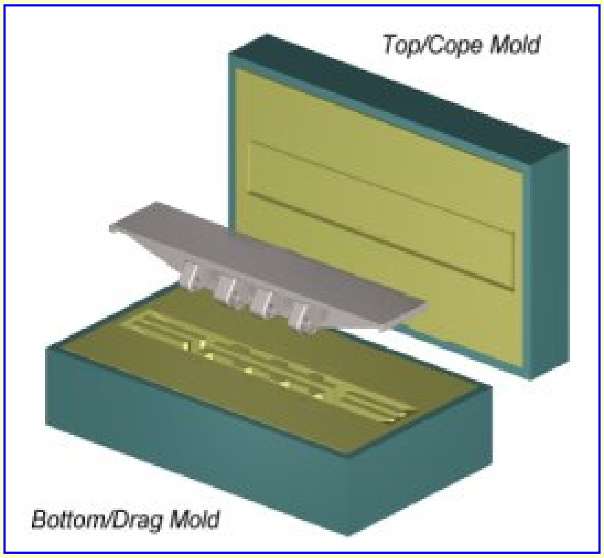
Page 1

In cooperation with ME Elecmetal

Orientation in the Mold

The pin lugs and center lugs are the critical features in the track shoe, because they have the critical surface requirements and see the highest stresses.





Option A -- Lugs Up Orientation	Option B -- Lugs Down Orientation
The center lugs and pin lugs are positioned in the upper/cope mold. The road surface is positioned low in the drag mold.	**The center lugs and pin lugs are positioned in the bottom/drag mold. The road surface is positioned high in the cope mold.**

Choose which shoe orientation in the mold is best for ensuring flaw-free lug sections in the casting.
Lugs Up or Lugs Down

Back

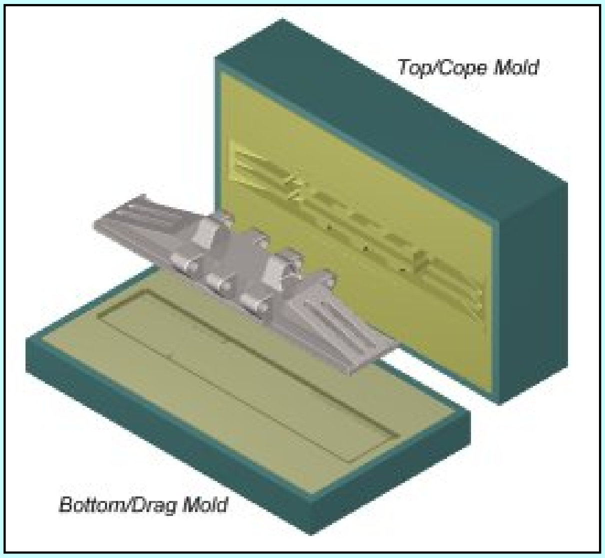
Select a design

Return to SFSA Home Page

Address comments to: blairr@sfsa.org
Last Modified:July, 2006 by STG

Page 1

In cooperation with ME Elecmetal



Option A -- Lugs Up

In Option A, the lug features are positioned high in the top/cope section of the mold. The road surface of the shoe is positioned in the bottom/drag section of the mold.

This orientation leaves the critical lug sections high in the mold, where inclusions and porosity may segregate causing localized flaws.

The "lugs up" is not a good approach for producing flaw-free lug features.

Go back and select another approach.

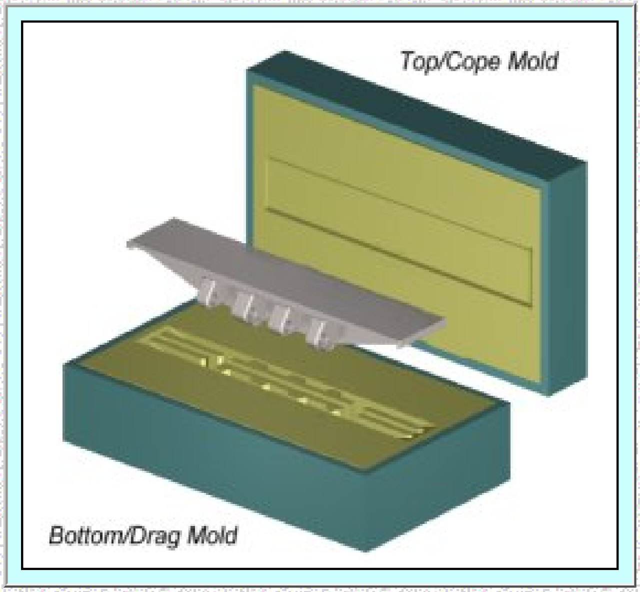
Back

Return to SFSA Home Page

Address comments to: blairr@sfsa.org
Last Modified:July, 2006 by STG

Page 1

In cooperation with ME Elecmetal



Option B -- Lugs Down

In Option B, the lug features are positioned in the bottom/drag section of the mold. The road surface of the shoe is positioned high in the cope section of the mold.

This orientation puts the critical lug features low in the mold, where they are isolated from inclusions and porosity.

If inclusions and porosity do develop, they will be segregated in the less-critical road surface area of the shoe.

"Lugs down" is the best orientation for producing a flaw-free casting.

Go on to the next design issue.

Back Next

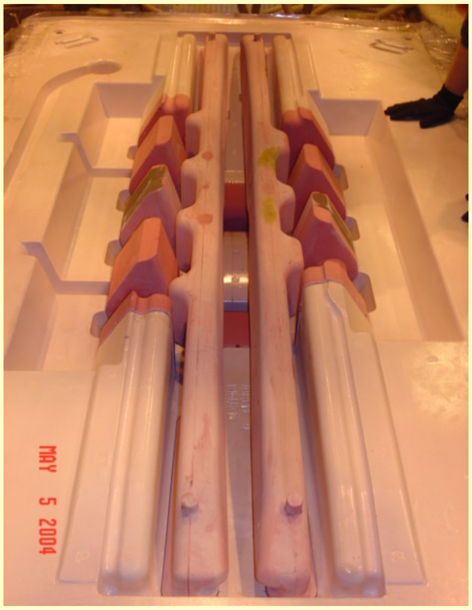
Return to SFSA Home Page

Address comments to: blairr@sfsa.org
Last Modified:July, 2006 by STG

Page 1

In cooperation with ME Elecmetal

Mold Cores



Cores Set into the Drag Mold

Cores are preformed sand shapes inserted into the mold to produce interior and exterior features in the casting.

ME Elecmetal foundry engineers use 19 cores in the mold for the track shoe.

- **The two large body cores form the center cavities in the shoe.**
- **The smaller cores form the pin lugs with their holes and the surface features on the shoe.**
- **The cores use a total of 700 lbs of zircon core sand.**

Address comments to: blairr@sfsa.org

Last Modified:July, 2006 by STG

In cooperation with ME Elecmetal

Final Mold Design

Pattern for Top Half (Cope) of the Mold

Pattern for Bottom Half (Drag) of the Mold

- The photos above show the patterns for the top and bottom mold sections.
  - The patterns are machined out of wood, because the V-process has no tool wear.
- The top/cope pattern shows the ten risers sitting in the top section of the mold.
  - These risers act as reservoirs feeding molten metal into the heavy sections of the casting as the casting cools in the mold.
- One track shoe is cast in each sand mold. The two mold halves are contained in 54" x 96" flasks.

Address comments to: blairr@sfsa.org
Last Modified:July, 2006 by STG

In cooperation with ME Elecmetal

The Casting Process

Metal Pouring into the Assembled Mold

Removal and "Shake Out" of the Casting

Swing Grinding the Riser Stubs

The track shoe is cast in a four step process.

1. The molten steel (2850F) is poured into the assembled V-process sand mold and allowed to cool for 40 hours in the mold.

2. After cooling, the casting is removed and "shaked out" of the sand mold.

3. The casting is shot-blasted for surface appearance.

4. The risers are knocked off and the riser stubs and flash lines are ground smooth.

Address comments to: blairr@sfsa.org
Last Modified:July, 2006 by STG

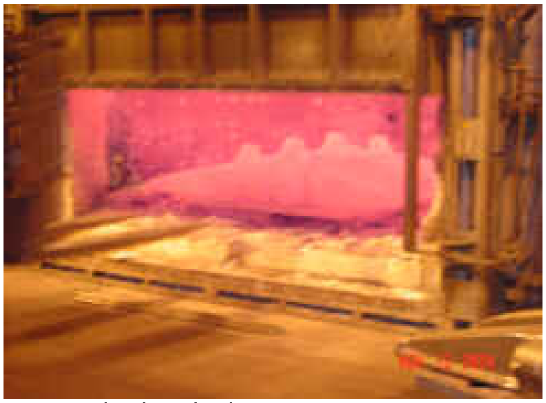
In cooperation with ME Elecmetal

Heat Treating

Heat treatment of the shoes was a critical process step to produce the required strength, microstructure, and hardness values in the track shoe.

The castings were heat treated in a proprietary high temperature heat, water quench, and temper cycle.

- **Control of temperature ramp rates, water agitation and water temperature were required to reduce the risk of quench cracking.**



Track Shoe in the Heat-Treat Furnace

Address comments to: blairr@sfsa.org
Last Modified:July, 2006 by STG

In cooperation with ME Elecmetal

Machining

The holes in the seven pin lugs were finish machined with a horizontal boring mill at Remmele Engineering (Big Lake, MN).

There were precise tolerances on hole diameter, location, pitch, and surface finish.


Track Shoe in the Horizontal Boring MIll

In cooperation with ME Elecmetal

Quality Assurance

NASA placed very stringent requirements for quality assurance on the track shoe. These QA directives covered both process control and documentation and evaluation and testing of the castings.

The initial Phase 1 prototype established the processes for mold and core fabrication, melting and pouring, heat treatment, finishing, and machining of the castings.

Surface Flatness Inspection

Magnetic Particle Inspection

Testing and inspection included --

- **The testing of 21 hardness points on each casting.**
- **Verification of surface finish on external and internal surfaces and magnetic particle inspection of each casting.**
- **Verification on each casting for conformance to height and road surface flatness requirements.**
- **Dimensional verification on each machined feature of pin lug pitch and location.**
- **One of every ten of shoes were randomly selected for ultrasonic and radiographic examination.**
- **One of every thirty-two shoes was subjected to a complete dimensional verification.**
- **One of every fifty-seven shoes was destructively tested to verify internal dimensions, soundness, uniformity of microstructure, through hardness, and mechanical strength.**

Back Next

Return to SFSA Home Page

Page 1

In cooperation with ME Elecmetal

Lessons Learned

In six months time the ME Elecmetal team successfully redesigned, prototyped, qualified, produced, and delivered over 1,000 of these 2,200 pound steel castings.

****

This success required detailed, collaborative design work and process optimization by the design team of ME Elecmetal casting engineers and NASA design engineers.

Track Belt Being Installed on the Transporter

Major lessons learned were:

- **Close collaboration and communication with the customer are essential for rapid, effective design development, process definition, and quality control management.**
- **Design confirmation in the prototype stage was critical for alloy selection and quality assurance. Solidification modeling was an important tool in effective and timely design.**
- **The six month production schedule, the challenges of prototype verification, and the high product count for this 2,100 pound casting called for strong project management skills and flexibility in resource allocation, production planning, and scheduling.**

Address comments to: blairr@sfsa.org

Last Modified:July, 2006 by STG

In cooperation with ME Elecmetal

Summary

Track Shoe for the NASA Crawler Transporter

The direct benefits of producing the track shoe as a steel casting are --

- **Rapid, Cost Effective Production** --The design flexibility, short lead times, near-net shape capability, and rapid production capacity of castings met the demanding 6-month delivery schedule at the target cost.
- **Performance** -- The 1000+ track shoe castings with their new design, tailored alloy, and rigorous process and QA control are anticipated to perform reliably throughout the life of the Space Shuttle program and on to service for the next generation space flight vehicle.

Shuttle Launch *(NASA Photo)*

For further information on casting steel alloys, contact --
Jeff Washburn at ME Elecmetal, Phone-- 763- 788-1276
E-mail: jwashburn@me-elecmetal.com ***Web Site = http://www.meglobal.com/***

Acknowledgment --
The metalcasting design studies are a joint effort of the Steel Founders' Society of America and the American Foundry Society. Project funding was provided by the American Metalcasting Consortium Project, which is sponsored by the Defense Logistics Agency, Attn: DLSC-T, Ft. Belvoir, VA, 22060-6221

Back ***The End***

Return to SFSA Home Page

Page 1

In cooperation with ME Elecmetal