An Example in Steel Casting

The Ice Cleat on the M1 Abrams Tank

The Application

The M1 Abrams tank uses rubber pads on the track to provide traction and reduce track noise. But under icy road conditions in hilly terrain, the rubber pads on the track loose traction, just like automobile tires loose traction on snow and ice in winter. On your car, you install tire chains in winter. The Army uses "ice cleats" on the track of the M1 tank to give more "bite" and to provide traction on icy, hilly roads and terrain.

The "ice cleats" are steel plates with an X-shaped cleat extending out from the base. They are substituted for the rubber pads on every fifth shoe on the tank track. Each tank uses two sets of 32 ice cleats for winter traction.

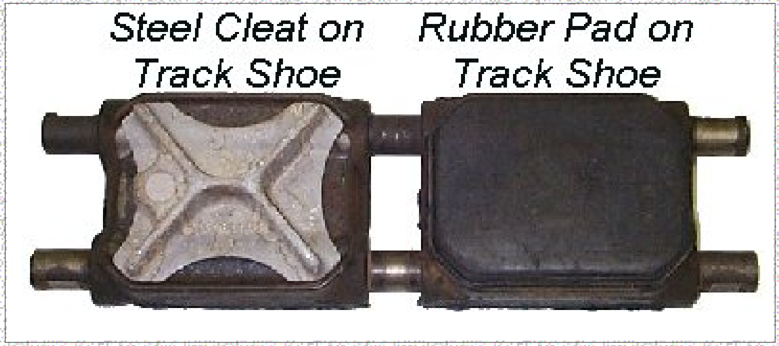
M1 Abrams Tank on a Winter Road

Ice Cleat Description

The ice cleat weighs approximately 8 pounds and has a footprint of 6" x 7" and a height of 2 ". It is bolted to the track shoe using the same mounting system used for the rubber pads.

The current ice cleat design calls for a heat-treated forging made from 4140 or 4340 steel alloy for high strength and toughness to survive road abrasion and impact at sub-zero temperatures.

The finished cleat requires dimensional tolerances on the order of 0.06" to fit snuggly into the track shoe. The only machining requirements are a drilled and tapped hole for the mounting stud and 3 milled locator pads on the flat face of the cleat.



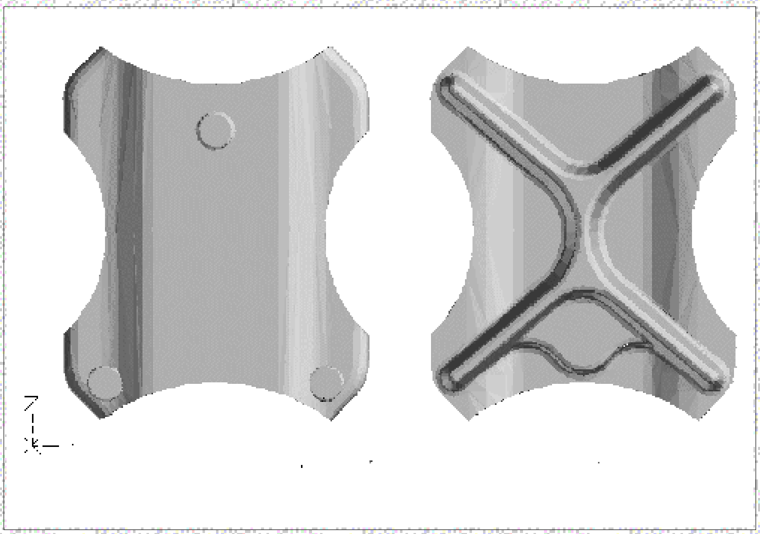
Track Section with Steel Ice Cleat and Standard Rubber Pad

Back Next

Acknowledgement --
The metalcasting design examples are a joint effort of the Steel Founders' Society of American and the American Foundrymen's Society.
Project funding was provided by the American Metal Casting Consortium Project, which is sponsored by the Defense Logistics Agency, Attn: DLSC-T, Ft. Belvoir, VA 22060-6221

How Can a Casting Cut Lead Time?

The Challenge



Two Faces of the Ice Cleat

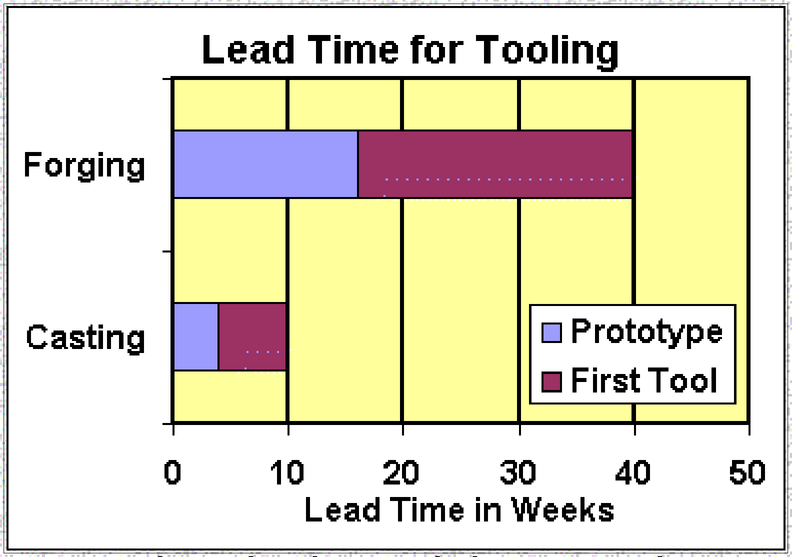
The original design of the ice cleat called for a closed-die forging. But this was a new item purchase, and there were no forging dies on hand. New dies would have to be designed and made, but would require almost six months of lead time for dies and a total lead time of 10 months for prototype production (80 cleats).

There had to be a faster manufacturing technology which could meet production and performance targets.

The Metalcasting Solution

A manufacturing study showed that a steel casting could be produced in a much shorter time, compared to a forging.

- Prototype tools could be made in two (2) weeks, , based on a CAD file and CNC machining of an aluminum tool. The first production tool for would be available at the 10 week mark.
- The foundry can cast six cleats with one pour in a flask, using a multiple castings on a tree. This raises the production rate.
- With a casting, the strength properties will be more uniform with no directional variations.



Bar Chart Showing Lead Time Comparison

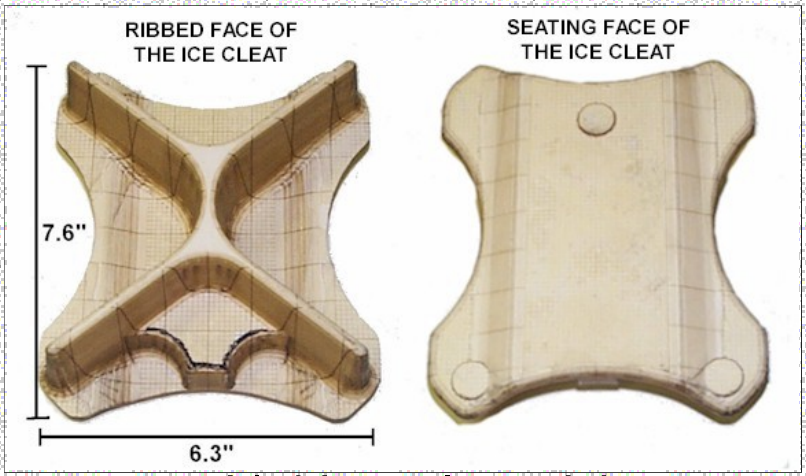
Back Next

What are the Steps in Designing the Casting?

Initial Casting Decisions

Before detailed design and manufacturing decisions are made, the casting designer has to consider two fundamental issues --

- **What is the most appropriate casting process?**
- **What is the most appropriate alloy to use in the casting, considering both the performance and the manufacturability (castability and machinability)?**



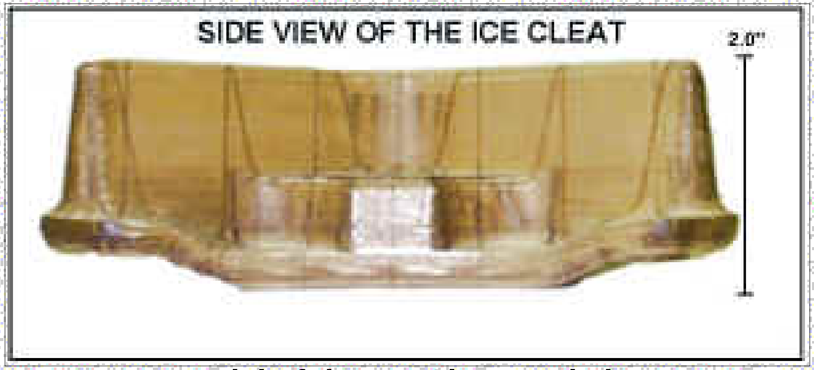
Model of the Ice Cleat made by Laminated Object Manufacturing

Go to the casting process and alloy selection pages.

Detailed Design Factors

Once the casting process and the alloy are selected, the casting designer carefully reviews the component, looking at the factors and design features that determine soundness and castability.

- **Draft Angles, Radii, and Fillets**
- **Hot Spots and Thin Sections**
- **Directional Solidification**
- **Parting Line and Orientation**
- **Risers for Metal Feed**
- **Gates and Runners**



Model of the Ice Cleat made by Laminated Object Manufacturing

Go to the detailed casting design pages.

Back Next

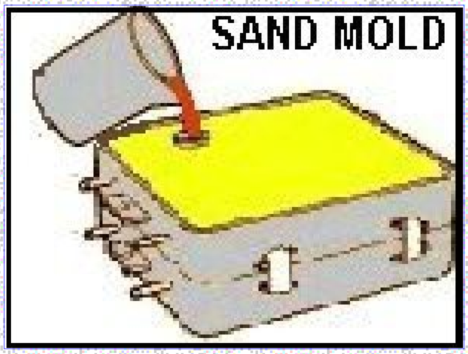
What is the Most Effective Casting Method?

Critical Requirements for the Ice Cleat

The ice cleat has the following performance and production characteristics which have an impact on the mold type--

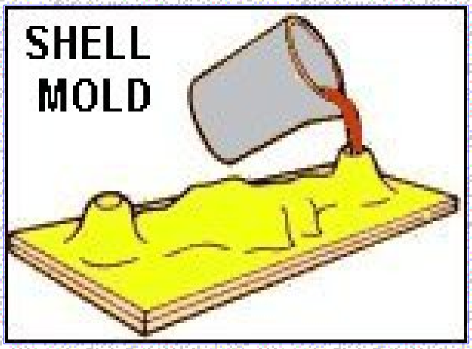
- ***Tolerances are +/- 0.06" with moderate surface finish***
- ***Fast first item delivery with low rate, long term production***
- ***Component design has moderate complexity.***
- ***Choice of molding method can be a major factor in production cost***

Casting Mold Options: *The casting can be produced by 3 different types of molds:*



Dry Sand Mold -- Made by packing loose sand around a pattern and removing the pattern to form a hollow mold.

Investment Mold -- Made by making a wax pattern in a metal tool and then coating the disposable wax pattern with refractory coating and melting out the wax.



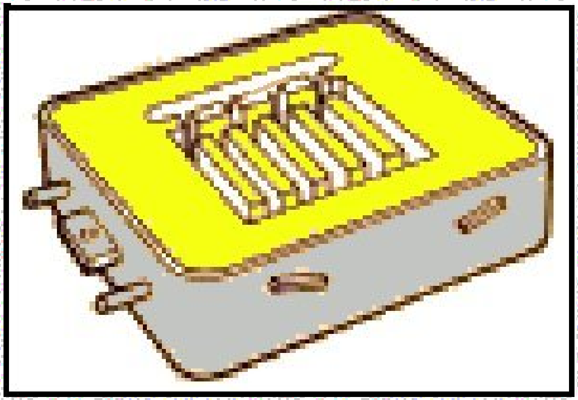
Shell Mold -- Made by heating a resin-sand mixture in metal tools, forming top and bottom shells which are joined to form a mold.

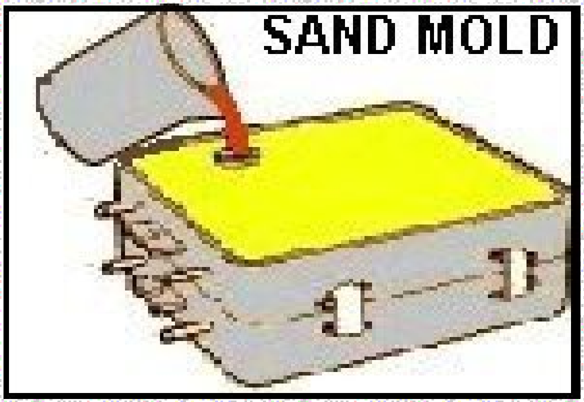
Given the following characteristics of the 3 molding methods,
choose the mold type
that is most appropriate for producing the ice cleat.

Characteristic	Green Sand Mold	Investment Mold	Shell Mold
Surface Finish & Intricacy	Good	Best	Better
Tolerances	Good (0.03")	Best (0.005")	Better (0.008")
Pattern Cost	Low	High	High
Tooling Lead Time	Short	Longest	Long
Design Adaptability	Excellent	Moderate	Low

Back Next

The Green Sand Mold





The Green Sand Mold

The green sand molding process is the casting mold process of choice because --

- **The patterns for the sand mold are low cost .**
- **A high surface finish and tight dimensional tolerances are not critical for the ice cleat.**
- **The prototype run has too short of a lead time for a shell or investment pattern.**
- **Sand molds are suitable for producing multiple castings in a tree configuration.**
- **If design changes are necessary, the pattern for the sand mold can be easily changed, with the opportunity for rapid tooling methods, such as laminated object manufacturing.**

Casting in a green sand mold is the right process choice.

Go to the section on alloy selection.

Back Next

The Investment Molding Process

Investment Mold

The Investment Mold

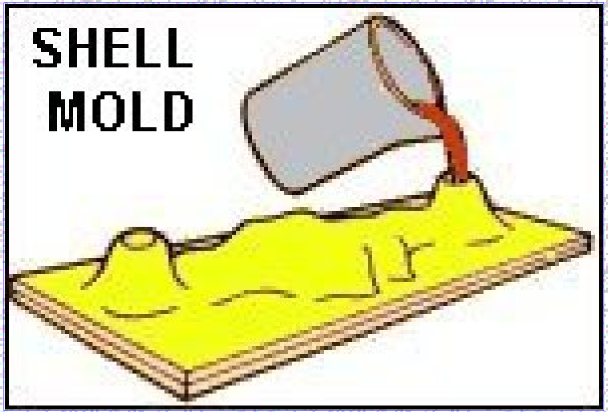
The investment molding process is not the best casting method for the ice cleat because --

- The lead time for the metal tool for the wax patterns too long.
- The production run is not large enough to justify the cost of a permanent metal tool for making the discardable wax patterns
- A smooth surface finish and tight dimensional tolerances are not critical for the ice cleat.

Go back to the molding process section and make another choice.

Back Next

The Shell Molding Process



Shell Mold

The Shell Mold

The shell molding process is not the best casting method for the ice cleat because -- --

- **The production run is not large enough to justify the high cost of a metal tool.**
- **The lead time for the metal tool is too long.**
- **A smooth surface finish and tight dimensional tolerances are not critical for the ice cleat**
- **Design changes are expensive and time consuming with the metal tool, as compared to a wood or laminated tool.**

Go back to the molding process section and make another choice.

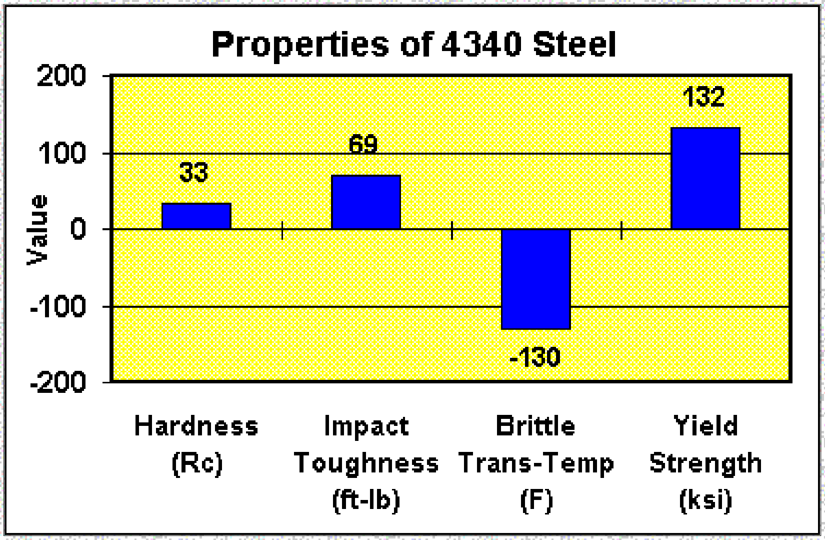
Back Next

Which Steel Alloy has the Optimum Properties?

The Alloy Requirements

The ice cleat has to survive in very abrasive and high impact conditions. The original forging design of the ice cleat called for a 4340 or 4140 steel alloy with a hardness of 34-40 Rc after heat treatment, an impact toughness of 50 ft-lbs, and a yield strength of 140 ksi.

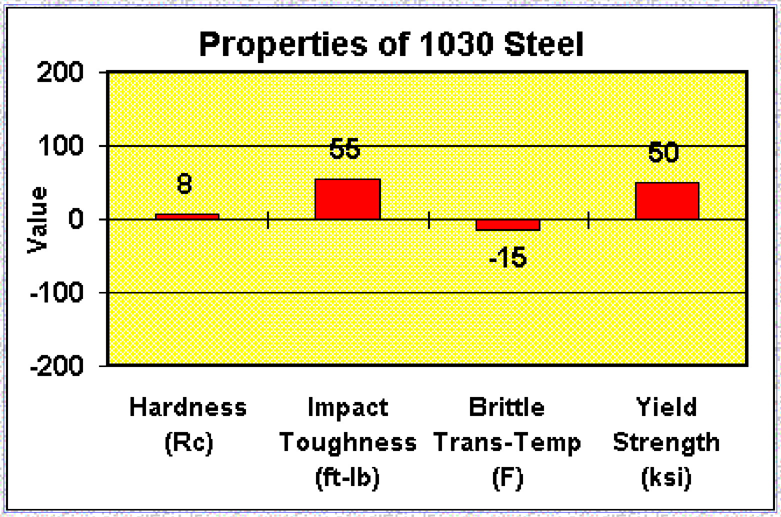
Some steel alloys shift from a strong, ductile failure to a low toughness brittle failure at cold temperatures. The temperature where this shift occurs is the "ductile-brittle transition temperature. The ice cleat will be exposed to sub-zero temperatures (-50F). The 4340 alloy is ductile down to -150F.



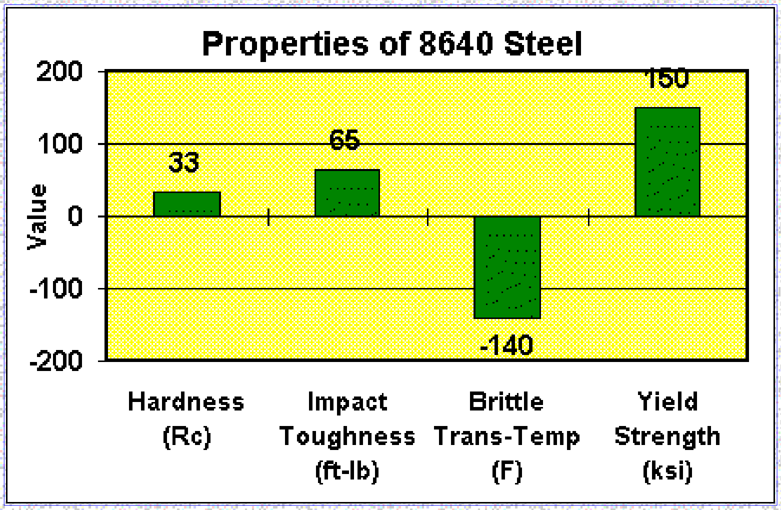
4340 Steel Properties

The casting engineer has to select a castable steel alloy that meets the performance requirements with a brittle transition temperature below -50F.

Choose one of the alloys below for the ice cleat.

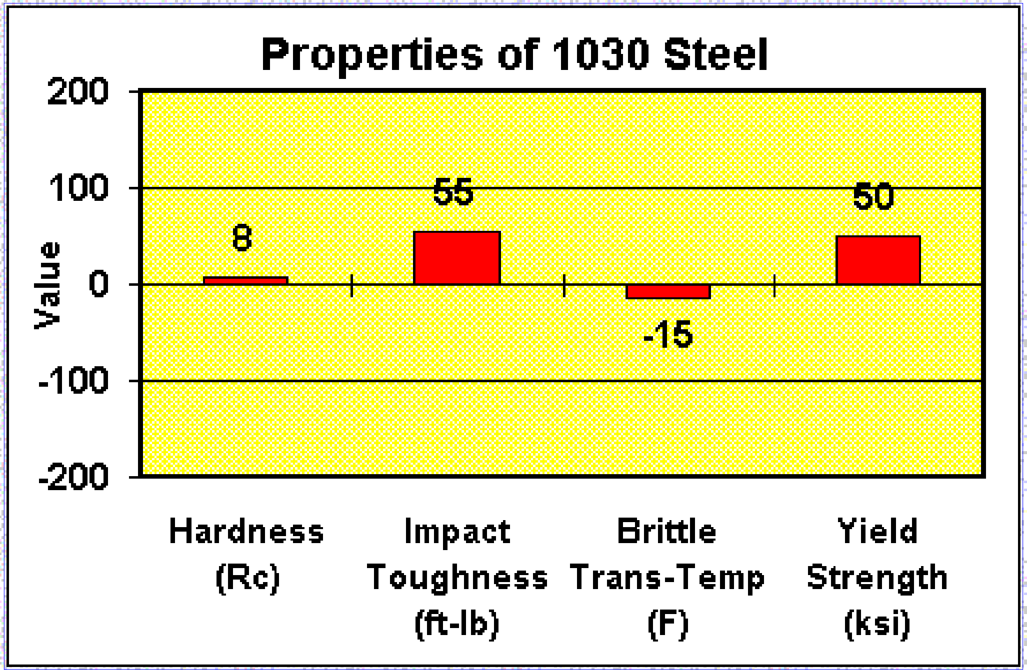


1030 Steel -- A Low Cost, Low Carbon Steel



8640 Steel -- A Low Alloy Steel

Steel Alloy 1030



1030 Properties

Alloy 1030

The 1030 alloy is a standard low carbon alloy with the right toughness value of about 50 ft-lbs. It is a low cost alloy, but it doesn't meet the other performance requirements --

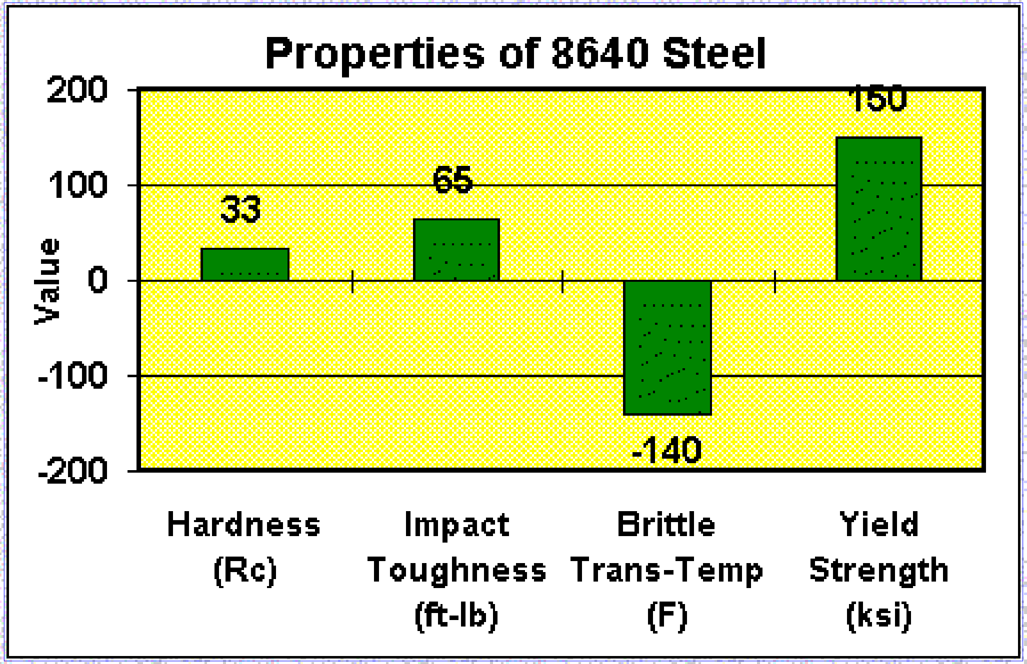
- The yield strength of the 1030 alloy is 50 ksi, less than the desired 140 ksi
- The hardness is only about 8 Rc, much less than the 35 Rc required for wear resistance.
- The brittle transition temperature is about -15F, much higher than the required -50 F.

The 1030 is not the best alloy for the ice cleat.

Go to back to the page on alloy selection.

Back Next

Steel Alloy 8640



8640 Properties

Alloy 8640

The 8640 alloy has the right yield strength (150 ksi), sufficient impact toughness (65 ft-lbs) , and acceptable hardness (35 Rc).

In addition the transition temperature is -140F, equal to the transition temperature of the original 4340 alloys.

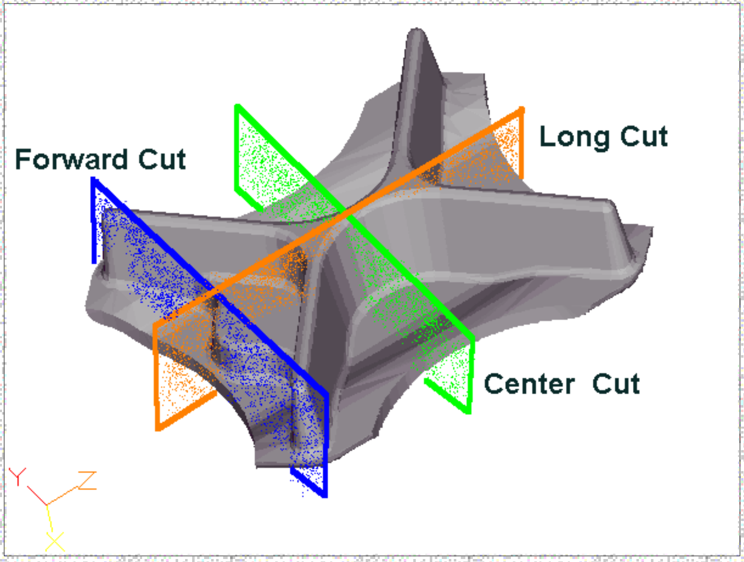
An additional benefit is that the 8640 is a lower cost alloy than the original 4340, because the 8640 has a lower nickel content than the 4340.

Go to the page on design issues.

Back Next

Draft Angles, Radii and Fillets

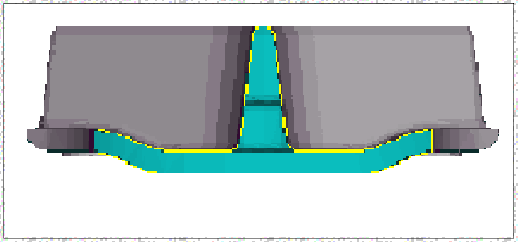
Design Criteria for Draft Angle, Radii, and Fillets



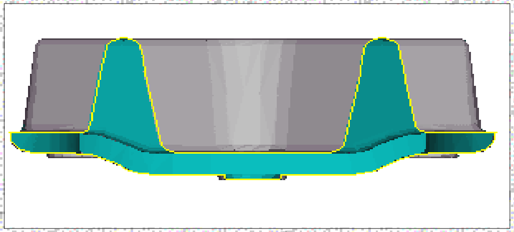
The ice cleat design is then reviewed to determine if --

- **Vertical surfaces have the proper draft angle so the mold can be drawn from the pattern. A draft angle of 1° is common.**
- **Sharp radii and fillets are smoothed and rounded to avoid turbulent metal flow and to avoid hot tearing, poor fill, and stress concentrations.**

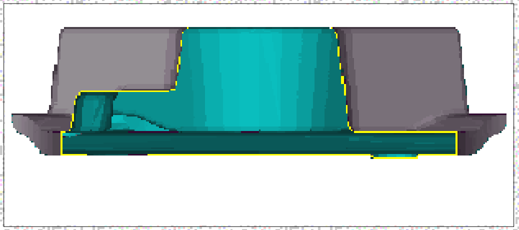
Three cross sections of the ice cleat are shown below illustrating the vertical draft angle and the radii and fillets on the original design.



Center Cut



Forward Cut



Long Cut

Since the ice cleat was originally designed as a forging, where mold release, metal flow, and stress concentrations are also important design issues, the draft angles, radii, and fillets are more than sufficient for good castability.

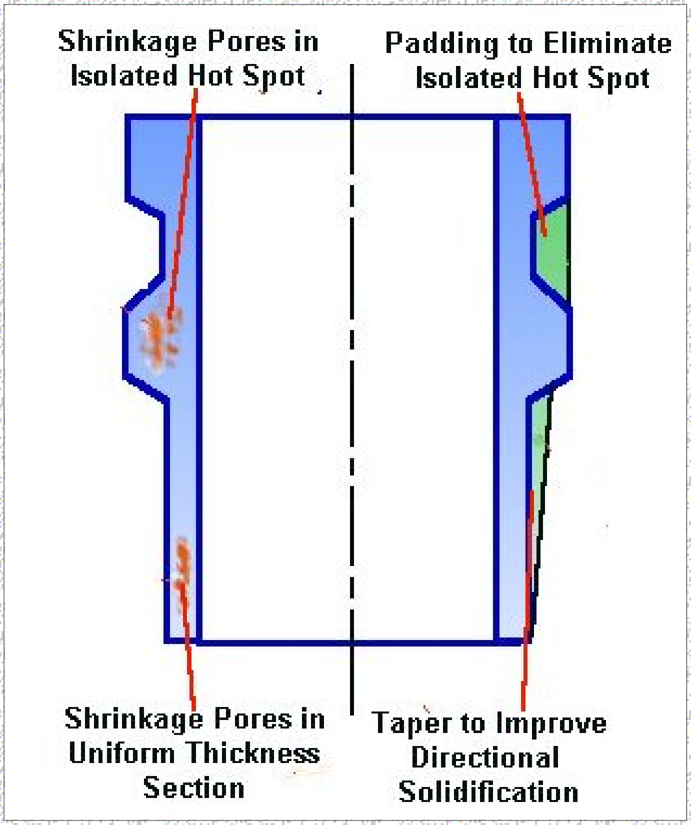
Back Next

Review for Hot Spots and Directional Solidification

Eliminate or Reduce Isolated Hot Spots

In evaluating a component design, the casting engineer looks for isolated thick sections which could be "hot spots" where shrinkage porosity or "hot tears" might form.

- As metal in thin sections solidifies first, the thicker section will be isolated from the molten metal feed and shrinkage porosity can form in the thick section .
- The thin connecting section into the thicker section should be "padded" to improve the thermal connection and metal flow into the "hot spot".

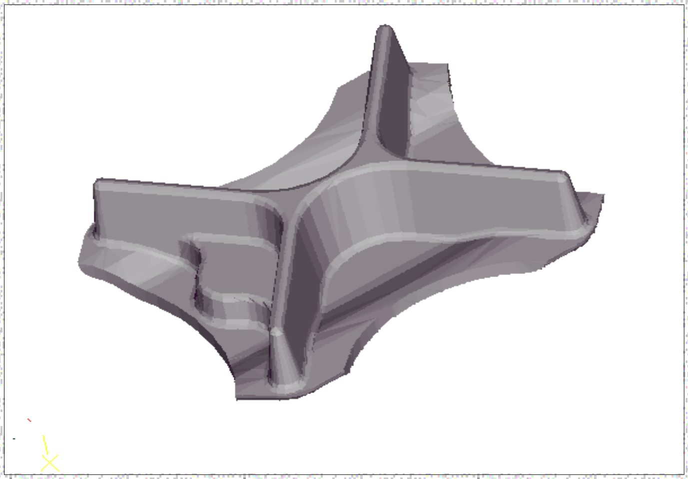


Generic Example of Padding and Taper

Directional Solidification

The casting engineer studies the design to see if the thermal gradients in the piece will promote directional solidification. Review the design, looking for flat sections that can be lightened and long thin ribs that need to be tapered to promote directional solidification

- Large flat sections are difficult to feed and to develop good directional solidification. Adding taper along a rib or section from the cold region to the hot region promotes directional solidification and prevents shrinkage pores.



A review of the ice cleat shows that there are no obvious "hot spots" or extended thin sections where padding or tapers are required.

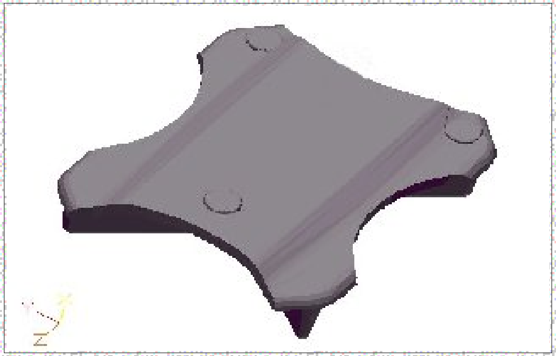
Back Next

Machining Features

Designing for Machining Features

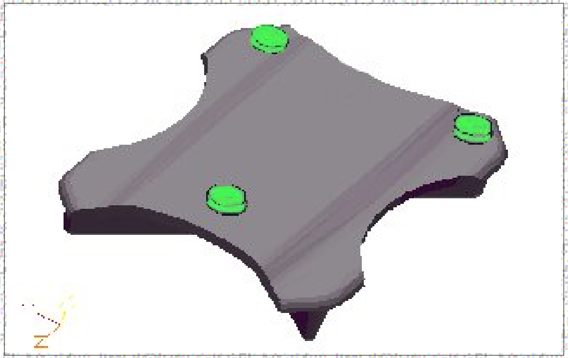
The ice cleat has a requirement for two features that have to be machined. These features are --

- **A shouldered hole in the center body through which the mounting bolt passes. There is sufficient stock in the body for the hole. No design features have to be changed in the casting.**
- **Three flat studs on the back face which act as locating pads for the ice cleat in the track shoe.**



Original Design

To provide enough metal stock for final machining of the flat studs, bosses are added to the design. These bosses are approximately 3/8" thick.



Design with Machining Bosses

Go to the next design section where parting lines and orientation are considered.

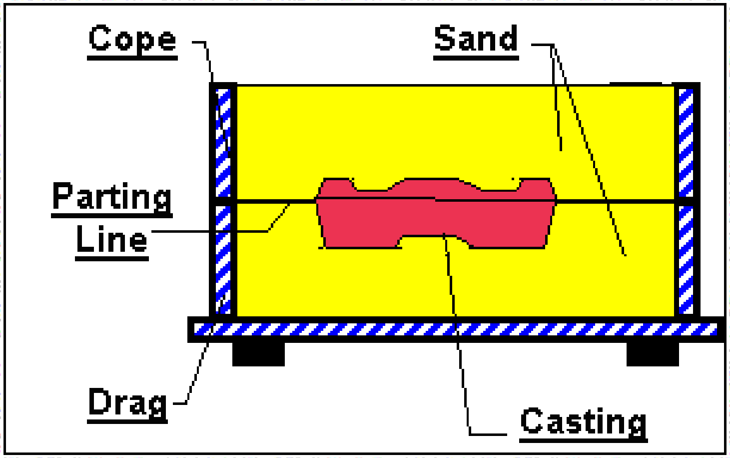
Back Next

Parting Line and Orientation

Parting Line and Orientation in the Mold

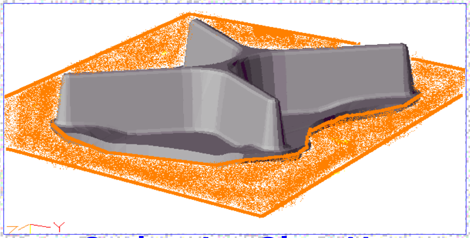
Design Criteria -- The pattern has to be planned and designed so that –

- **The parting line is in the largest cross-sectional plane of the casting.**
- **The component face with the greatest surface detail is in the drag, because fluid fill is better in the drag and low-density, non-metallic inclusions tend to segregate in the cope at the top of the casting .**
- **The pattern is oriented for continuous, low velocity , non-turbulent fluid flow.**
- **The need for cores is minimized or eliminated.**

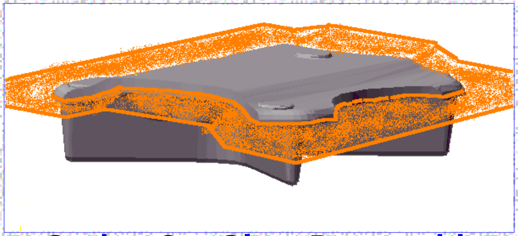


Schematic of Parting Line in a Sand Mold

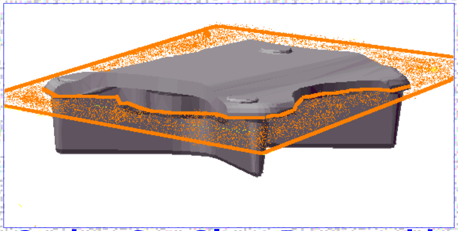
Three pattern orientations and parting line options are shown.
Choose the one that bests meets the design criteria



Option 1 -- Cleat Up



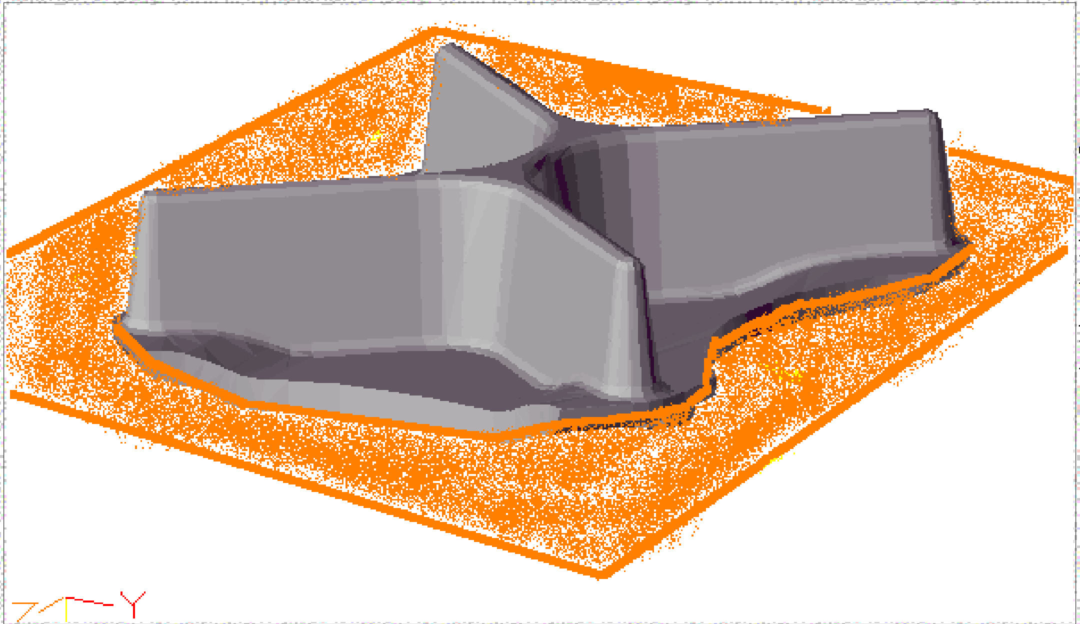
Option 2 -- Cleat Down with Curved Parting Line



Option 3 -- Cleat Down with Straight Parting Line

Back Next

Option 1



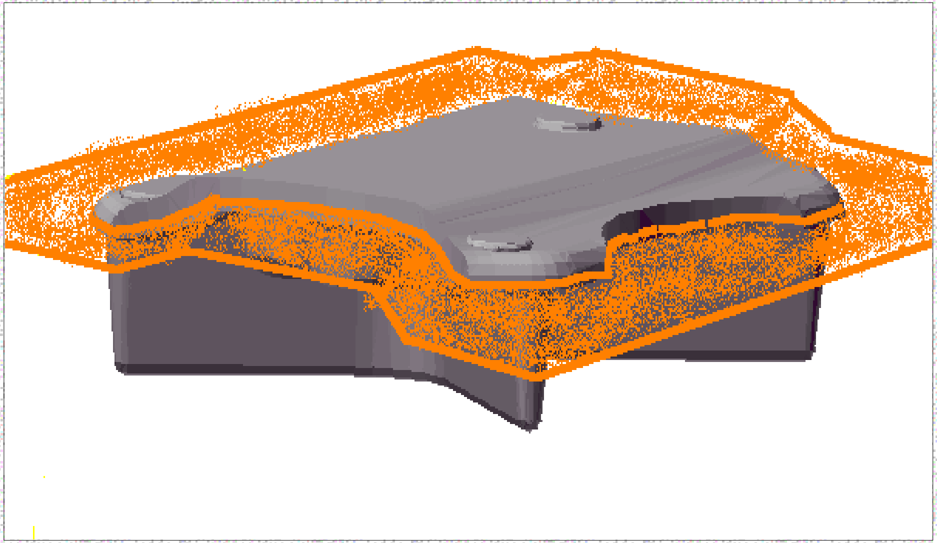
Option 1-- Cleat Up

The ice cleat is oriented with the cleats and finer detail facing up. It is preferable for the detailed features to be facing down in the mold with the large flat surface facing up.

Go back to the parting line and orientation page and choose another option.

Back Next

Option 2



Option 2 -- Cleat Down with Curved Parting Line

The ice cleat is oriented with the cleats and finer detail facing down in the mold. This allows any porosity or inclusions to rise to the thicker, unstressed flat section.

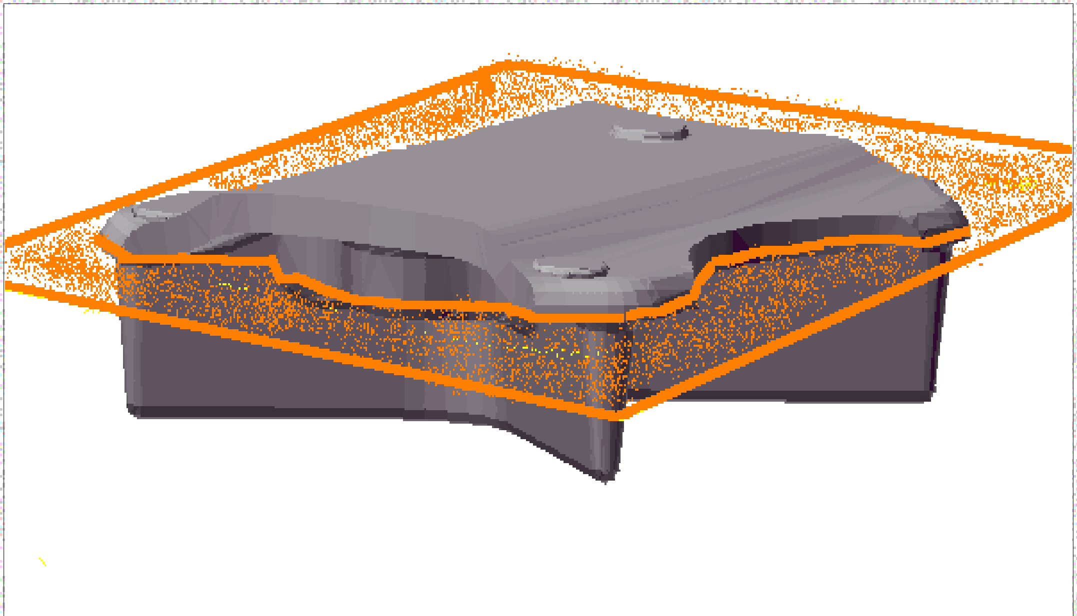
The parting line has been curved to fit along the curved plane of the base section. If the parting line is kept straight, the curve in the base section would require a core.

This is the best option for the parting line and component orientation in the mold.

Go to the next page, showing the cope and drag designs

Back Next

Option 3



Option 3 Cleat Down with Straight Parting Line

The ice cleat is properly oriented with the detailed features down in the mold. But the parting line is perfectly horizontal and does not follow the curve in the base plate section of the cleat. With a flat parting line, a core would have to be used to introduce the curve in the base section.

There is an alternate way to shape the parting line so that a core isn't needed.

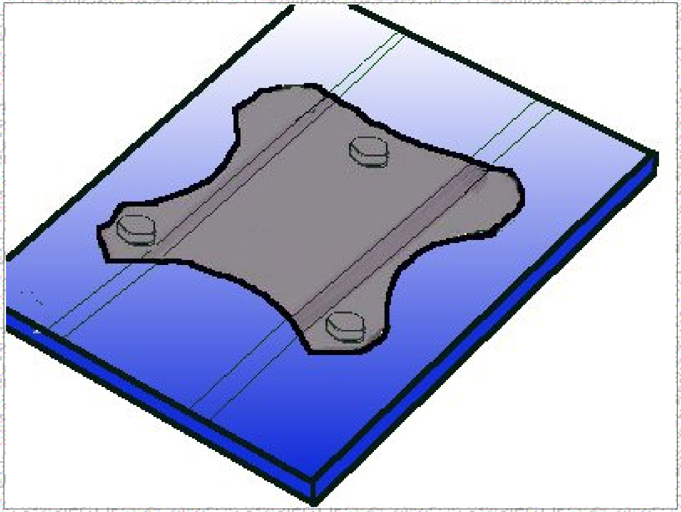
Go back to the parting line and orientation page and choose another option.

Back Next

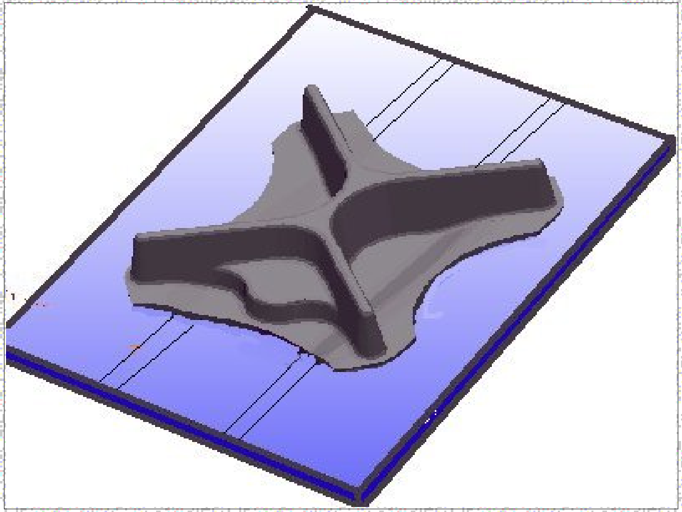
Baseline Design for the Cope and Drag Patterns

Baseline Pattern Design

After reviewing the component design from a casting perspective, the patterns for the cope and drag sections of the mold are prepared incorporating the casting features on the component.



Baseline Cope Pattern



Baseline Drag Pattern

The next step is to add rigging features to the pattern to fill the cavity and control the solidification.
These features are risers, gates, runners, and sprues.

Back Next

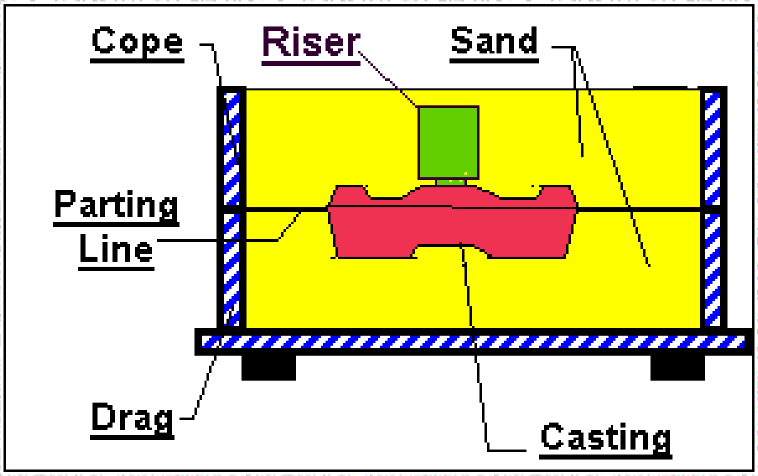
Riser Placement and Sizing

Risers

Risers are reservoirs of molten metal to supply the solidifying sections of the casting with make-up metal. The molten metal in the risers accomodates liquid-to-solid shrinkage and prevents internal or external voids.

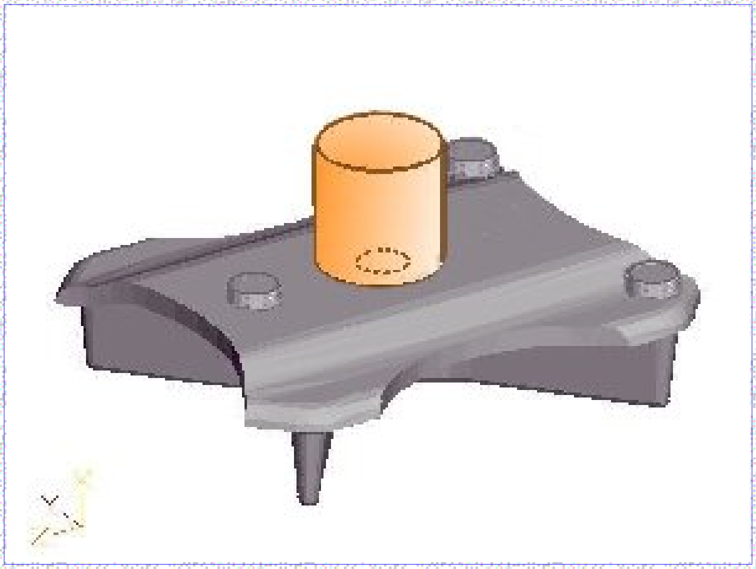
- Risers are placed and sized to provide sufficient metal flow into the mold during cooling to compensate for shrinkage.
- Steel castings have a short metal flow range and a high shrinkage factor. This requires large risers that feed uniformly into the casting.

The riser design for the cope pattern should provide the shortest, most direct metal feed into the hottest sections during cooling. It should be large enough to retain heat and be the last section to cool, so that the final solidification shrinkage is in the riser, not in the casting.

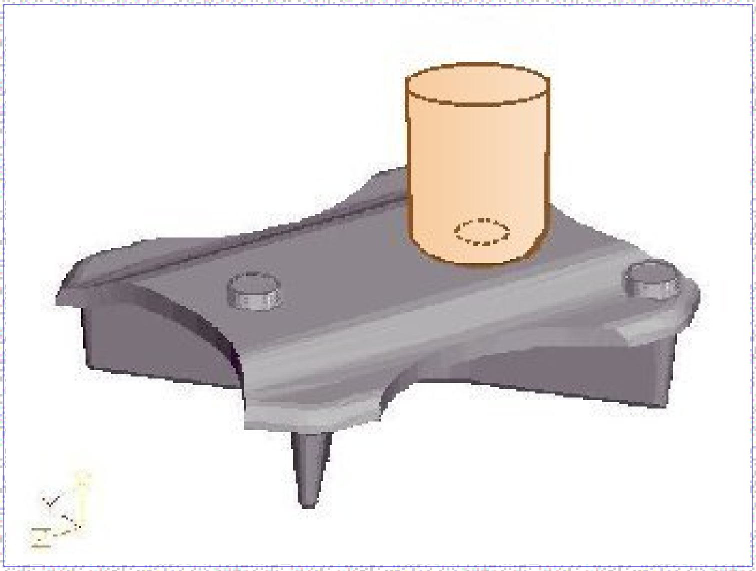


Schematic of Riser Position

Two riser options are shown. Choose the one that bests meets the design criteria



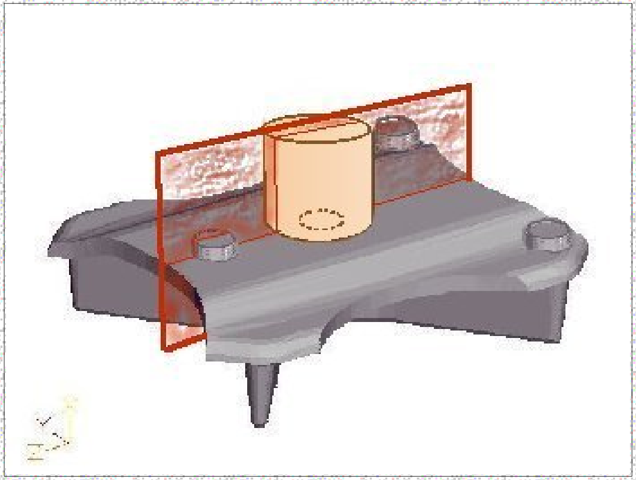
Option 1 -- Short Centered Riser

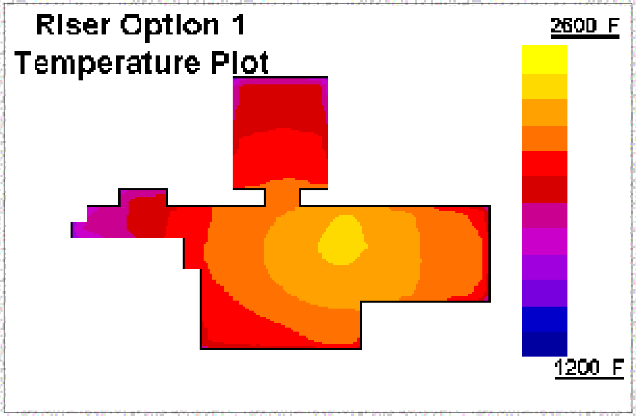


Option 2 -- Tall Offset Riser

Back Next

Riser Option 1





Riser Option 1- Solidification Model

The lower diagram shows the results of a solidification analysis of Riser Option 1. What you see is a vertical cut across the thickest, long section of the casting with the thick boss section to the right.

The colors show the temperature distribution in the casting after solidification has finished -- blue is coldest (1200F), yellow is hottest (2600F)

The yellow section (the hottest section) is down in the thick section of the casting and would freeze last, producing shrinkage porosity in the body.

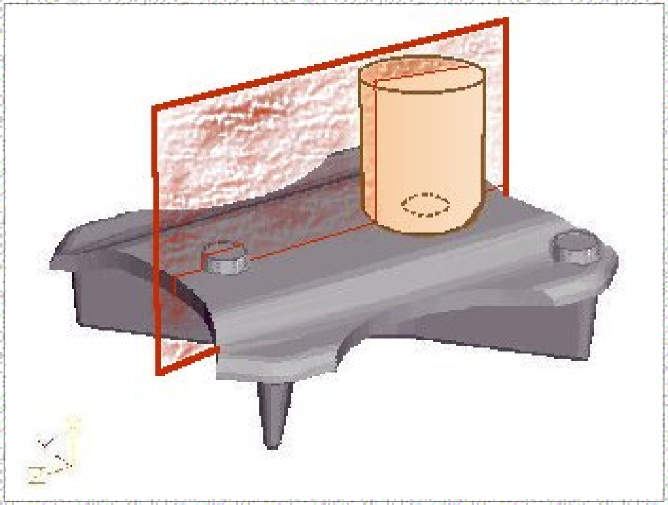
The riser is not tall enough nor positioned correctly to provide enough feed metal into the thick section of the casting.

[Go back to the riser selection page and choose another design]

[Back] Next

Acknowledgement: Solidification modeling was done with AFSolidification System (3D) software available from AFS Software (http://www.afsinc.org/Newafsoftware.html)

Riser Option 2

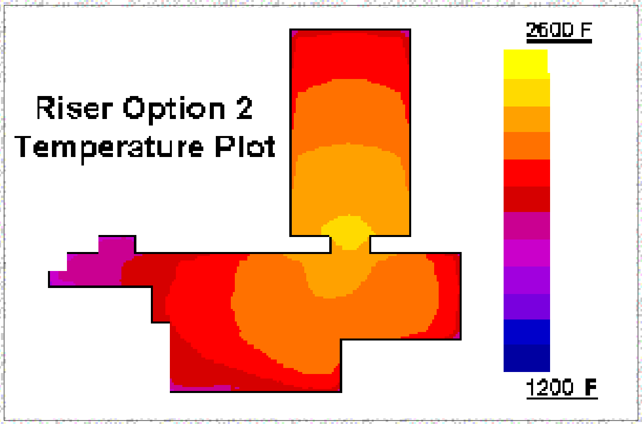


The diagram shows the results of a solidification analysis of Riser Option 2. What you see is a vertical cut across the thickest, long section of the casting.

The colors show the temperature distribution in the casting after most of the cooling has occurred -- blue is coldest, yellow is hottest.

With the taller riser centered over the thickest section of the cleat, the hottest section (marked in yellow) is in the riser and would freeze last. The casting itself would be sound with good metal feed during cooling, because the riser is properly sized and positioned.

Go to the next section on gating.



Riser Option 2-- Solidification Model

Back Next

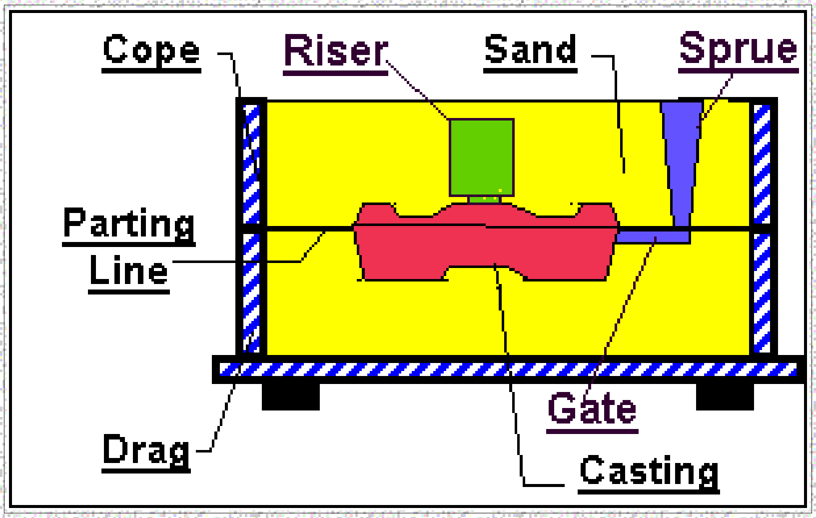
Acknowledgement: Solidification modeling was done with AFSolidification System (3D) software available from AFS Software (http://www.afsinc.org/Newafsoftware.html)

Gating Systems

Metal Flow into the Mold

The gating system (sprues, runners, and gates) provides paths for the molten metal to flow into the mold. For steel castings, it is important that the mold fills quickly, without turbulent flow.

- Runners and gates have to promote high volume, low velocity flow.
- On the ice cleat, the logical location for the gate is directly into the thickest section of the cleat.
- The size of the ice cleat is small enough that multiple items can be produced in one pouring by putting several ice cleat patterns on a "tree" with the gates connecting into a single runner.

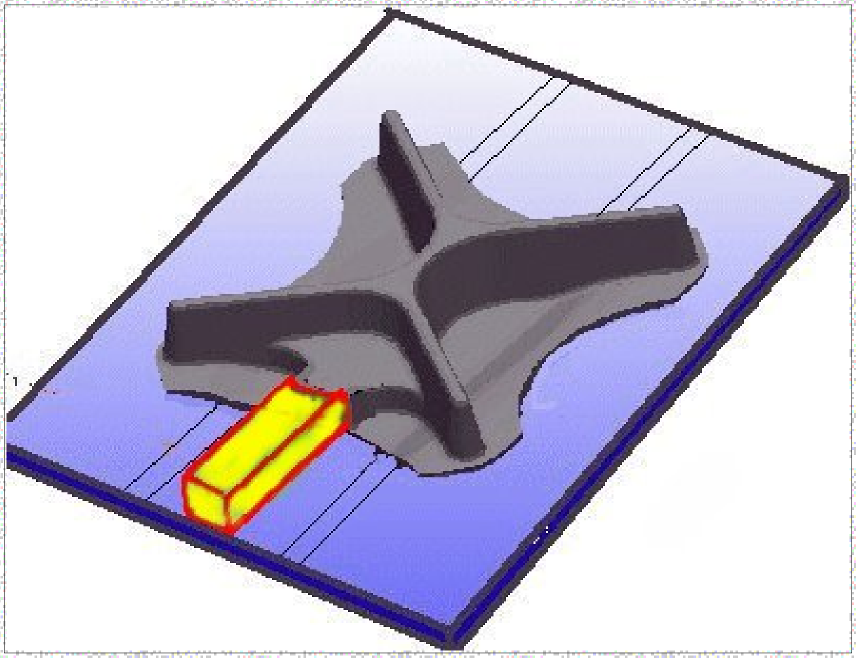


Schematic of a Gating System

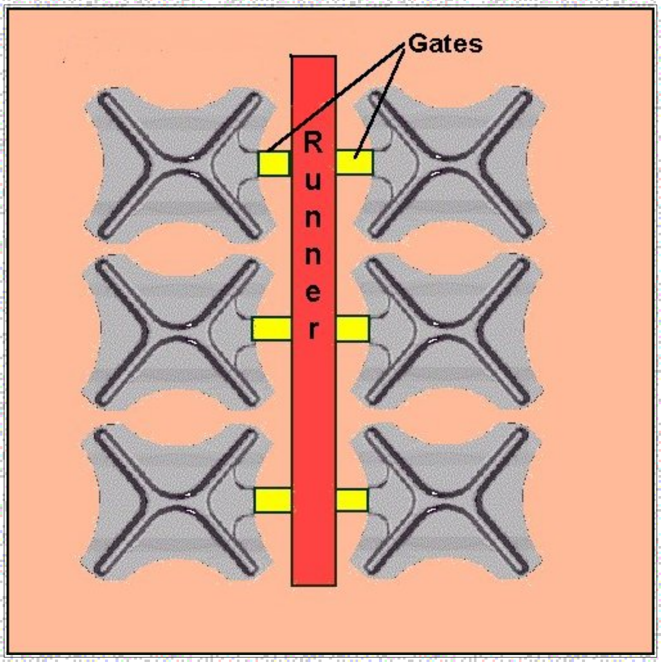
The runners and gates need to be integrated with the placement of the risers.

The two diagrams below show two views of the gating design. The first diagram shows the detail of how the gate is integrated into the baseline design.

The second diagram shows how multiple components are branched onto a runner and gating system to produce six ice cleats in one pouring.



Detail of Gating into Cope Section



Drawing of 6-On Gating System

Back Next

Finished Cope and Drag Patterns

Baseline Pattern Design

The patterns for the cope and drag sections of the mold are prepared incorporating all the casting features and setting up for a 6-on pattern

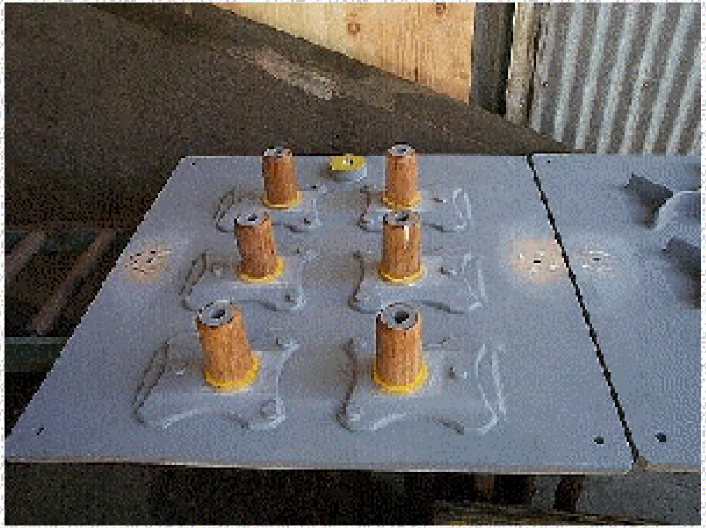


Photo of Final Cope Pattern showing the Risers on Each Cleat

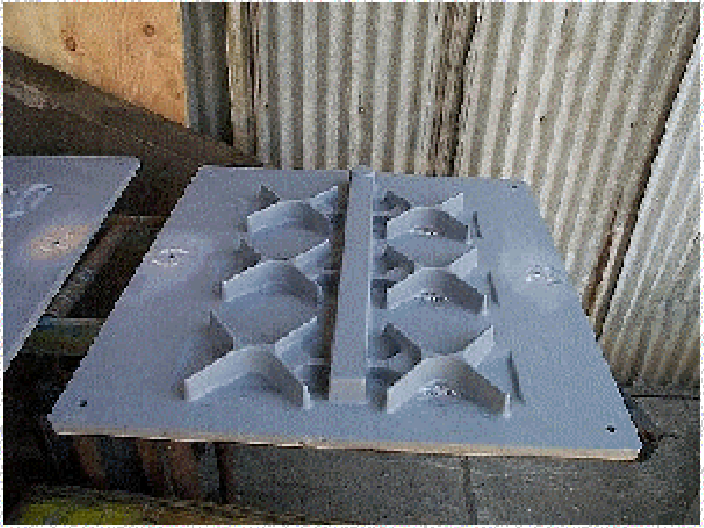


Photo of Final Drag Pattern showing the Gates and the Runner

With these patterns, molds were made and the cleats were cast using standard practices.

Back Next

Shakeout and Finishing

SHAKEOUT

After the casting has solidified in the mold, the casting is removed from the sand mold by a process called "shake-out." Typically the entire mold is vibrated to "shake" lose the sand from the metal casting. . Additional clean up of mold material can be accomplished by abrasive blasting.

With the Ice Cleat, the part was allowed to solidify and then conveyed to a mechanical vibrator. The mold and part were shaken for several minutes until the majority of the sand was removed. The sand from the mold is then recycled to make new molds. The part, still very hot, is then removed from the vibrator and allowed to continue cooling. Before the finishing process begins, the part is abrasive blasted to remove the remaining sand.

FINISHING

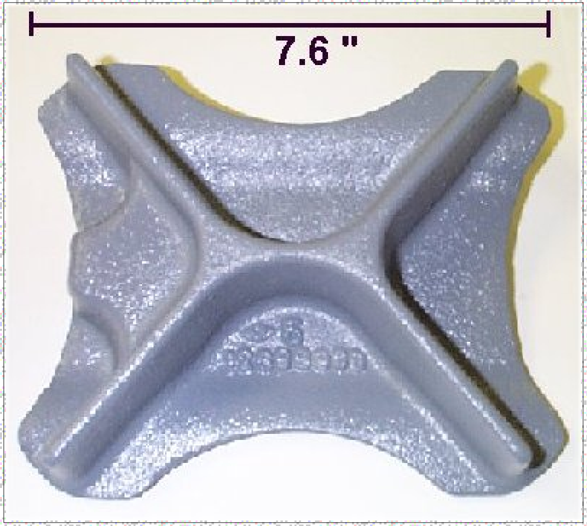
The finishing operation begins after the part has been removed from the mold. During this process the gating system is removed from the mold. The risers and gates are removed from the part with a torch, grinder, or saw. Typically, additional clean up of flash and other final touch-up is done with a grinder. This step yields a casting that is ready for heat treatment, machining, and/or coatings.

After the mold material is removed from the cleat, the risers are removed with a torch. Then the Ice Cleats are removed from the "tree", or the gate and runner system that delivered the molten metal to the mold of the cleat, also with a torch. The part is then ground to clean up the edge of the cleat at the parting line to remove any sharp burrs from flashing, and to touch-up the area where the riser was torched the part. Finally, the part is sand-blasted for a final clean-up.

The Ice Cleat Casting

The Ice Cleat in the Finished Condition

The ice cleat was successfully cast using the 6-On pattern. The photos show the ice cleat in the as-cast condition after finishing and coating, but before final machining.



Detail Photo of the Ice Cleat Face

Detail Photo of the Ice Cleat Base

Back Next

An Example in Steel Casting

Summary -- Casting the Ice Cleat for the M1 Abrams Tank

The Benefits

- Tooling was completed in 2 weeks. Prototype part assemblies were completed in 6 weeks.
- The casting met all performance requirements -- wear, toughness, and durability -- in a field test.

Ice Cleat Mounted for Testing

M1 A1 Abrams Tank

Acknowledgement

The metalcasting design examples are a joint effort of the Steel Founders' Society of American and the American Foundrymen's Society.

Project funding was provided by the Lead Time and Cost Reduction Program, cosponsored by the American Metalcasting Consortium and the Defense Logistics Agency, Attn: DLSC-T, Ft. Belvoir, VA 22060-6221

The developers would like to thank Ray Schneider, John Steadman, Ken Porter and Dick Wooding of Varicast for their time and information used in the making of this metalcasting design example.

www.varicast.com

Your comments and suggestions on these metalcasting design examples are welcome -- monroe@scra.org.