A Design Study in Ductile Cast Iron

THE UNIVERSAL JOINT COUPLER IN A MARINE INBOARD-OUTBOARD ENGINE

Design Study Outline

- Introduction
- Selecting an Iron Alloy
- Reducing Machining Steps
- Optimizing for Production Costs
- Designing for Manufacturability
- Controlling Pattern Costs
- Summary

Start the Design Study

Acknowledgement --
The metalcasting design examples are a joint effort of the American Foundrymen's Society and the Steel Founders' Society of America.
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Universal Joint Coupler for the Inboard-Outboard Engine

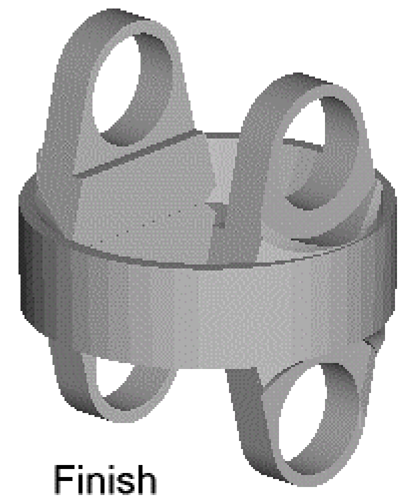
<u>The Application</u> -- The universal joint coupler is a key component in the drive train of the Mercury Marine Inboard-Outboard engines. The double-center universal joint transmits power from the in-board engine to the out-board stern drive unit and allows the drive unit to:

- pivot for steering
- change the propeller angle-of-attack
- provide easy access to the propeller and lower drive section for maintenance and inspection.

<u>Component Description</u> -- The coupler is a 3 ½ in diameter ring with 4 tabs (with holes for the coupling pins) extending from the ring, two on each side. The overall length is 4 inches and the weight is approximately 2 pounds.

- The critical performance and engineering issues for the coupler are fatigue life and precise dimensional tolerances for assembly and alignment.
- The annual production is 250,000 units.

How Can a Ductile Iron Casting Reduce Costs?



<u>The Challenges</u> -- Originally designed as a steel forging, the coupler --

- Required 10 machining steps to achieve final shape and to meet dimensional tolerances.
- Was purchased from off-shore sources for the lowest forging price. however off-shore purchase required --
  - large-lot production
  - long lead times
  - substantial shipping costs.

<u>Benefits of Using a Ductile Iron Casting</u> --

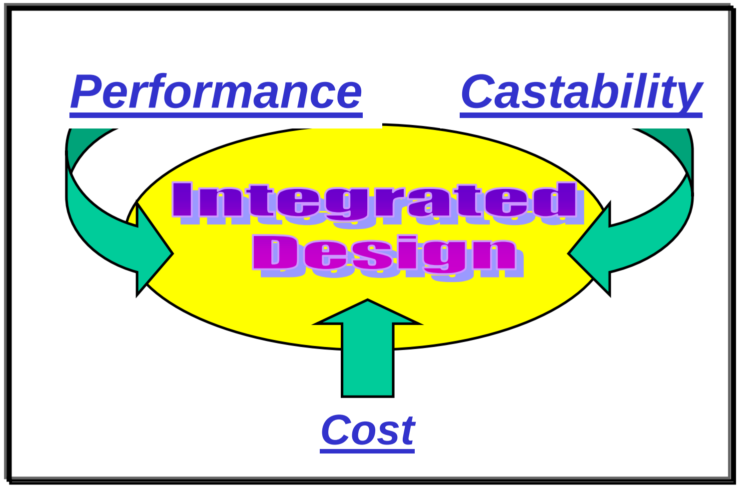
A casting design study showed that the component cost could be reduced by 50% (compared to the original forging design) by using ductile iron casting. This cost reduction was achieved by:

- Improved near-net shape which reduced machining operations.
- Casting in sand for low cost, high efficiency production.

Conversion to a domestic source casting also reduced inventory costs by offering "Just-In-Time" production lots with shorter lead times and lower total shipping costs, compared to the off-shore forging source.

The Casting Design Issues

- **The Casting Design Approach** -- The casting design engineers at the Dotson Company of Mankato, MN had three imperatives for an integrated casting design:
  - ***Design for Performance***
  - ***Design for Castability/Manufacturability***
  - ***Design for Cost***



Critical Casting Design Issues --The requirements for performance, manufacturability/castability, and cost are closely interconnected. Five design issues played a major role in meeting the three design imperatives using ***sand mold casting***:

- ✓ Choose a *iron alloy* that meet the strength, fatigue life, and machining requirements
- ✓ Review the *component design* to produce the near-net shape and reduce finish machining operations.
- ✓ Design the *mold system* to reduce overall manufacturing costs.
- ✓ Develop *the riser system* to insure quality and improve yield
- ✓ Select a *tool material* to minimize tool cost over the large production volume.

Which Iron Alloy has the Best Combination of Properties?

The Alloy Requirements

- Iron is the metal of choice for mechanical properties and unit cost, but performance requirements will drive the choice of a specific iron alloy.
- For mechanical performance, the iron alloy has to be both strong and resistant to cyclic fatigue, because stresses are high and brittle failure has to be avoided.
- The design engineers set mechanical specifications of 80 ksi ultimate tensile strength, 50 ksi tensile yield strength, and a fatigue limit of 30 ksi.
- The coupler requires precision machining, so the selected alloy must be machinable with a baseline machining speed of 60m/min.
- The coupler is finished with a black phosphate corrosion protection coating, so corrosion resistance is not a factor in alloy selection.

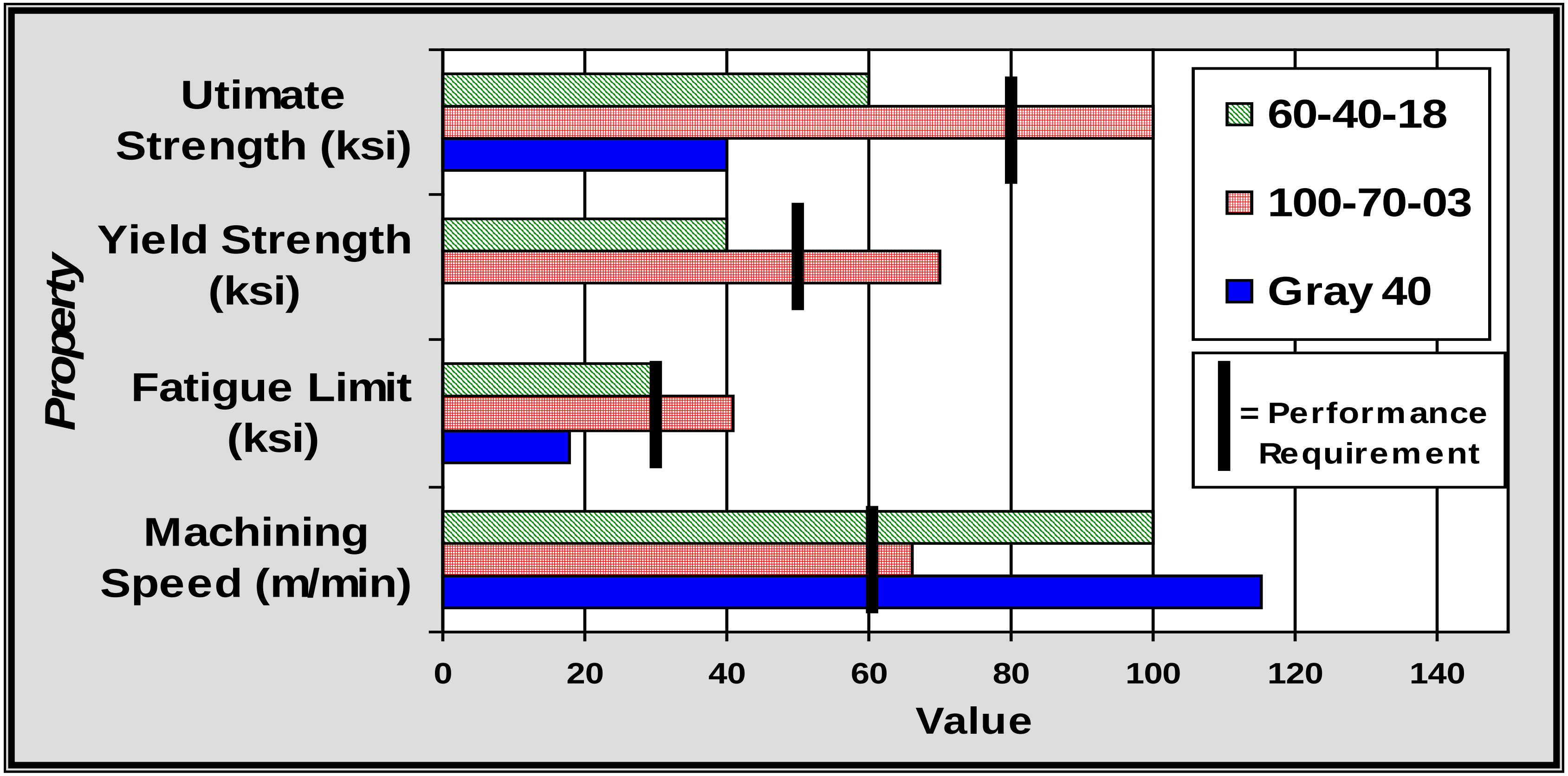
Three grades of cast iron can be considered-

- ***ASTM Grade 100-70-03 Ductile Iron***
- ***ASTM Grade 60-40-18 Ductile Iron***
- ***ASTM Class 40 Gray Iron***

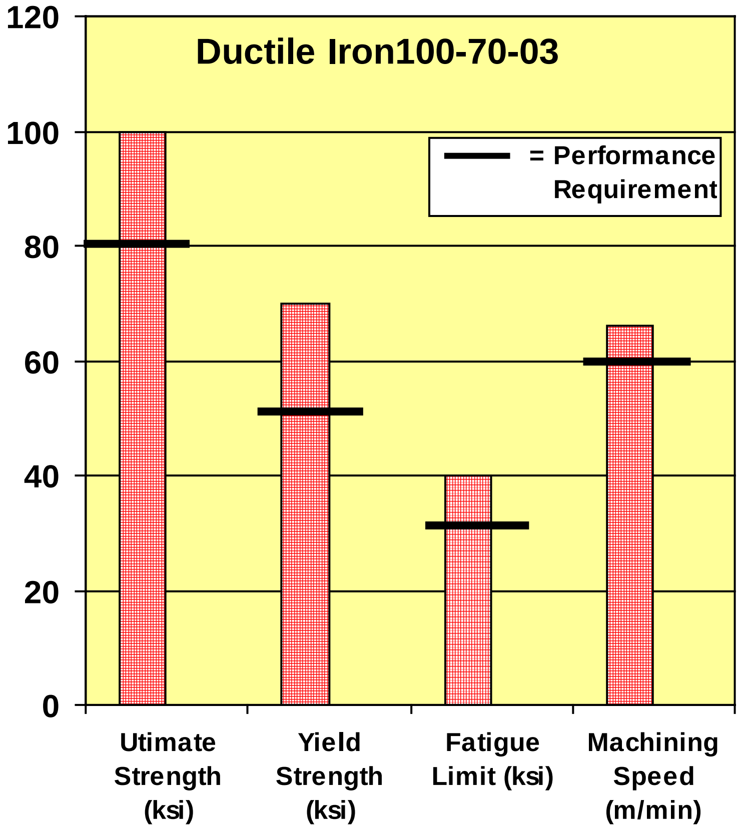
Which Cast Iron Alloy Would You Choose for the Coupler, Based on Strength, Fatigue Limit, and Machinability Requirements?

Review the Chart below and Choose One of the Alloys!

Ductile Iron 60-40-18 ***Ductile Iron 100-70-03*** ***Gray Iron Class 40***



ASTM A536 Grade 100-70-03 Ductile Iron

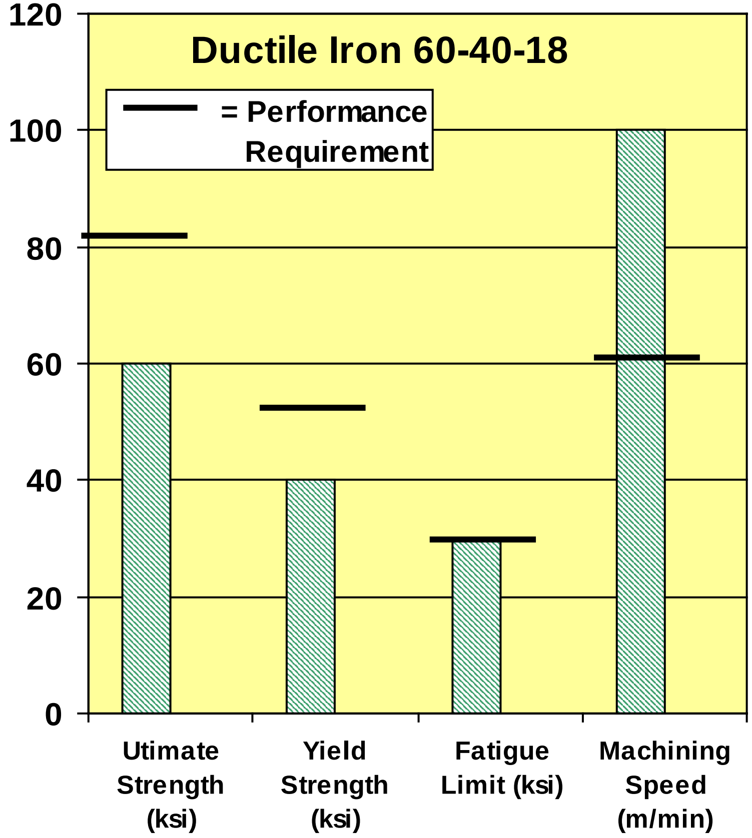


ASTM A536 Grade 100-70-03 Ductile Iron

- The 100-70-03 ductile iron is a high strength alloy (100 ksi ultimate and 70 ksi yield) that can easily meet the mechanical requirements of the coupler. The ductility is limited to 3%.
- The fatigue limit of the 100-70-03 alloy is 40 ksi and does meet the performance requirements.
- The alloy has a nominal machining speed of 66 m/min with carbide tools
- Overall, the 100-70-03 alloy is the best alloy selection

The 100-70-03 ductile iron alloy is the best alloy choice. Go on to the next design issue.

ASTM A536 Grade 60-40-18 Ductile Iron

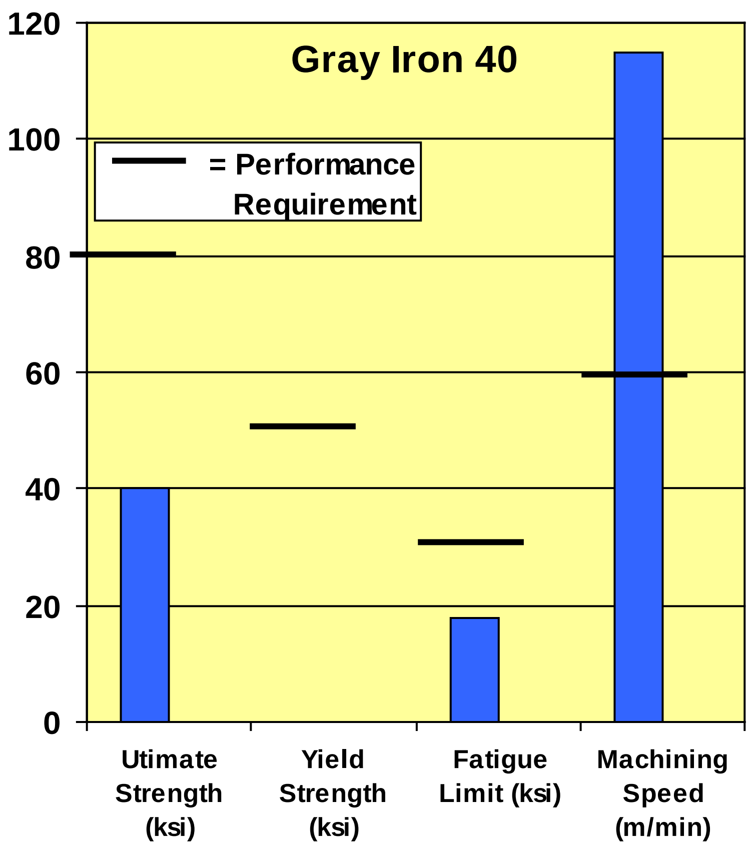


ASTM A536 Grade 60-40-18 Ductile Iron

- The 60-40-18 ductile iron alloy has moderate strength (60 ksi ultimate and 40 ksi yield) that cannot meet the mechanical requirements of the coupler. The ductility of 18% is high.
- The fatigue limit of the 60-40-18 alloy is 30 ksi and does meet the performance requirements.
- The alloy has a nominal machining speed of 100 m/min with carbide tools which meets the machining requirement.
- The 60-40-18 ductile iron alloy does not meet all the performance requirements

Go back to the alloy page and select an alternate cast iron alloy

ASTM A438 Class 40 Gray Iron



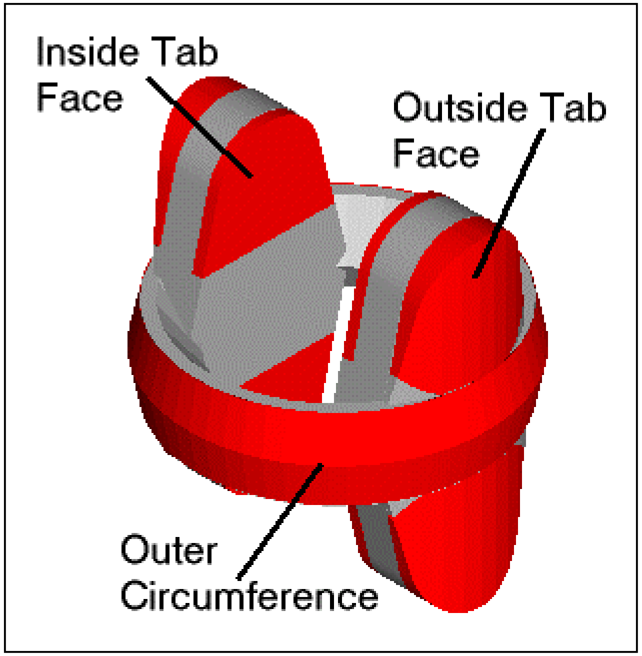
ASTM A438 Class 40 Gray Iron

- The gray iron class 40 alloy has moderate strength (40 ksi ultimate), but low ductility (<0.5%) that that will not meet the mechanical requirements of the coupler.
- The fatigue limit of the gray iron 40 alloy is 18 ksi and does not meet the performance requirements.
- The alloy has a nominal machining speed of 115 m/min with carbide tools which exceeds the machining requirement.
- The gray iron class 40 alloy does not meet all the performance requirements and should not be selected.

Go back to the alloy page and select an alternate cast iron alloy

Design for Near Net Shape

- The final design for the coupler requires that the four tabs on the ring have a final thickness of 0.445" and that the ring circumference be machined for balancing
- The drawing to the right shows **three** areas (highlighted in red) where machining was required on the original design.
  - *Outer faces of the tabs*
  - *Inner faces of the tabs*
  - *Outer circumference of the ring for balancing the coupler.*



Casting technology provides more near-net shape flexibility, offering --

Sharper and more rapid geometric transitions between sections.

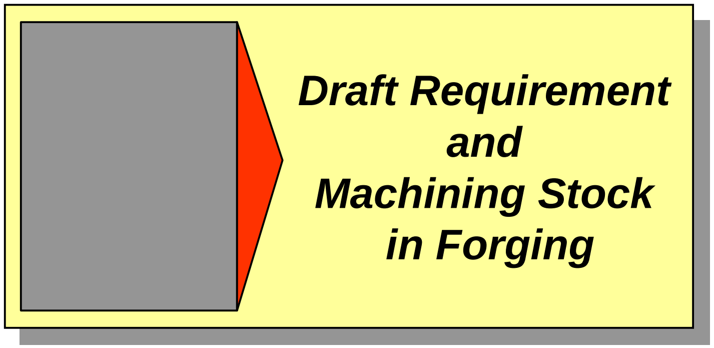
Greater detail and tighter tolerances in thin sections

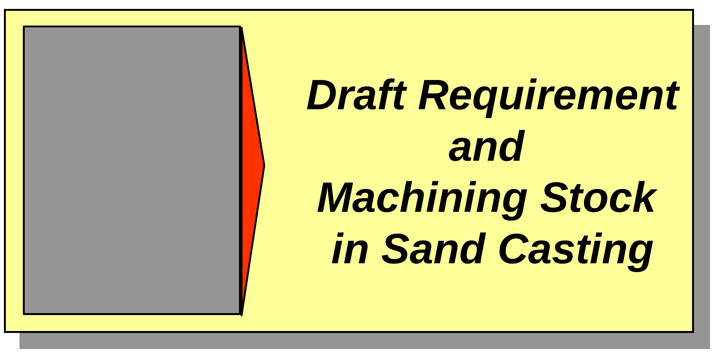
This offers the opportunity to eliminate or reduce machining requirements, as compared to other fabrication methods.

- ***Choose two areas (Inside Tab, Outside Tab, Outer Circumference) where the near-net shape capability of casting would eliminate or reduce the machining requirements.***

Machining Circumference

Ring Cross Sections, Showing Draft and Machining Stock Requirements





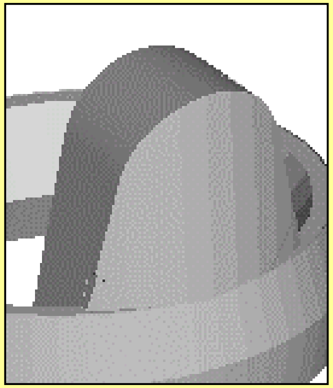
The circumference of the ring is a good candidate for reduced machining.

- In the original design extra stock was required on the circumference because of the draft requirements of the forging dies.
- Using metal casting in sand molds, less draft is required on the circumference, so there is less stock to remove in the machining operation.

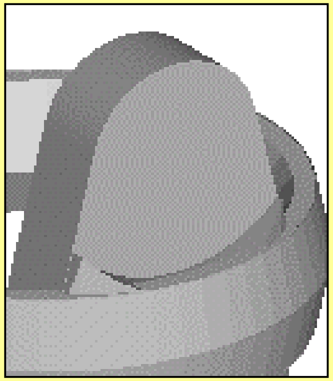
Go Back and Choose another Machining Feature (Outer or Inner Tab Faces)

Or Go on to the Next Design Issue

Machining Outer Tab Faces



Original Design with Extra Stock for Machining on Outer Face of Tab



Near Net Shape Tab Face with No Machining Requirement

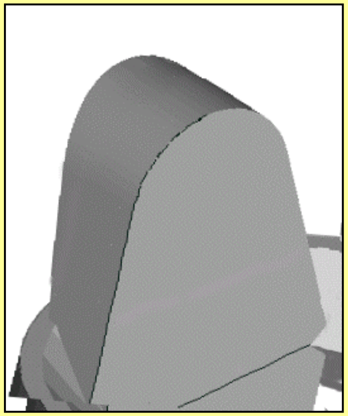
The outer faces of the four tabs are a good candidate for eliminating machining.

- In the original design extra stock was required on the outer faces of the tabs to accommodate the limits of the forging dies.
- Using metal casting in sand molds, the flats on the outer faces of the dies can be produced in the casting, totally eliminating the face machining on the four tabs.

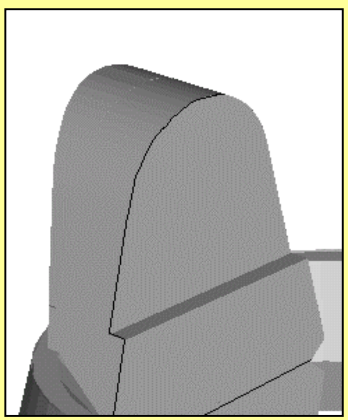
Choose another Machining Feature (Inner Tab Face or Circumference)

Or Go on to the next Design Issue

Machining Inner Tab Faces



Inner Tab Face in As-Cast Condition



Inner Tab Face in Machined Condition

The inner faces of the four tabs will require finish machining, in all cases.

- The inner faces of the tabs will require precision machining to meet the fit and tolerance requirements.
- A machining step is necessary, because casting in sand molds does not provide the degree of final precision required.

Choose another Machining Feature (Outer Tab Faces or Circumference)

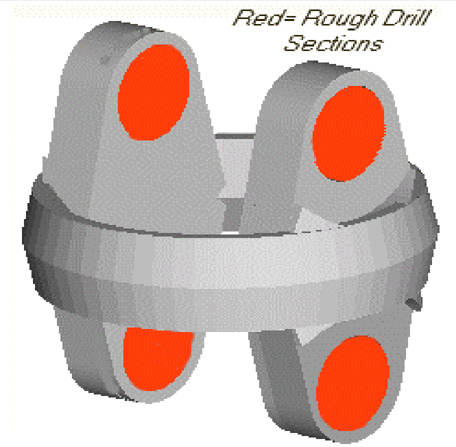
Or Go on to the next Design Issue

Near-Net Shape and Machining Costs

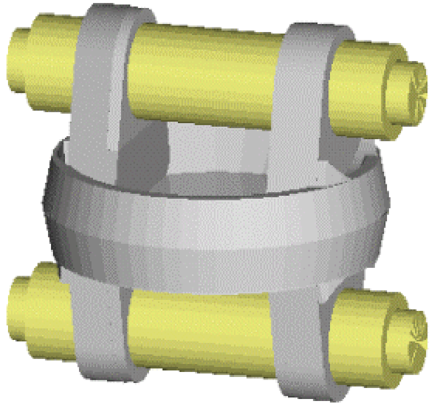
- **The universal joint requires through-holes on each of the four tabs. The holes are 1.075" in diameter and have to be machined for precision fit.**

- **The casting engineer has two options in producing these holes.**
  - ***Option A*** -- Produce the holes in a 2-step machining operation - rough drill and ream.
  - ***Option* B** -- Produce the holes with a rough diameter using two sand cores in the mold. The sand cores are removed from the casting and the holes are finish reamed.

- ***Which option would you choose (Option A or Option B)?***



Casting with No Cores
Rough Drill and Ream
Required for Each Hole

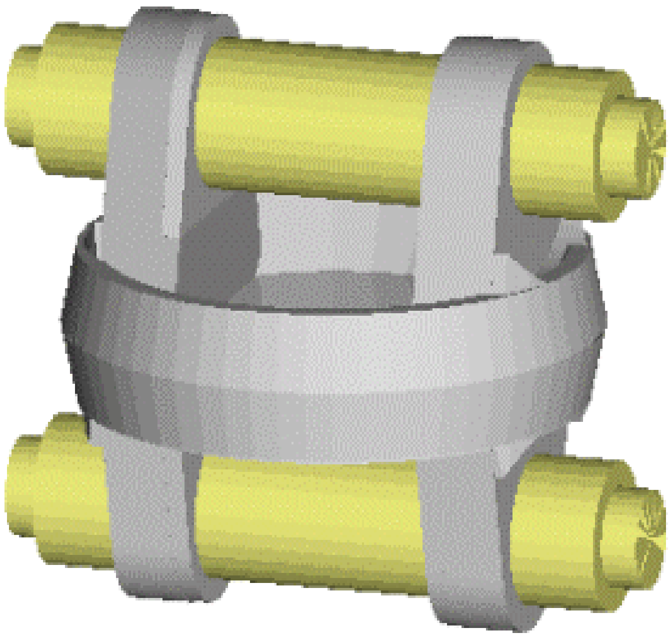


Casting with 2 Cores
Finish Ream Required
for Each Hole

Option A -- Two Step Machining

- In Option A the holes are produced in the tabs by a two step machining process -- rough machine and finish ream.
- A comparative cost analysis showed that for this component at a production rate of 250,000/year, the rough machining operation for the four holes was less expensive than the cost of making and placing the sand cores in the mold.
- The two step machining procedure is more economical for this application and production rate, compared to the alternative method of making and aligning/positioning multiple cores to produce the rough holes in the castings.
- ***Option A is the right design choice. Go to the next design issue.***

Option B -- Core and Finish Machining

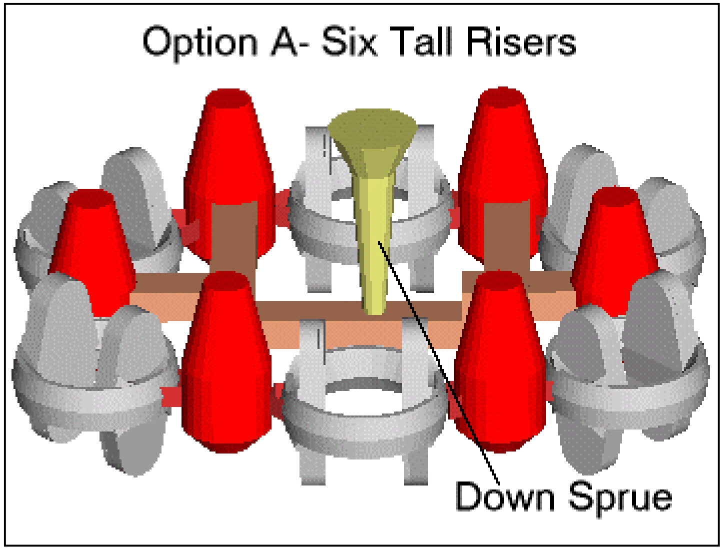


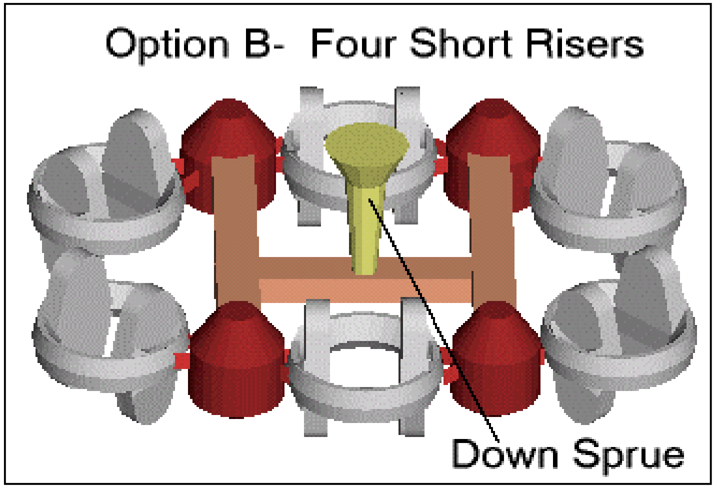
Casting with 2 Cores
Finish Ream Required
for Each Hole

- In Option B the holes are produced in the tabs by using two cores to introduce rough undersized holes in the coupler. Using the cores will eliminate the rough machining requirement for the holes.
- Since the holes have a tight dimensional requirement, the holes will still have to be finish reamed.
- A comparative cost analysis showed that, for this component at a production rate of 250,000/year, the cost of fabricating and placing the cores in the mold was more expensive than the rough machining step.
- ***Option B is not the right design choice.***
  Go back to the Options page

Designing for Manufacturability and Quality

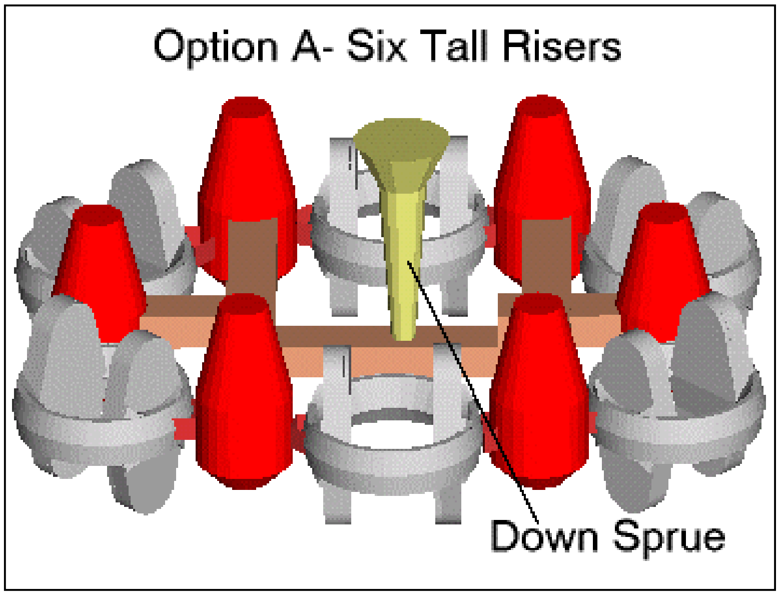
- The coupler is cast as a cluster of six couplers in a single casting. After the casting is removed from the flask (the box which holds the sand mold) and cooled , the rough casting is cleaned of adhering sand in the "shake-out" process.
  - The "shake-out" machine is a mechanical shaker. The casting sits on a steel screen and is vigorously vibrated to shake off the molding sand.
- If the rough casting cluster rests on the coupler tabs in the "shake-out" machine, the tab edges will be abraded and damaged.
- The couplers tabs can be protected during shake-out by sizing and positioning the risers so that the cluster rests on the risers, not on the tabs, during shake-out.





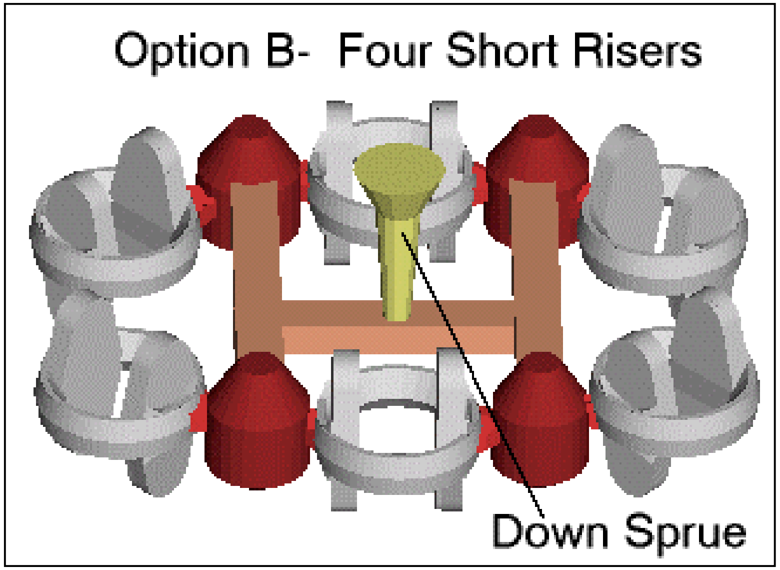
•Two options (Option A and Option B) are shown with different sizes and positions for the risers. Which riser design will protect the components during the "shake-out" step of production?

Option A for Positioning and Sizing the Risers



- Option A positions and sizes the risers, so that the as-cast cluster of couplers is supported on the risers during “shake-out”. The coupler tabs are protected during”shake-out.”
- Each coupler is fed on each side by a riser, providing uniform metal feed into the coupler.
- ***You have chosen the best locations and size for the risers.***
  Go on to the next design issue --

Option B for Positioning and Sizing the Risers



- Option B positions and sizes the risers so that the as-cast cluster of couplers can rest on the tabs during“shake-out”, rather than on the risers. This could damage the coupler tabs, when they abrade against the support screen.
- And the four couplers on the corners are fed by only one riser each. This gives uneven metal feed into those four components.
- ***Go back to the riser page and select an alternate design.***

Controlling Pattern Costs

- One of the manufacturing costs in casting is the cost of preparing the pattern.
  - The pattern is used to form the cavity in the sand mold. The cavity is shaped to the desired contours and dimensions of the final casting.
  - The pattern is positioned in the the open frame (flask) and sand is packed around the pattern. The pattern/tool is then removed, leaving the casting cavity in the sand mold.

- Patterns are commonly machined to the desired shape in wood, plastic, or metal. The cost of machining the pattern depends on the hardness of the pattern material. Softer materials are less expensive to machine.

The sand used to form the mold has an abrasive character which will wear away the surface of the pattern with repeated use.

Sharp contours are more susceptible to wear than flat or curved contours on the pattern
This is a particular issue for automated molding machines in which the sand is mechanically rammed in the molding operations.

The durability of the pattern depends on the hardness of the pattern material. Harder materials are more durable and have longer life but they are also more expensive to manufacture.

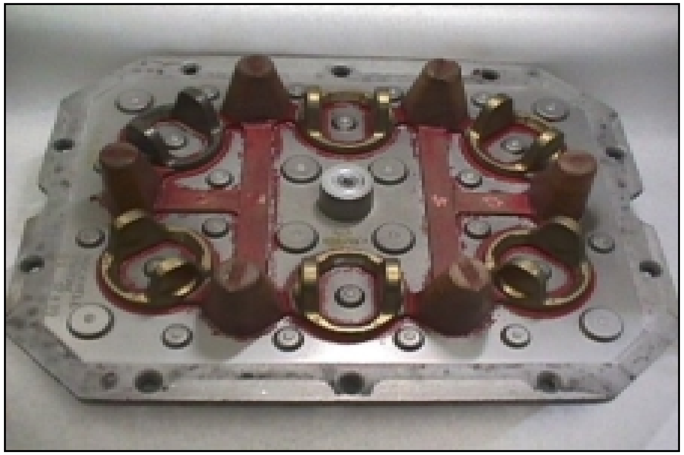
Choose a pattern material -- WOOD, PLASTIC, METAL -- based on your estimate of machining costs and pattern life.

Pattern Materials

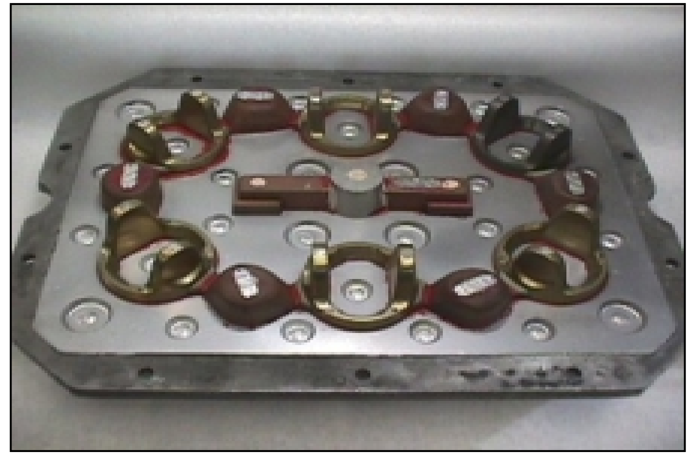
Material	Relative Machining Cost	Pattern Life
Wood	1X	5 Mold Impressions
Plastic	2X	1,000 Mold Impressions
Metal	3X	100,000 Mold Impressions

Metal is the most cost effective pattern material for this long term (250,000/annum, multi-year) production run.

Final Design of the Cope and Drag Patterns



Cope Pattern



Drag Pattern

- The photos above show the patterns for making the cope and the drag sections of the mold.
- The final mold design uses a horizontal parting line with six couplers in a rectangular pattern.
- Molten metal feeds down a center sprue, and spreads through runners into the gates with the risers.
- There are six risers positioned on the gates going into the six couplers. Each coupler is fed molten metal from two sides.

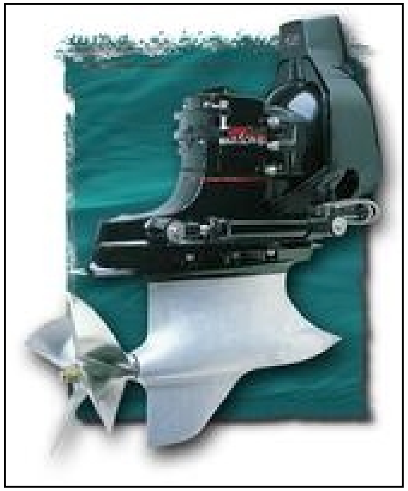
Photo of the Coupler Casting - As Cast and Machined

- After casting and trimming the coupler is checked for dimensional tolerances and prepared for three finishing operations --
  - ***Non-Destructive Evaluation*** - X-ray radiography and dye penetration of selected lot pieces.
  - ***Machining*** -- drill and ream the four holes, broach the inside faces of the tabs, and machine the outside diameter for balance
  - ***Coating*** -- Protect the coupler with a phosphate coating for corrosion resistance.

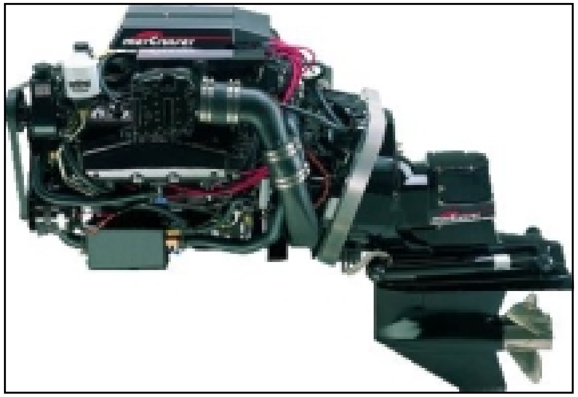
The Lessons Learned

With the universal joint coupler in the sixth year of production, there were three important lessons learned in this successful redesign and production effort.

- A ductile iron casting replaced a steel forging with equivalent performance, 50% cost savings and lead-time reduction.
- Conversion of the forging to a casting produced a near-net shape piece with a reduced machining requirement and lower metal usage.
- Concurrent engineering between the foundry and the buyer was critical for meeting cost, quality, and schedule goals.



Summary -- Casting the Universal Joint Coupler for a Marine Engine in Ductile Iron



- **The universal joint coupler in the marine engine drive train was converted to a ductile iron casting with a cost savings of 50%, achieved by --**
  - **Improved near-net shape which reduced machining operations.**
  - **Casting in sand for low cost, high volume, just-in-time production.**
- **Conversion to a casting also reduced inventory costs by offering "Just-In-Time" production lots with shorter lead times and lower shipping costs, compared to the off-shore forging source.**

For further information on the design and production of this and other ductile ironcastings, contact **-- Todd Nelson at the Dotson Company,**
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