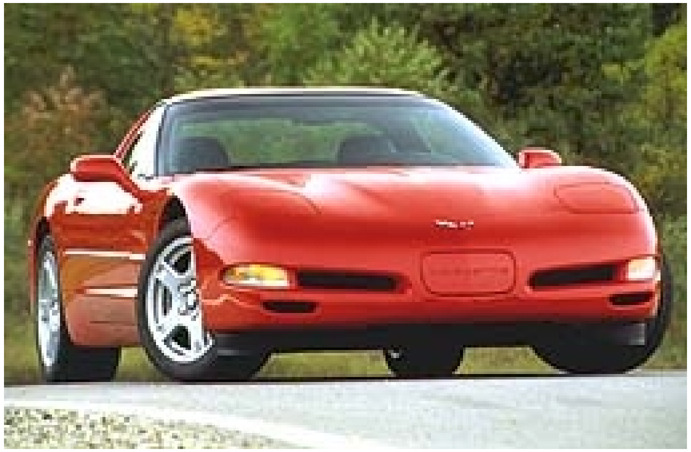
A Design Study in Aluminum Casting

The Brake Pedal for the Chevrolet Corvette

Study Outline

- Introduction
- Choosing a Molding Method
- Selecting an Aluminum Alloy
- Developing Casting Soundness
- Controlling the Metal Flow
- Insuring Quality
- Summary



[*Start the Design Study*]

Acknowledgement --
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American Foundrymen's Society and the Steel Founders' Society of America.
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An Example in Aluminum Casting

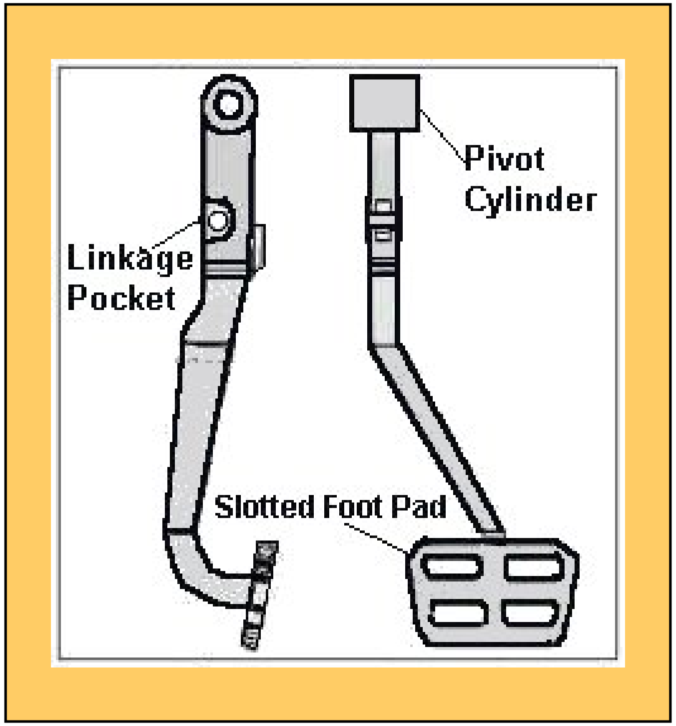
Brake Pedals for the Corvette Sports Car

- **The Application** -- The Chevrolet Corvette is a world-class sports car with outstanding road performance and unique styling. In designing the Corvette, General Motors engineers had the mandate to develop a vehicle design that communicated unrivaled performance and style, while reducing weight for fuel efficiency and acceleration.
- One component of the interior design is the brake pedal. The brake pedal was originally designed as a welded steel assembly that was heavy and required finish treatments for appearance.

- **Component Description** -- The brake pedal in the Corvette is designed as a offset bar approximately 15" long with an integral foot pad (with four slots on the face) on one end of the pedal bar. The opposite end of the bar has a perpendicular pivot cylinder for mounting and rotation. On the under side of the bar there is a pocket in which the brake actuator rod sits with a pivot pin
- Functionally, the brake pedal has to be a high strength component (35 ksi tensile strength and 25 ksi yield strength) with high ductility (7%). The appearance of the foot pad and the visible section of the pedal bar should integrate with the overall interior design.

How Can an Aluminum Casting Save Weight?

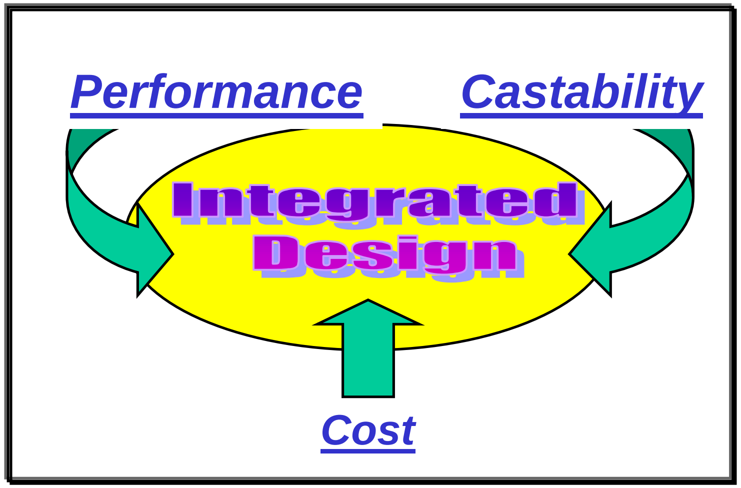
- **<u>The Challenges</u> --** The GM engineers had the mission of reducing the overall weight of the new Corvette. Weight savings translate into improved performance and better fuel economy.
- This required a comprehensive review of every component in the car, looking to cut, not just ounces, but pounds on every component.
- The weight reduction had to be done with <u>no</u> cost penalty, or even better, a cost benefit.
- The previous brake pedal design utilized a welded steel assembly with a total weight of 6 pounds.



- **<u>Benefits of Using an Aluminum Casting</u>** --Aluminum is the obvious light-weight material replacement for steel. Specific benefits in using an aluminum casting were --
  - Reduced weight from 6 pounds to 1.7 pounds
  - A high tech appearance for the brake pedal with the elimination of the rubber boot on the foot pad section.
  - Reduction of machining requirements, compared to the original steel assembly.
  - Elimination of the fixturing, welding, and finishing operations required for the original steel welded assembly.

The Casting Design Issues

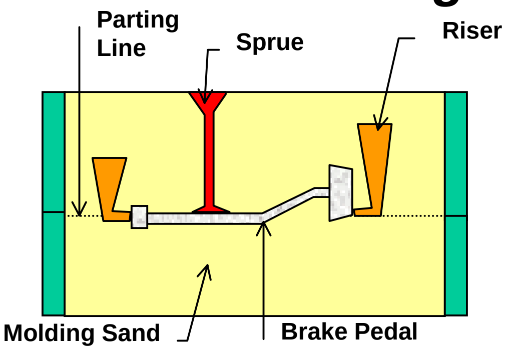
- **<u>The Casting Design Approach</u>** -- The casting design engineers at Eck Industries of Manitowoc, WI were given the challenge of producing the brake pedal as an aluminum casting, meeting stringent quality, cost, and delivery targets from GM.
- The metalcasting engineers had three design imperatives --
  - Design for Performance
  - Design for Manufacturability/Castability
  - Design for Cost



- **<u>Critical Design Issues</u>** --The requirements for performance, manufacturability/ castability, and cost are closely interconnected. Five design issues played a major role in meeting the three design imperatives
  - Select a *<u>casting/molding method</u>* for surface finish, dimensional tolerances, productivity, and tool life.
  - Choose an *<u>aluminum alloy</u>* with the best balance of strength, ductility, and castability.
  - Review the *<u>component design</u>* to eliminate hot spots and stress concentrations in the casting.
  - Engineer the *<u>metal flow into the casting</u>* to promote soundness and high production yield.
  - Develop *<u>quality assurance methods</u>* to verify soundness.

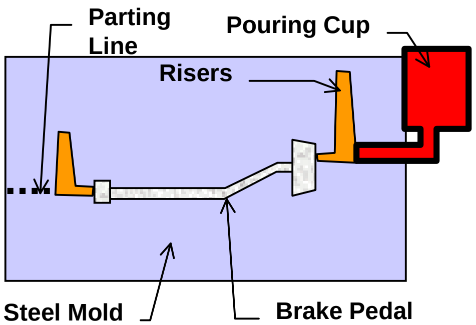
Casting/Molding Methods

- The selection of a casting/molding method is a critical production decision, because different molding methods have trade-offs between initial cost, tool life, surface finish, dimensional tolerances and production cycle time.
- In considering molding methods, the Corvette brake pedal had two important production factors --
  - Moderate rate (35,000/year), long term (10 year) production
  - Stringent dimensional and surface finish requirements.
- ***Three casting/molding options were considered --***



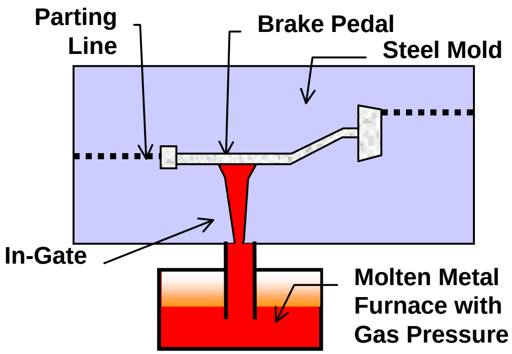
Green Sand Mold

A green sand mold is formed by packing a mixture of sand, clay and water around a pattern to form a mold cavity. Molten metal is poured in the sand mold through the sprue.



Gravity Feed Permanent Mold

A permanent mold consists of two steel/iron halves in which the mold cavity has been machined. Molten metal is poured in the mold cavity through the in-gate



Low Pressure Permanent Mold

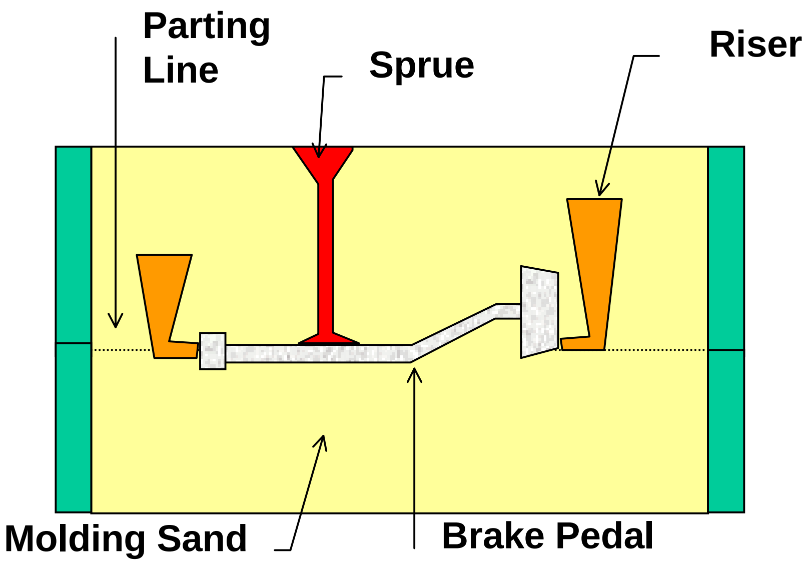
A low pressure permanent mold uses 3-15 psi of gas pressure to push the molten metal up into the mold cavity.

Choose a Casting Method

The following table describes the relative benefits and characteristics of the three casting approaches. Choose one casting/molding method that best meets the requirements.

Characteristic	Green Sand Mold	Gravity Feed Permanent Mold	Low-Pressure Permanent Mold
Pattern/Mold Cost	Low	Moderate	Moderate
Dimensional Tolerance	Fair	Moderate	Moderate
Surface Finish	Fair	Good	Better
Pattern/Mold Durability	Good	Good	Good
Production Rate	Moderate	High	High
Casting Soundness and Mechanical Properties	Moderate	Good	Better

Green Sand Mold



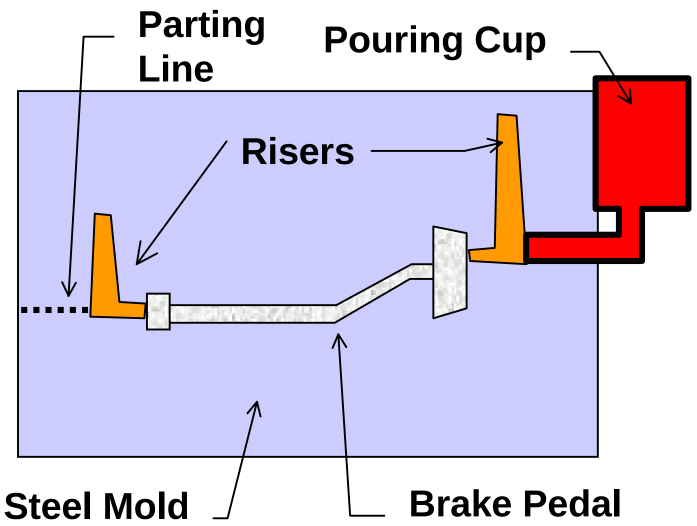
Green Sand Mold

The green sand mold is not the best choice of molding method for the brake pedal

- The sand mold cannot provide the needed dimensional and surface finish. Sawing and grinding operations are required to remove the rigging and will introduce variations in the finished appearance.
- The lower thermal conductivity of the sand mold slows the solidification in the casting, producing a larger grain size and lower strength.
- The extra rigging (risers) required for sand castings will require additional metal feedstock and will reduce the metal yield.

Go back to the mold page and choose an alternate molding process.

Gravity Feed Permanent Mold



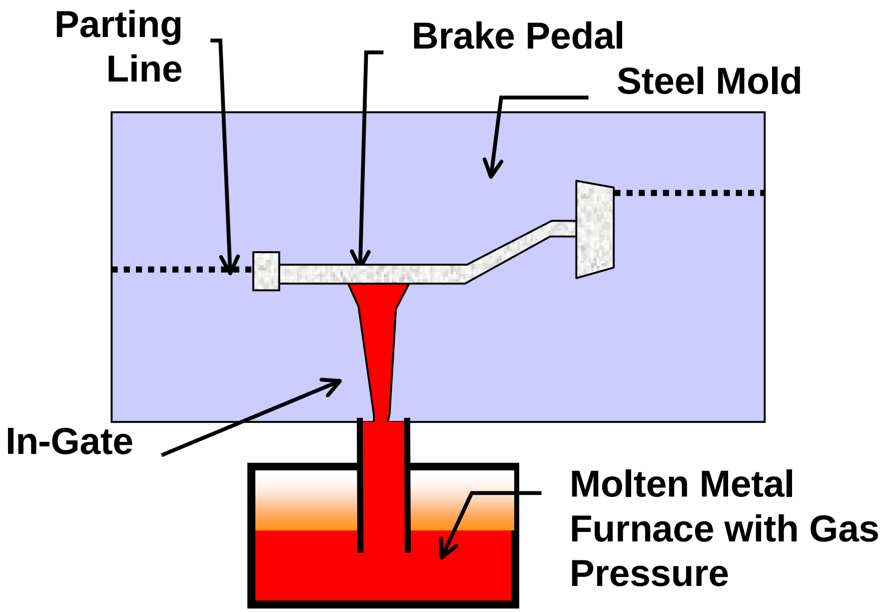
Gravity Feed Permanent Mold

The gravity feed permanent mold is not the best choice of molding method for the brake pedal

- The permanent mold can provide the surface finish and dimensional tolerances needed for the brake pedal.
- The durability of the steel mold will insure that the surface finish and dimensional tolerances are maintained across the multi-year production run.
- Gravity feed of the metal requires risers to feed molten metal in to the thick sections of the casting. Those risers will require cutting and grinding with the greater variability in finished appearance.
- Gravity feed does not provide rapid mold filling and makes it more difficult to obtain smooth surface finish and casting soundness.

Go back to the mold page and choose an alternate molding process.

Low Pressure Permanent Mold



Low Pressure Permanent Mold

The low pressure (LP) permanent mold is the best choice of molding method for the brake pedal

- The LP permanent mold can provide the surface finish and dimensional tolerances needed for the brake pedal.
- The fast cycle times in casting in permanent steel molds can support the production rate needed for the brake pedal.
- The durability of the steel mold will insure that the surface finish and dimensional tolerances are maintained across the multi-year production run.
- The low pressure fill of the permanent mold will give a more rapid and uniform fill of the mold and provides good surface finish and casting soundness.
- LP molds use simpler gating systems and do not need risers to feed solidification shrinkage. This reduces the metal costs and eliminates a trimming/grinding operation.

Move to the next design issue -- aluminum alloy selection

The Alloy Requirements

- Aluminum is the alloy of choice for weight savings, but the performance requirements and manufacturability issues will drive the choice of a specific aluminum alloy.
  - For mechanical performance, the aluminum alloy has to be both strong and tough, because brittle fracture in a brake pedal is unacceptable in a fracture critical part.
  - GM engineers set mechanical specifications of 35 ksi ultimate tensile strength, 25 ksi tensile yield strength, and 7% elongation.
  - The brake pedal has to maintain its surface appearance in a wide variety of environments. Corrosion of the aluminum has to be minimized.
- From the casting perspective, the long, narrow geometry of the brake pedal requires an aluminum alloy that will flow and fill the mold easily, but will not solidify too quickly. Rapid solidification can produce cracks (hot tearing) in the casting.

Which Aluminum Alloy has the Best Combination of Properties?

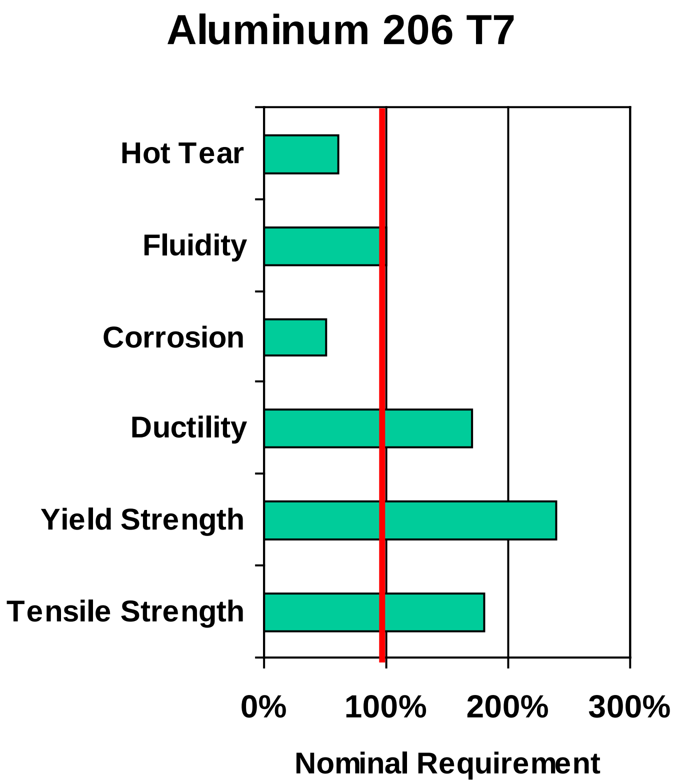
Three types of aluminum alloys can be considered for this application --

- *a 206 aluminum alloy with a T7 heat treat*
- *a B356 aluminum alloy with a T6 heat treat requirement*
- *a 535 aluminum alloy without a heat treat requirement.*

Which aluminum alloy would you choose for the brake pedal, based on strength, ductility, corrosion resistance, and castability requirements, as shown below?

Alloy	Requirement	206 T7	B356 T6	535 F
Performance				
Ultimate Tensile Strength (ksi)	35	63	38	40
Tensile Yield Strength (ksi)	25	60	30	18
Ductility (% Elongation)	7%	12%	7%	13%
Corrosion Resistance (1=Excellent, 5= Poor)	2	4	2	1
Castability				
Fluidity (1=Excellent, 5 = Poor)	2	2	1	5
Hot Tear Resistance (1=Excellent, 5= Poor)	2	3	1	4

Aluminum 206 T7

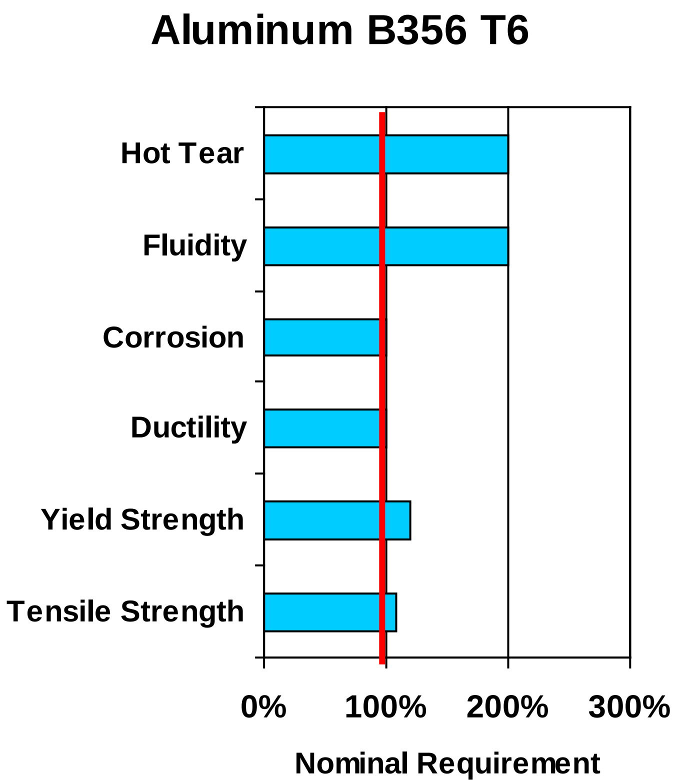


The 206 T7 aluminum alloy

- The aluminum 206 alloy with a T7 Heat Treat is a high strength, high ductility alloy that can easily meet the mechanical requirements of the brake pedal.
- The copper content in the 206 alloy is high enough to cause a potential corrosion and pitting problem, which would require an additional protective coating on the pedal.
- The alloy has enough fluidity to fill the long thin geometry of the mold. But it is susceptible to "hot tearing" which would reduce production yield. An increased possibility of "hot tearing" will require 100% non-destructive inspection of the brake pedal castings.
- Overall, the 206 T7aluminum alloy exceeds the mechanical requirements, but falls short on corrosion resistance and castability.

Go back to the alloy page and select an alternate aluminum alloy

Aluminum B356 T6

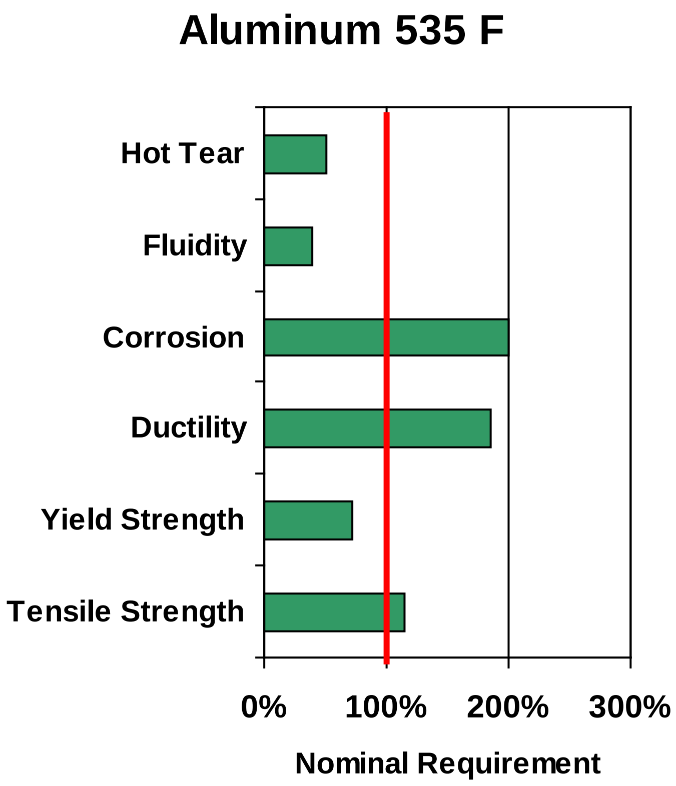


The modified B356 T6 aluminum alloy

- The aluminum 356 alloy has moderate strength and good ductility that can meet the mechanical requirements of the brake pedal.
- The alloy has significantly better corrosion resistance than the 206 alloy, because of its lower copper content.
- The 356 alloy has good fluidity and resists "hot tearing". This will ensure high production yield and reduce the need for extensive inspection.

The B356 T6 alloy is the best choice. Go on to the section on "Design for Castability"

Aluminum 535 F



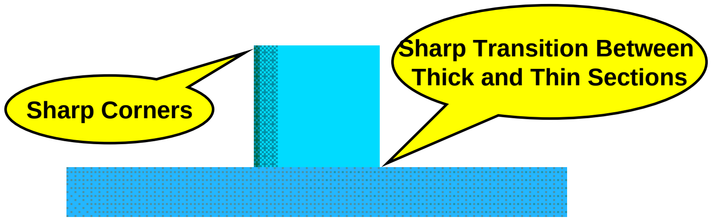
The aluminum 535 F alloy

- The aluminum 535F alloy has excellent strength and very high ductility, but its yield strength is less than the specification.
- The 535F alloy has exceptional corrosion resistance, because there is no significant copper content.
- But the alloy has low fluidity and is susceptible to hot-tearing. For that reason it is not a good choice for the brake pedal with its narrow cross-section and extended length.

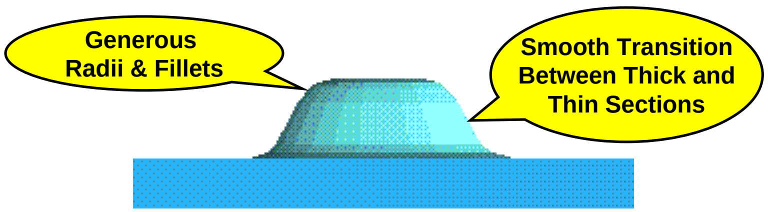
Go back to the alloy page and select an alternate aluminum alloy

Design for Casting Soundness
Eliminating Hot Spots and Stress Concentrations

- **Two important design principles in casting are --**
  - Round corners generously to reduce stress concentrations.
  - Avoid isolated thick sections where “hot spots” could develop.
    - “Hot spots” in casting are regions which become thermally isolated and are the last to cool, forming shrinkage porosity or cavities in the casting.
  - Reduce the size of isolated thick sections or provide gradual transitions between sections of different thickness.



Original Design with Problem Areas



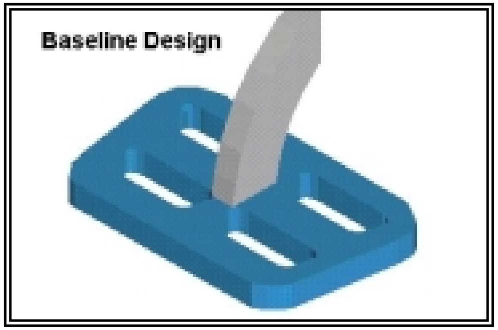
Redesign for Soundness and Stress Reduction

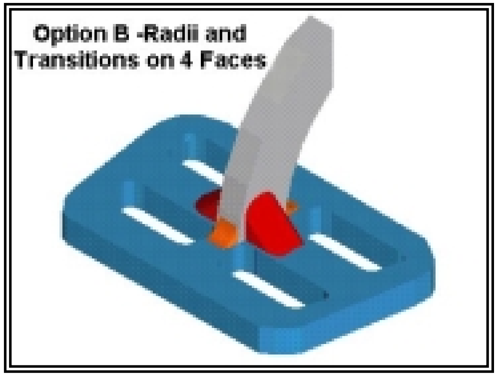
- **The casting engineer will always review the component design looking for those features which have**
  - sharp corners and fillets
  - isolated, thick sections.

A Review of the Pad-Arm Joint

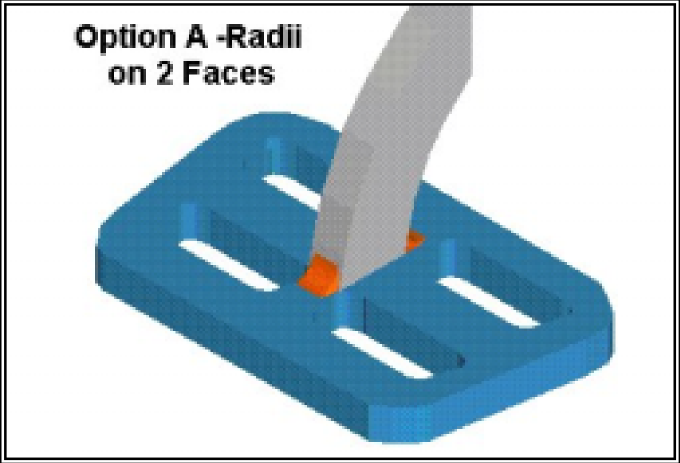
•A review of the original design for the brake pedal showed a potential problem in the region where the foot pad joins with the brake pedal arm. It originally was a direct transition into the foot pad with sharp corners.

Choose an alternate design (Option A or Option B) that will reduce the stress concentrations and the potential for isolated “hot spots” in the casting.





Option A -- Rounded Corners on 2 Faces

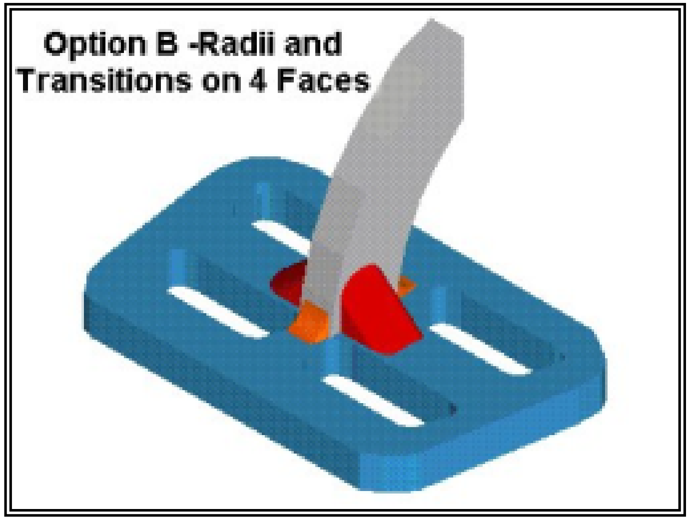


- In Option A the joint between the pedal bar and the foot pad was redesigned with larger rounded edges on the front and back. This will significantly reduce stress concentrations during cooling and solidification, as well as in service.

- However, there is still a sharp transition between the foot pad and the long sides of the pedal bar. This region needs a smoother transition to reduce the isolation of the “hot zone” and avoid sharp stress-concentrations at the corners.

Go back to the previous page and reconsider your choice.

Option B -- Transition Sections on 4 Faces



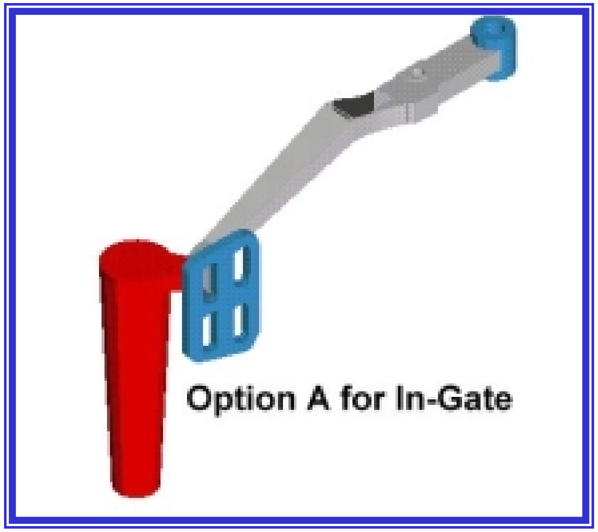
- In Option B the joint between the pedal bar and the foot pad was redesigned with large tapered transition flanges on the two long sides, as well as smaller radii on the front and back edges.

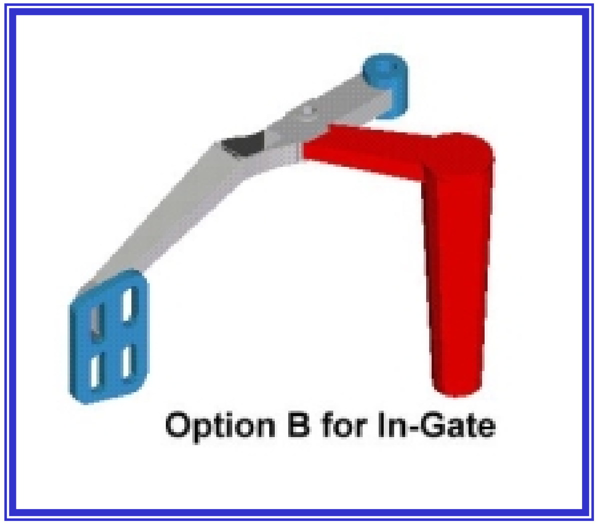
- These features will smooth the transition from the pedal bar into the foot pad and prevent isolation of the "hot zone", as well as providing for smoother metal flow into the foot pad.

Option B is the right design choice. Go to the next design step.

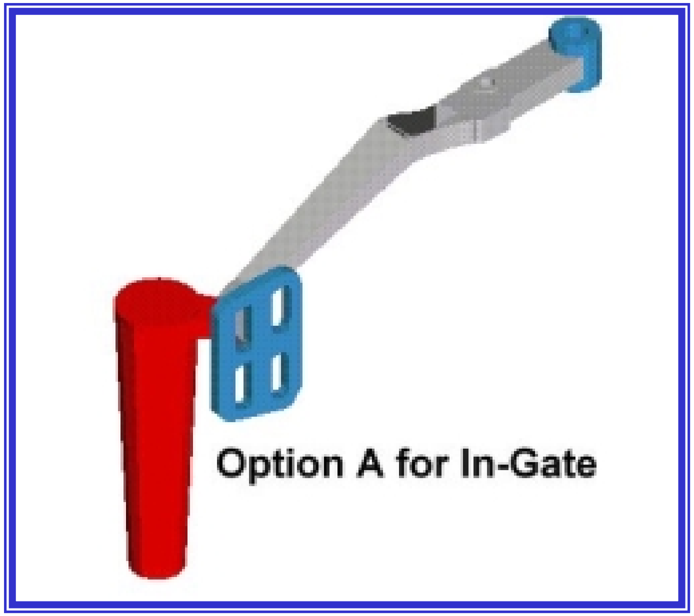
Controlling for Metal Flow in LP Permanent Molds

- Low pressure permanent mold casting is done in steel molds, using low pressure gas to force the molten metal into the cavity. These two process features drive two design factors --
  - The casting cools and solidifies rapidly because of the high thermal conductivity of the steel mold.
  - The gas pressure feeds molten metal into the mold during the cooling/solidification step, eliminating the need for the risers (metal reservoirs) used in gravity feed casting.
- The positioning of the metal feed port (the in-gate) is important to get rapid and uniform metal fill into the die. The in-gate should be positioned to feed into the heavier sections of the component and also minimize the length of the longest run path.
- **Two options are shown with different positions for the in-gate. Which gate design will give more uniform and rapid liquid feed into all sections of the casting**?





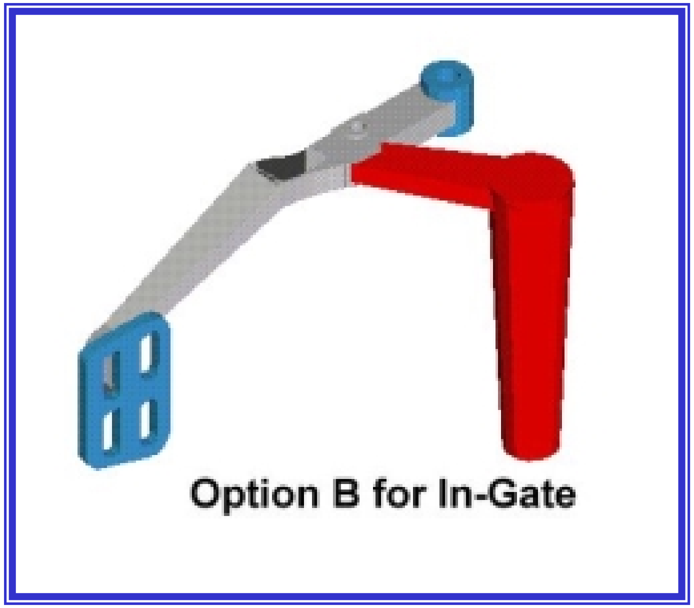
Option A for Positioning the In-gate



- Option A places in-gate feeding directly into the flat pedal section of the component. This will provide good metal feed into the heavier pedal section.
- But the molten metal will have to travel the full length of the arm to reach the the pivot cylinder section at the opposite end.
- This is not the best location for the in-gate

Go back to the gate selection page and select an alternate design.

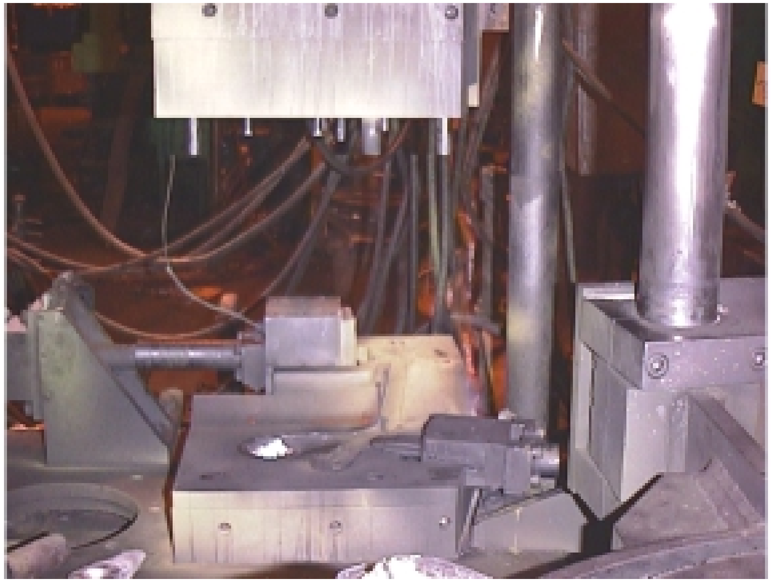
Option B for Positioning the In-gate

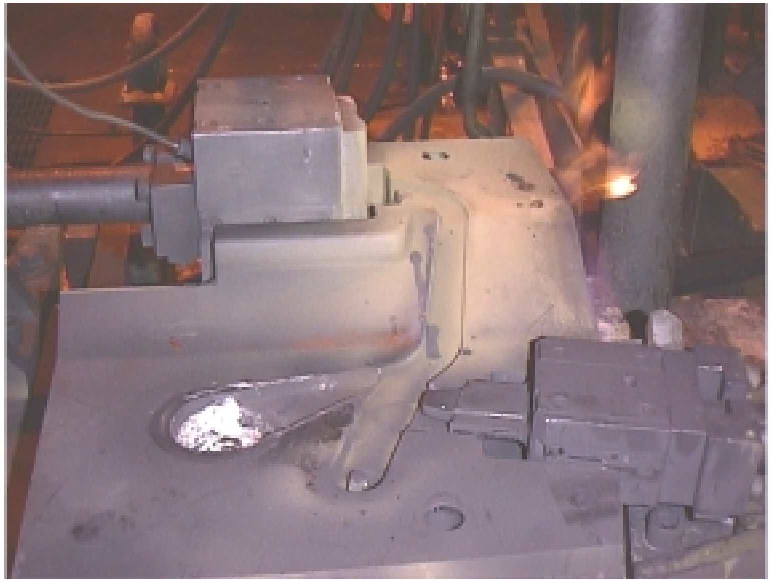


- Option B places in-gate feeding closer to the center of the transverse arm of the brake pedal.
- Center feed provides more uniform metal feed into both ends of the brake pedal.
- With rapid, even fill of the two ends of the brake pedal, the casting will be sound with less risk of porosity and “hot tearing”.

- **You have chosen the best location for the in-gate. Go on to the next design issue --**

Final Design of the Permanent Mold





- The permanent mold design was completed with an offset horizontal parting line. The two mold sections were fabricated in H13 tool steel.
- The mold design includes a partial core seated in the top and bottom molds to provide a center hole in the pivot cylinder. The use of the core eliminates the rough machining step for the pivot hole.
- The close-up photo on the right shows the two movable steel plates, used to produce the pocket in the bar and the slots on the brake pedal.

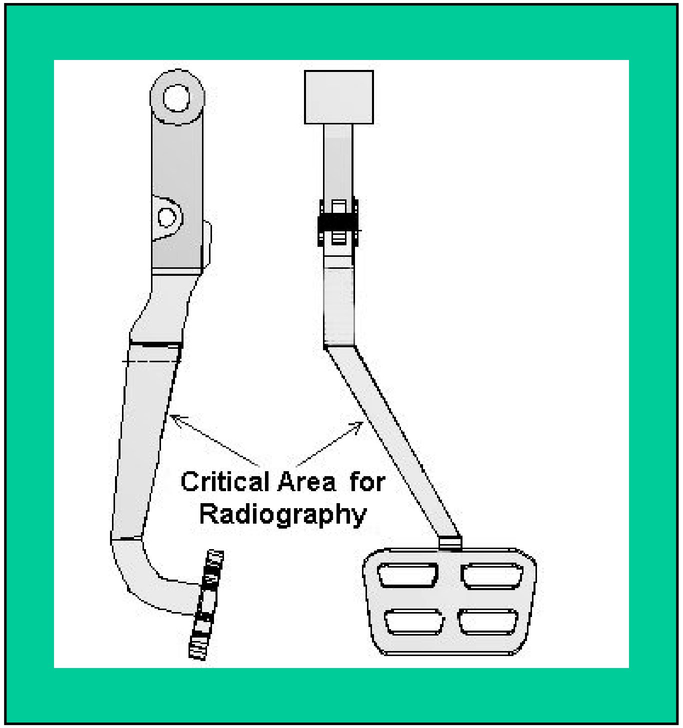
Cast Aluminum Brake Pedal

- The photo to the left shows the brake pedals in the as-cast condition, before the in-gate is trimmed off.

- After casting and trimming the brake pedal is checked for dimensional tolerances and prepared for two finishing operations --
  - Heat-treating to the required T6 condition
  - Machining -- a reaming operation for the pivot hole and a rough drill and finish ream for the cross hole in the linkage pocket.

Quality Assurance

- The brake pedal is a safety-critical component with a high standard for material performance and quality.
- The drawing indicates the sections of the brake where stresses are high and casting soundness is imperative.
- To insure quality, Eck Industries uses X-ray radiography to insure the soundness of the brake pedal castings.
- In the first production run, each brake pedal was checked with X-ray radiography. The X-ray evaluation showed that the castings met or exceeded the casting quality standards.



With four years brake pedal production experience, radiography is now done on a statistical basis, evaluating 10% of each production run.

The Lessons Learned

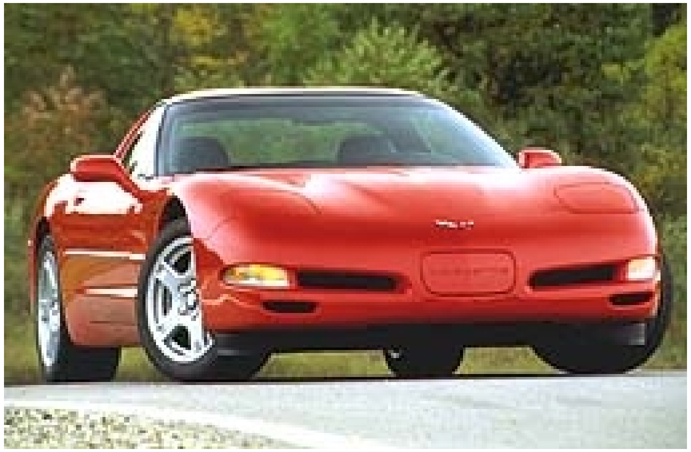
With the Corvette Brake Pedal in the fourth year of production, there were two important lessons learned in this successful design and production effort.

1. *A close working relationship between the foundry and the customer is essential for the effective design of the casting for performance, cost, and manufacturability.*

2. *Alloy selection is a critical issue in meeting both the mechanical performance requirements and the castability requirements.*

Summary --
Casting the Corvette Brake Pedal in Aluminum

- **The cast aluminum brake pedal in the Chevrolet Corvette provided the following benefits --**
  - Weight savings of 72% over the original steel welded assembly
  - Cost reduction through elimination of fixturing alignment, welding, and finishing operations required for the welded steel assembly.
  - A stylish, high tech appearance to the brake pedal with no additional finishing operations.



For further information on the design and production of this and other aluminum castings, contact -- **Dave Weiss at Eck Industries,**
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