Society of Acredited Marine Surveyors® Inc.

MARSKEEL TECHNOLOGY

Keel Construction, Design and Repair

William Souter

MarsKeel Technology

Chief Technologist

WHERE TECHNOLOGY MEETS PASSION

Introduction

MARSKEEL TECHNOLOGY

WHERE TECHNOLOGY MEETS PASSION

2016 SAMS® International Meeting & Conference

Presentation Outline

This presentation will follow these subjects in this order……

- History of Lead Casting
- Ranger J Boat Keel Casting Illustration
- Keel Design
- Types of Keels
  - Traditional keel
  - Modern fin keel
  - Modern wing keel
  - Fabricated keel fin
- Modern Pattern Making
- Modern Mold Making
- Modern Casting procedure
- Keel Damage
  - Grounding Damage
  - Frost Damage
- Keel Bolt Replacement
- Keel Bolt Corrosion
- Precision of Keel Making

History of Metal Casting

- Lead is a soft, malleable, ductile, bluish-white, dense metallic element, extracted chiefly from galena (primary mineral in lead) and found in ore with zinc, silver and copper.
- the oldest known lead article is a figurine found in Egypt that dates back to 4,000BC.
- lead was used extensively by the Romans for water pipes, aqueducts, tank linings and cooking pots and then by ancient scientists in early cosmetics, paints and pigments, and in lead-rich glazes.
- Significant production of lead began about 3000 BC, and large mines in Spain and Greece.

History of lead casting

- The Roman Empire was the first society to use lead widely; in fact, the word plumbing is derived from plumbum, Latin for lead, which also gave rise to the chemical symbol for lead, Pb.
- The casting method used was the lost wax method,
- A wax object is sculpted, coated in layers of clay.
- The molten lead is poured into the top of the mold, the melted wax runs out the bottom, leaving the lead in the mold.
- A method of casting still used today, for small objects

Examples of small cast objects

Large keel casting example, Ranger J class keel

Ranger Keel photos and notes taken from Maine Maritime Museum, collection No. 20

- Her keel of 100 tons of carefully formed lead ballast poured in one day in late December 22 of 1936
- The pattern for the keel 39 ft. long, being swung into position
- The pattern was an exact duplicate of the desired lead shape, and had foundry sand compacted all around it.

Large keel casting example, Ranger J class keel

- The ..... pattern has been carefully pulled up out of the form, leaving this smooth, cavity into which the molten lead will be poured.

Ranger Keel photos and notes taken from Maine Maritime Museum, collection No. 20

Large Keel casting example, Ranger J class keel

- Once the pouring began ....it could be no stopping the flow of molten lead, if the integrity of the keel mass was to be maintained.

Ranger Keel photos and notes taken from Maine Maritime Museum, collection No. 20

Large Keel casting example, Ranger J class keel

- Lots of manpower needed to be on hand, handling the continuous chain of lead ingots, relayed to the staging by the overhead beam crane, into the initial meltdown troughs and then down into the mold, all the while kept at molten temperature.
- Checking the level as the pool of molten metal nears the top; Burgess again, on the right, possibly looking a bit edgy for a man on the brink, literally, of his unknown, untried keel design

Ranger Keel photos and notes taken from Maine Maritime Museum, collection No. 20

Modern Keel casting process

Modern casting process is a combination of tried and true technologies and modern processes.
The stages of modern production are…

Design
- Still, coming from talented designers
- Now, CAD used throughout production

Pattern,
- Still, using wood to make patterns
- Now cut by CNC machine
- Now have the proper shrinkage built in

Molding
- Now, re useable ceramic is used, cast iron is used.
- Still, sand molds are used for one off custom projects

Casting process
- Still, melting material in a furnace
- Now, use a natural gas fired, computer controlled burner

Now, ……let us look briefly at each process……

Keel Design

The MarsKeel Group
Design and Engineering Services

MarsKeel Technology is associated with two designers, engineers who offer our customers a comprehensive service package.

Keel Design

- The keel design process begins with the definition of what type of boat it is being made for, racing yacht, racer/ cruiser or cruising yacht and therefore the performance needs of each yacht.
  - There is a large combination of designs and materials available for modern keel construction.
  - The higher the performance desired the more complex the keel.
- The other consideration defining the keel is price point.
- After the type of keel is defined, the manufacturing process is considered. The process could be any of the following
  - All lead casting
  - Cast iron keel
  - Cast iron keel with lead bulb
  - Fabricated (hand faired) keel fin and cast bulb
  - Fabricated (CNC machined exterior) keel fin and lead bulb
  - Fully CNC machined fabrication with lead bulb.
- Generally speaking as you go down the above list the price point increases, as the amount of work needed increases. Both design work and manufacturing costs, labour and materials.
- As you go down the list the performance of the keel also increases
- The difference between a production yacht keel and an open 60 keel .....

Keel Design

- The keel designs can be generally broken into these main categories.
  - Traditional cast lead keels
    - Full keel designs, for example: modern J class yachts, heavy displacement cruising yachts
  - Modern fin keels
    - Typically used on moderate performance yachts, production and custom designs
  - Modern wing keels
    - Typically used on moderate performance yachts, production and custom designs
  - Fabricated keel find and cast lead bulbs
    - This design is used on yachts that require higher performance, both production and custom.
  - FRP fins and cast lead bulbs.
    - This design is utilized on the very highest performance yachts.

Let us look at examples of each…….

Traditional keels

- Traditional Keels
  - Traditional lead cast keel, 6m, 8m, ……
    J class
    - The keel is mounted to a deep sump or deadwood.

Scheherazade keel shipping to customer, 153,500 lbs.

WHERE TECHNOLOGY MEETS PASSION
2016 SAMS® International Meeting & Conference

Modern fin keels

- Modern Fin Keels
  - Cast Fin keel, is the evolution of the keel design, from a full traditional keel.
  - The change in keel design came along at the same time as the change from wood to FRP hull construction.
  - These changes offered improved sailing performance, deeper CG etc.

J 111 deep keels completed

Modern wing keels

- Modern Wing Keels
  - Wing keel, the evolution of keel design offering a simpler option then a Center board or dagger board for shallow draft.
  - This change opened the interior volume of the "small yacht" to be used as cabin space.

Hunter Yachts wing keel

Fabricated Keel Fins

SWS 94 keel

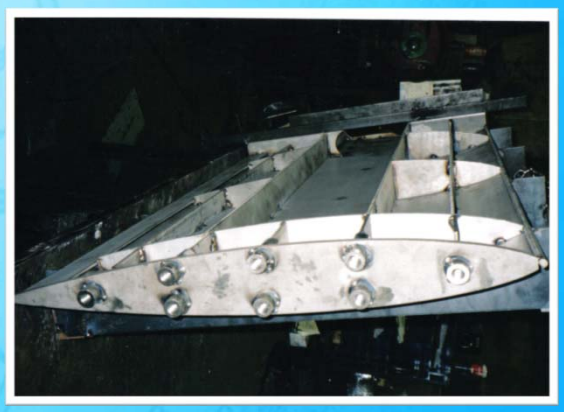
Langan Design Associates Inc.

Fabricated Keel Fins

- Generally known as dissimilar metal keels
- This is a keel type that is a combination of materials and processes used to push the sailing performance as far as the engineering and price point will allow.
- They utilize materials from cast iron to high strength steel, lead
- Manufacturing processes range from hand faired castings to fully CNC machined parts.
- This type of keel can use the most accurate manufacturing processes, (example CNC machining). Can be some of the highest performance and technically most complicated keel types
- As shown in the chart to follow, these types of keels bring together a wide range of materials, from high strength materials, (such as A514, 2205 Duplex SS)

Fabricated steel keel fins

- Fabricated- hand faired, moderate performance production yachts.
- Fabricated -CNC machined exterior, moderate performance semi-custom and production yachts.
- Fabricated -Fully CNC machined steel fin (internal parts and exterior surface.) high performance semi-custom and production and racing yachts.
- FRP fin with bulb. high performance semi-custom and production and racing yachts



Hinckley 42 lifting keel

Fabricated Keel Fins

As shown in the chart these types of keels bring together a wide range of materials, from high strength materials, (such as A514, 2205 Duplex SS)

Type of Keel	Materials/ Process	Stages
lead cast keel	typical 3% antimonial lead	Design pattern molding casting (CNC machining to final shape) finishing
fabricated steel fin (used with a cast lead bulb)	A514 Weldox 700, 900 2205 duples SS 316 SS A36/ 44W	Design material cert material cutting per forming of needed plates, side plates fitting/ fabrication/insepction of welds, NDT finishing
CNC machined Fabricated fins (used with a cast lead bulb)	A514 Weldox 700, 900 2205 duples SS 316 SS A36/ 44W	Design material certification , MTR material rough cutting CNC machining of parts to final shape fitting/ fabrication/insepction NDT of welds Stree relief, typically thermal CNC surfacing of fabrication to 0.004" of surface or better NDT for plate thickness finishing
FRP fin (used with a cast lead bulb)	Carbon fiber laminating	design tooling for internal and external parts laminating of parts assembly of parts, bonding of parts final lamination if needed on joints finishing

Patterns

Patterns

Let us now look at the pattern process.....

- Once we have the keel design we then work out how we are going to physically cast the part.
  - The patterns are made in a very similar way to wooden yacht construction. This method created a light, hollow, yet strong shape that will withstand the forces of mold making
  - The process of working out the actual casting process includes defining if a 1,2, 3 or 4-part mold is necessary.
  - What parts we need to design to generate any required details in the casting, such as holes, recesses and passages.
- The small keel patterns are caved from solid material, shaped by templates.
- The most modern method of making patterns uses high density foams and CNC machines.

Molding

Molding Materials

- Sand, traditional
  - size and use limitations
    - not practical for large molds, i.e. 10,000 lbs. castings and up.
  - Sand molds can be used only once.
    - Sand will not withstand, intact, the forces of opening the mold.
  - easy to alter but therefore fragile

Typical sand mold, interior coated with mold release, blue- white colour

Molding

Ceramic molds

- most common type of mold, at MarsKeel Technology
- no size or use restrictions
  - You can build molds with walls as thick as necessary to carry the casting loads of parts up to 200,000 lbs.
  - The limiting factor is the lifting ability of equipment to move the molds.
- molds can be used up to 40 times or more before needing to be replaced.
- This material generates a high level of detail.
- It can be used in the production if…….one, two, three or even four parts, depending on the part needs.

Typical two part ceramic mold, interior coated with release wash.

Keel Casting Process

Pouring a large *keel*

Keel Casting Process

Casting Process

- The actual casting process has change little technically from the time of Ranger.
- There is the use of less men, better material handling, tow motors loading melt pots.
- We have the ability to pour from multiple furnaces, increasing the efficiency of the pouring
- We have computer controlled burners, thermal couple temperature, better heating and pouring control

Keel Casting Process

- **The pouring or casting process for a keel is now based on preparation and safety.**
- Once the mold is cured, dried it is closed.
- After closing the keel bolt racks, casting fixtures, core boxes, core rods and internal weldments are positioned.
- The mold is moved "under" the melting furnaces.
- Pours no matter how large the casting they have to be completed in a single pour.
- The act of stopping and restarting a pour puts cold shots in the part which are not attached to each other and therefore create a failure point in the casting.

Keel Casting Process (continued)

- The vents are tended, keeping them liquid and free of any slag that collects. As the body of the casting begins to cool it contracts pulling material from the liquid vents. As this process continues more material is poured into the vents keeping them full. This process of cooling and filling continues until the vent have stabilized.
- When no more emptying is seen to be happening it is then that the mold is left too cool. This process can go on the 12 hours or more on very large pours, ex. 154,000 lbs. Once the part has cooled sufficiently it is released from the mold and taken to the finishing rooms to be completed.

That is more then enough on casting.....

Lets move on to Keel damage.....

Keel Damage

- Now that there is a general outline for the manufacturing process for the major types of keels (designs) we can begin looking at the areas of damage commonly found at MarsKeel Technology. The most common type of damage that we see at MarsKeel Technology are the following,
  - Grounding damage in lead keels
  - Frost damage in lead keels
  - Corrosion of keel bolts.

Grounding in Lead Fin Keels

- Grounding damage is generally the following types, deformation from impact, bending damage and twisting damage as well as cracking.
- Most of the time the damage forms are combined in a single keel.
- The amount and type of damage is also related to the boat speed, bottom conditions, angle of impact.
- The simpler or stronger the keel, example a mid-80's fin keel will be able to withstand impact, showing less damage then the modern refined keel.
- The problem is if the keel didn't "eat" the impact energy, where did it go and what did it do when it got there?
- Now that the damage has been defined the next questions are,
  1. can it be repaired?
  2. what will it cost?
  3. How long will it take?

Grounding of Shoal Draft Keels

- Generally, it is the wings that sustain the damage due to a grounding. The reason is that the fin section of the keel is rather "short" and "thick" therefore it is able to withstand the force of the grounding without deforming.
- The wings will absorb some of the force, protecting the fin section and the hull from some of the forces.
- The most common outcome of a grounding of a wing keel is bent wings.
- The damage can also be caused by boats settling onto the bottom, tide going out, dragging anchors, that is usually both wings being bent.
- An active grounding during sailing will cause a single wing to bet bent.
- If the damage is minor, just a wing tip bent or a very slight bend these can be repaired on the boat.
- At that point, plan B, call us, we will let you know if to is best to remove the keel and send it to us for repair.

Grounding of shoal draft keels

Hylas 70 in for grounding and keel bolt repair

Hylas 70, all damage repaired ready to shipping

WHERE TECHNOLOGY MEETS PASSION
2016 SAMS® International Meeting & Conference

Grounding in Dis-similar Metal keels

- After a grounding of a high performance yacht the entire process becomes more complicated and involved then on a traditional cast lead keel.
- One has to take into consideration many factors when trying to answer the basic questions following a grounding event.
- There are many design and manufacturing factors that need to considered after a grounding. i.e. material type, fabrication type etc.
- There can also be many components to this type of keel that should be all checked for damage.
  - This includes the bulb, lower bolts, keel fin, upper bolts, as well as possible hydraulics components, bearings, trunk.
- Specific professionals should be brought it to define if any part is damaged and hoe badly.
- Once the damage level has been defined, as closely as possible, using NDT methods, it becomes a question of can it be repaired.
- The questions now become,
  1. What is the extent of the damage, seen and unseen?
  2. What is it made of?
  3. How is it made?
  4. Can it be repaired, or does it need to be replaced?
  5. What will it cost?
  6. How long will it take?

Grounding in Dis-similar Metal keels

- This assessment will very likely require the involvement of some or all or even more people or groups in the below list,
  1. Yacht/ keel designer
  2. third party engineer/ naval architect,
  3. NDT company
  4. .metallurgist,
  5. casting house,
  6. fabrication people,
  7. machinist

WHERE TECHNOLOGY MEETS PASSION
2016 SAMS® International Meeting & Conference

Keel bolt assemblies

We should look at how keel bolts are cast into the keel to understand removal, when and if possible.....

Keel bolts that are connected below the lead line would make replacement impossible, individual bolts are very simple to replace. As seen the above photos.....

Replacement of Keel Bolts

Keel bolt Replacement in Lead Cast keels

- Most bolts in cast lead keels can be replaced easily
  - The process does get complicated if we do not get a design of the keel bolts below the lead. the bolts are welded together in very different ways, complicating or making their replacement impossible.
- The keel does have to be taken off the boat and sent to us for repair.
  - This is not a yard or do it yourself project.
- The process is to melt out the damaged bolt from one side of the keel
- The existing bolt is removed, if we do not have the technical information on the keel, the bolt is sent out for material analysis, to define the alloy it is made of.
- This recess that was left in the keel by the original bolt is used to position the new bolt in the casting.
- A new bolt is manufactured it is positioned into the casting, the lead is refused back over it.
- if this process is done incorrectly you have soldered the bolt into place and it will fail. You need to re fuse the casting, this is done by bringing the existing cast material and the new material to the melting point at the same time. Once the lead is refused the keel is faired and painted with typically Interprotect 2000E barrier coat.

Keel bolt Replacement in Cast iron keels

- The process for replacing bolts in non-lead keels, or fins is very different then doing it in a lead keel.
- Most keel bolts are drilled and tapped into a non-lead fin or keel the only means of replacing them is to send it to a machine shop and have the bolts in questions machined out.
- This might require the holes to be over sized to remove any corrosion on the fin, or even sleeving the bolt into the casting.

Corrosion of Keel Bolts

Corrosion of Keel Bolts

- The corrosion of the keel bolts is generally found on older keels where there is a long history of water being allowed to get to the bolts.
- The water path could be,
  (1) through having standing water in the bilge,
  (2) a compromised hull keel joint that allows water directly at the bolt.
- The real concern with bolt corrosion is that it is occurring usually out of sight, not in the bilge but in the area between the top of the keel and below the internal washer plates in the bilge.
- The best that can be expected is that the people maintain as dry a bilge as possible and take the time to inspect and maintain a water tight hull keel joint. If water is allowed to stay in the bilge or pass through as weak hull keel seal over time the last sign of real trouble is rust stains running down from the hull keel joint down the keel.
- There are some SS alloys, such as 2205 duplex, that have been developed to withstand the marine environment better than the traditional 316 or 304 SS.

Frost Damage to keels

Opened frost bubble in side of keel

Exposed corrosion affect just under root cord

Frost Damage to keels

This is by definition a northern climate concern. The boat, cast lead keel, has to have the opportunity to freeze.

(1) The water can collect in the deep sump, follow a keel bolt into the casting, finding a void in the casting to collect in.

(2) The water can get through the hull keel joint, finds its way to the keel bolts and into the casting.

(3) The last and least likely is the water can go straight into the keel. It would have to enter through a flaw in the barrier coat, a flaw in the casting that opens to the outside.

The problem with this type of damage is that it is hard to find at the beginning stages. After the first season it is likely very hard to see any sign of damage.

This continues until there is a very noticeable budge on the keel. Now you run into the possible problem of the lead losing its grip on the keel bolt, now it could be a safety concern.

This is where it goes from a problem to a concern needing to be dealt with by MarsKeel.

The general repair process for the damage is,

(1) to remove the keel from the boat,

(2) open the bulge, allow it to dry out,

(3) re fuse the lead back into place.

It is also good practice to inspect the keel bolt to ensure there are no visible signs of deterioration. If the water has been in the keel for long enough it might get to the point that the keel bolt has to be replaced before the repair can be closed.

This opens the last point of water damage, even if the boat is not in a climate that doesn't freeze there still can be water in the casting and it can still be doing damage to the keel.

The problem is that there is not the telltale sign of the bulge to let you know where and when

It could still lead to keel bolt failure. The best solution for both problems is to spend a little time to inspect and maintain a dry bilge in the boat and a good sound seal on the hull keel joint outside the boat.

Keel tolerance

Machined bulbs and fins

- When the very highest accuracy is required
- Accuracy is 0.004" off designed surface
- Lead castings can be machined perfectly even though lead is very soft.
- Machining scallops are blended off
- Surface is then coated with required coating, i.e. Interprotect 2000E barrier

Custom cast retro bulb being CNC surfaced

Design and Manufacturing of Keels, Precise?

Cast keels

- With the most price constrained customers, a standard cast lead keel is faired to approx. +/- 1-2mm of design.
- This final surface is a combination of what is defined by the following inputs, pattern, molding, casting shape and hand fairing process.

Examples of different sized cast bulbs, approx. 7,000 lbs. to 30,000 lbs.

Keel tolerance

Level of tolerance is based on design needs, manufacturing process used and price point.

Lead Castings

- Tolerance in a hand faired casting is generally +/- 1-2mm
- Tolerance is an amalgamation of pattern, mold and finishing tolerances.
- If there is a need any part can be templated and faired to a higher level.

CNC cut parts

- The normal tolerance for a CNC surfaced part, keel fin or bulb is 0.004" or better off surfaced.

Keel tolerance (continued)

- For fabricated fins, there is an entirely different set of conditions and

Both photos are examples of CNC machined, fabricated keel fins.

Keel Tolerance (continued)

- There are of course at least two different methods of fabricating keel fins.
  - The simplest is a laser cut set of parts, both internal and external, with a minimum of machining required, bolt holes etc. that can be used.
  - The external shape is therefore developed by the shapes of the internal parts
  - Once the parts are completed they are fitted, welded and checked. It is in the human level that the tolerance can be maintained or improved as opposed to machine tolerance.
  - This is the final stage at which the required surface is refined to be as close as possible to the desired shape. Typically, there is possibly 1.5mm or less of filler on a formed surface The most technical method of fabrication that requires CNC machining made from precut and machined flat or formed plates of steel.
  - This maintains the highest level of accuracy and weight tolerance possible.
  - A finished completely CNC machined part will be 0.004" or better off the offered surface file

Inspection of rough fabrication by QC inspector, using a Faro Arm.

Finish

On behalf of **MarsKeel Technology** I would like to thank you for attending the presentation. We all hope it offered information that added to your understanding of keels. Please enjoy the rest of the conference.

Thank you.

William Souter