Paper No. 21

Performance/Construction/Maintenance

“A Comparison of Steel Castings vs. Forgings for Large Structural Components” or “How to Separate Fact from Fiction”

Tim Zwirlein
The Falk Corporation

HEAVY MOVABLE STRUCTURES, INC.

TENTH BIENNIAL SYMPOSIUM

OCTOBER 25 - 28, 2004
The Omni Orlando Resort at ChampionsGate

Abstract:

Material selection is one of the most crucial decisions made in the design, manufacture, and application of large structural components. Material selection naturally influences the entire performance of the design, and thus it is critical that informed decisions are made during the design stage. Steel castings and steel forgings are two alternatives for large structural components. For many design engineers it is often assumed that a forging is a better product because it is formed or worked during the manufacturing process. It also assumed that castings are inferior because they may contain porosity. Nothing could be further from the truth. Each process has its advantages and disadvantages. It is just as possible to produce an inferior product whether it is a forging or a casting. This paper will present an honest evaluation of castings and forgings, so that those in the design community can make an informed choice.

Introduction

This paper will concern itself with the differences between forged and cast steels in heavy sections. Heavy sections will be interpreted to mean parts in excess of 10 tons and a minimum metal section of 200 mm (5"). All steel products whether they are cast or wrought (forged) start from a batch of molten steel that is allowed to solidify in a mold. The difference is that a wrought product is mechanically worked by processes such as rolling or forging after solidification, while a casting is not.

Melt Shop Practice

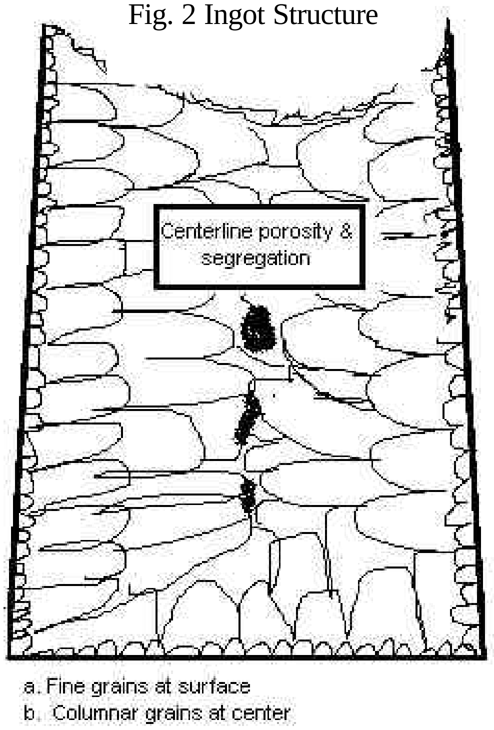
The process of steel making is essentially the same for both wrought and cast steels. Liquid steel is principally an alloy of iron and carbon. Other metals such as chromium, nickel, manganese, and molybdenum are added as alloying agents to impart particular properties to the steel. The raw materials used to make steel also contain undesirable elements such as phosphorus and sulfur, which form inclusions in the steel, that can never be completely removed from the steel. Thus the quality of both forgings and castings is dependent upon the quality of the molten steel that is poured into the mold.

Fig. 1 Bottom Pouring in a Steel Foundry

Since most forge shops purchase their steel ingots, they are dependent upon the steel mill to control the quality of the raw material that is used in their product. This also limits forge shops to supplying the standard alloy grades that the steel mill offers. Conversely steel foundries have to both make and pour their own steel to produce a casting, and thus have full control of the metal that is used to produce the casting. This also allows the foundry to supply virtually any alloy grade that the customer may want.

Liquid steel has a high affinity for oxygen and it will form oxide inclusions that can also become trapped in the final product. Molten steel must be handled properly to minimize the formation of re-oxidation products. Once the steel is refined in the melting furnace it is tapped into a ladle, which is a refractory lined vessel made to handle molten steel. Good steel making practice dictates the use of a bottom pouring ladle. The reason for this is that a slag layer is developed on top of the molten steel by use of fluxes. This slag layer is less dense than steel and thus floats on top while at the same time forming a protective barrier from the atmosphere. This protective barrier is maintained since the steel is poured from the bottom of the ladle. The bottom pouring technique is used for both steel castings and for steel ingots.

Fig. 2 Ingot Structure

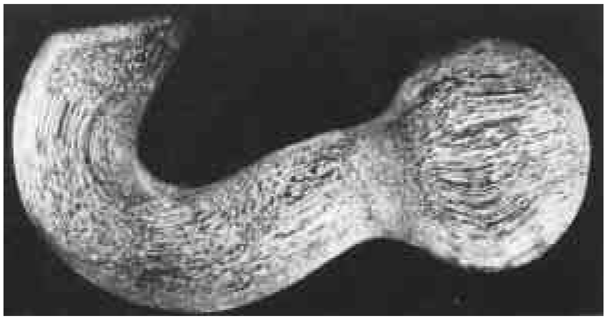


One important distinction between wrought and cast steels is the de-oxidation practice that is used. Wrought steels are typically "aluminum killed" which means that a small amount of aluminum is added during the melting process for the purpose of removing oxygen from the steel. While very effective at removing oxygen the aluminum forms microscopic aluminum oxide particles, which are abrasive during the machining process. Some steel casting shops de-oxidize with calcium which also removes the oxygen but produces a softer more machinable inclusion.

Forging Process

Wrought or forged materials by definition are made from cast ingots, which are then mechanically worked after solidification. Ingot castings, are the raw materials from which all wrought products such as forgings, plate, and barstock are produced, and are nothing more than a casting that is produced by pouring the liquid steel into a reusable metal mold. The cast ingot structure consists of different zones that contain porosity and segregation as shown in Fig. 2.

Fig. 3 Forging Flow in a Crane Hook



After solidification the ingot is hot forged into the desired shape using a hammer, press or ring-rolling machine. As the forging is hot worked into shape, the inclusions, porosity, and grains within the steel ingot are forced to flow in the direction the part is being worked. This imparts directionality to the finished part. According to the forging industry this grain flow makes forgings superior to castings. However the fact is that although the mechanical properties of a forging are higher in the longitudinal direction (direction of working), they are significantly lower in the transverse direction or perpendicular to the grain flow. Thus, when using a forging the design engineer needs to evaluate the loading characteristics in both the transverse and longitudinal direction. The effects of grain flow are shown in Fig. 3.

Large forgings are hammered or pressed into rough shapes, which then require extensive machining or welding to other components to produce a more complex shape. This adds to the cost of the overall product. Large forgings are limited as to the amount of mechanical working that can be done.

The forging industry typically refers to the term "reduction ratio" which is the ratio of crossectional area before and after forging and is used as a means to specify the quality of the forging. The typical standard for very large forgings is to require a minimum of three reductions. It is recognized by the forging industry that excess hot working can impart too much directionality into the part.

Forgings are subject to process variables and have the same potential for defects just as any manufacturing process. For example a large forging may actually burst or crack internally during forging if not heated properly (Fig. 4).

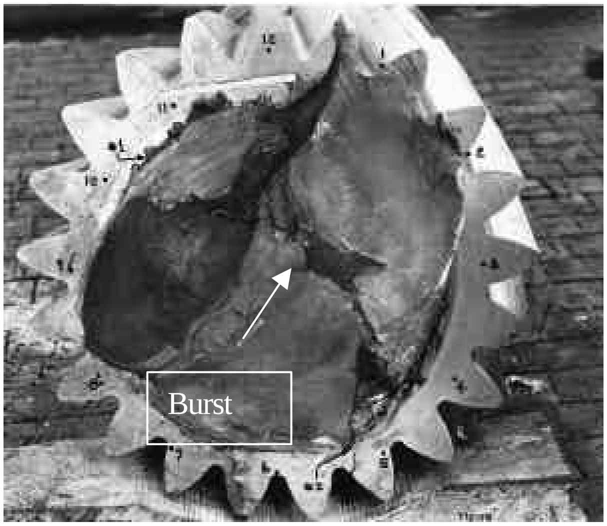


Fig. 4 Internal Burst in a Large Forging

Casting Process

Most steel castings are produced in expendable sand molds. The mold is produced by forming sand around a pattern, which is replica of the finished part. Molding sands are mixed with materials that will allow it to hold the desired shape after the pattern is removed. Holes or cavities are created by assembling sand cores in the mold. The pattern equipment also includes the gates and risers which are needed to produce a quality casting. The gating system is designed to allow the metal to flow into the mold in a controlled manner. Risers are reservoirs of molten metal which allow the casting to solidify without shrinkage porosity (Fig 5.).

Post solidification processing includes, sand removal or shakeout, removal of gates and risers, inspection, weld upgrading and heat treatment. The main advantage of the casting process is its versatility. Castings are best suited for complex geometries that cannot be easily produced by the forging process.

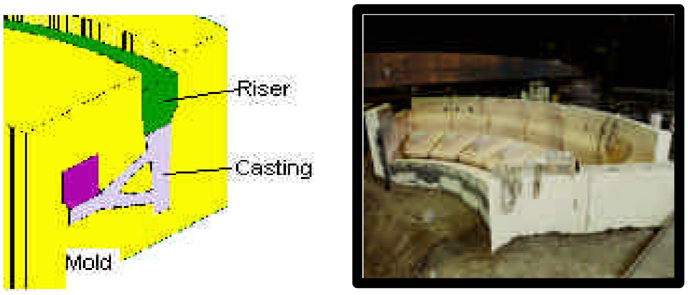


Fig. 5 Ring Gear Casting Mold

The principal difference between a casting and a forging is that the final part shape is created when the molten metal solidifies in the mold. Since the sand mold produces the desired finished shape, all that remains is to process the casting through various finishing operations in the foundry. This processing does not alter the directionality of the casting. A steel casting is homogenous. This means that the mechanical properties of a casting are the same regardless of the direction of applied stresses.

It is very important to understand the underlying principles that dictate how a casting solidifies. As steel cools in the mold it naturally changes from a liquid to a solid resulting in volumetric contraction. Additional feed metal in the form of risers must be supplied to the casting to make up for this loss in volume. There also needs to be a pathway for the additional metal to feed the casting as it solidifies. If a region of a casting is isolated from the riser a shrinkage cavity will form (Fig. 6). In this case it is necessary to add material to allow the molten metal to be properly fed form the molten riser.

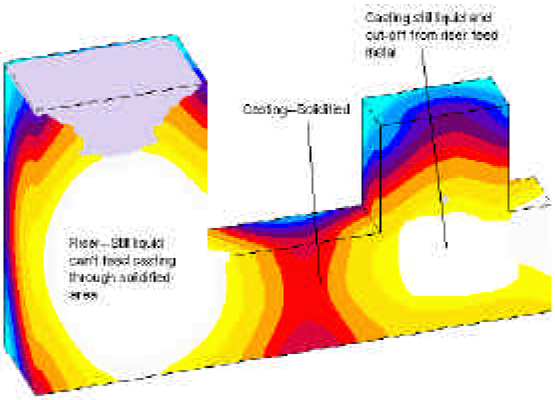


Fig. 6 Directional Solidification

The Foundry Engineer evaluates the shape of the casting and then determines how to modify the casting so that solidification progresses from the thinnest section back through progressively heavier sections. This progressive, controlled manner of solidification is termed directional solidification. Directional solidification can only occur if the temperature gradient is controlled by proper casting design. The temperature gradient can be modeled using solidification software, as demonstrated in Fig. 7. Thus the Foundry Engineer can validate the casting design by solidification modeling before the part the part is actually poured.

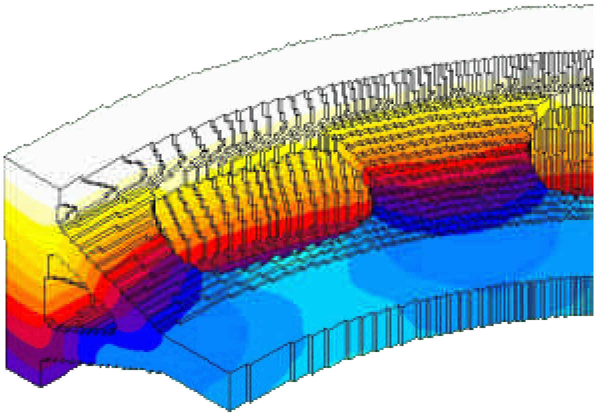


Fig. 7 Solidification Model of a Gear

All castings naturally begin to solidify at the mold wall because that is where the heat is first extracted from the molten metal. Solidification continues to proceed in the regions of the casting that are cooling the fastest. Good casting design practice seeks to make sure that the last part of the casting to solidify always has a supply of molten metal available to avoid the formation of shrinkage cavities. Since the last area to solidify is primarily influenced by part shape, it is critical that the casting user and the foundry work closely together to make sure that the part is designed in such a way as to optimize it’s castability, while at the same time taking advantage of the castings processes ability to produce the part to a near net shape.

Mechanical Property Comparisons

As previously stated the forging process produces a part that is anisotropic. This means that the mechanical properties of a forging are better in the longitudinal direction (parallel to lines of flow) direction versus the transverse direction (perpendicular to lies of flow). Conversely a casting is homogeneous this means that the mechanical properties of a casting are the same, regardless of the orientation of test bar material.

In order to demonstrate this difference a 5” thick test casting was poured from a typical low alloy cast steel. Equivalent test material was also cut from a 5” thick plate of rolled 4340 steel. Both test plates were then heat treated in the same production furnace load. Thus the test materials were equivalent in all respects of processing except one was cast and the other was wrought. Test bars were removed from the test plates in the orientation shown in Fig. 8.

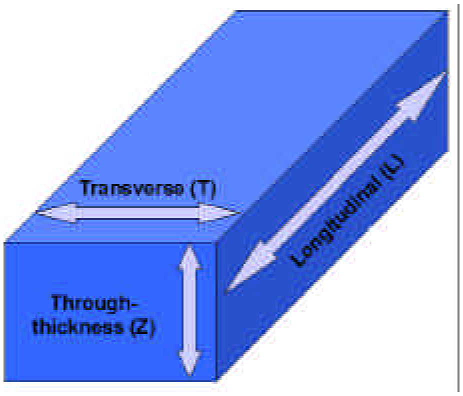


Fig. 8 Test Bar Orientation

Test results shown in Table 1 demonstrate that the mechanical properties of the cast plate are essentially the same regardless of test bar orientation. The mechanical properties of the wrought plate are lower in both the transverse and through thickness orientations, especially the ductility (indicated by % elongation and % reduction in area) which shows a significant degradation when compared to the longitudinal direction. The tensile ductility of the cast material is significantly higher than for the wrought material in the through thickness orientation, although lower than in the longitudinal direction.

TABLE 1

	Tensile (ksi)		Yield (ksi)	
	Wrought	Cast	Wrought	Cast
Longitudinal	141.0	147.6	113.5	117.1
Transverse	138.0	146.5	110.5	116.8
Thru Thick	134.5	147.6	108.5	116.9

	% Elongation		% Red. In Area	
	Wrought	Cast	Wrought	Cast
Longitudinal	15.5%	12.0%	46.5%	26.0%
Transverse	12.5%	11.0%	33.5%	21.7%
Thru Thick	8.5%	11.0%	13.0%	24.8%

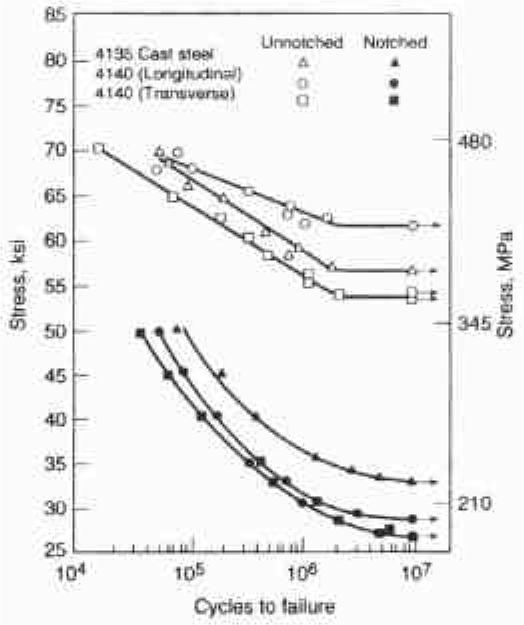


Fig. 9 Fatigue Properties

The same directionality effects are demonstrated when comparing fatigue strength of cast and wrought alloys. Fig. 9 shows that the unnotched fatigue properties of cast steel test are below that of wrought steel in the longitudinal direction but above wrought steel in transverse direction. However the notched fatigue properties test bars cast steel are actually superior to wrought steel regardless of orientation. This demonstrates that cast steel is less notch sensitive than wrought steel. Notched fatigue properties are a more accurate representation of actual service conditions because most large parts whether cast or forged would be expected to have some type of a notch.

Non-Destructive Testing

Large, heavily loaded parts are often non-destructively tested (NDT) in order to verify internal part integrity. The most common methods are ultrasonic (UT) and radiographic testing (RT).

Common specification pitfalls are to discount the effects of surface finish and machining when specifying NDT methods. For example since UT functions by measuring reflected sounds waves it works best on a part that is machined and has two parallel surfaces. Using UT on an un-machined surface compromises the sensitivity of the test. RT indications will change appearance before and after machining since the section thickness is reduced.

The main benefit of RT is that a permanent record is created. The acceptance criteria are based upon a comparison against ASTM reference radiographs, which are rated 1 through 5 (best to worst). The SFSA (Steel Founder's Society of America) sponsored a research project to determine the applicability of the ASTM referenced radiographs. In essence the study had experienced ASNT Level III radiographers evaluate the reference radiographs in a blind test. This group was able to agree on the best and worst conditions (levels 1 and 5). However, this expert group could not agree on which reference radiographs represented the middle levels 2, 3, and 4.

Both of these examples demonstrate that each method has its limitations and the purchaser and the producer need to understand these limitations. Application of a stringent NDT requirement does not necessarily result in a high quality part.

Summary

The main difference between a steel casting and a forging is that the forging is mechanical worked after solidification. This mechanical working imparts directionality or anisotropy to the forging. Castings and forgings are both susceptible to manufacturing problems and misapplication by the buyer.

In general a forging is best suited to simple configurations that can be easily worked in a die or other tooling. It is also suited to applications in which the principal applied stresses are the same as the direction of mechanical working.

A casting is best suited to complex shapes, custom or tailored chemistries and to applications that are subject to multi-axial stresses.

Casting buyers need to work closely with foundries at the design stage in order to insure that the design is able to take advantage of directional solidification. The poor quality image of castings is often the result of the buyer not understanding this process. The casting buyer must also understand that there are limitations to relying solely on NDT to verify quality. Quality is best enhanced by using tools such as solidification modeling at the design stage to insure the production of a high quality product.

References

1. *ASM Metals Handbook Desk Edition, 1985, pp. 4-43*

2. *ASM Metals Handbook Vol. 19 Tenth edition, pp. 657-658*

3. *Fatigue Properties of Cast and Comparable Wrought Steels, Evans, Ebert, & Briggs, Proc., ASTM, Vol. 56, 1956*

4. *Analysis of ASTM X-Ray Shrinkage Rating for Steel Castings. Presented at the 2000 SFSA T&O Conference by Carlson, Ou, Hardin, & Beckermann*

5. *Falk Corp. Materials Laboratory Mechanical Test Data*