# Computer Design of Feeding Systems for Iron Castings

# Or, How to Avoid Years of Problems with 20 Minutes of Analysis

L E Smiley
Finite Solutions Inc, Hamilton, OH

D C Schmidt
Finite Solutions Inc, Slinger, WI

## ABSTRACT

Iron foundries use a variety of methods for design of feeding systems for iron castings. Many of these methods are based on non-scientific principles, or principles which neglect the actual behavior of the cast metal during solidification. There is now available a set of tools and principles which, if applied correctly, will reduce or eliminate the vast majority of feeding problems encountered in iron foundries. Application of these techniques to a given casting may often require only 20 or 30 minutes of human and computer time, yet this may eliminate years of problems in subsequent production of the castings. Considerable cost savings in terms of reduction of scrap and customer returns can be realized. This paper will explain the principles and the use of computerized tools, as well as present multiple examples where these methods have been successfully applied in actual foundries to improve quality and reduce defects.

## INTRODUCTION

Proper design of feeding systems for iron castings (grey and ductile, also called nodular or spheroidal graphite, iron) requires an understanding of how these alloys differ from other alloys such as steel. If these differences are not properly taken into account, then the feeding systems may be less than adequate and casting quality will suffer. It has been our experience that many iron foundries do not properly take into account the solidification characteristics of iron when designing feeding systems; in many cases, feeders for iron castings are designed essentially as feeders for steel castings and the result is the presence of defects in the production castings. Often the suggested remedies for these defects worsen the situation, due to the same lack of understanding. It is the intention of this paper to present a few relatively simple design rules which, if followed, will help the iron foundry engineer to design casting processes which have a higher degree of success.

The design methods explained in this paper are generally quite easy to implement and require only a minimal investment of time. We have seen a number of castings in ongoing production in foundries where defects were a continuing problem for the foundry and the customer, resulting in excess costs, delays and in some cases loss of business. Most of these problems could have been prevented had the foundry engineers applied correct design methodology from the start, and in most cases this methodology would have taken no more than 15 or 20 minutes of time to implement. Spending such a short amount of time to prevent ongoing problems in foundry production over months or years results in an extremely high return on investment.

## DESIGN PRICIPLES FOR CAST IRON

The most fundamental difference between iron and other alloys is the expansion that occurs in the iron as graphite precipitates during solidification. This expansion is significant in that, in most situations, the casting can become “self-feeding” after the onset of expansion, meaning that no further feeding is required. Thus, the object of designing a feeding system for iron castings is to provide feed metal only for the contraction of the liquid alloy as well as the contraction of the solidifying iron prior to the start of expansion; once the expansion begins, a well-designed feeding system should control the expansion pressure to ensure that the casting is self-feeding during the remainder of solidification. This is in contrast to other alloys such as steel, where feed metal must be supplied to the casting during most or all of solidification and there is no expansion involved.

Another major difference between cast irons and other alloys has to do with the mechanism involved in “piping”, or the onset of feeding behavior in the feeder. Cast irons (particularly ductile iron) do not readily form a solid skin during solidification; rather the freezing mechanism is often described as “mushy” or “pasty”. This freezing pattern is what renders atmospheric cores (Williams’s cores) ineffective with these alloys. For blind feeders to pipe effectively, atmospheric pressure must be able to collapse the weak plastic skin after the internal pressure drops below atmospheric. Once one feeder punctures, the internal pressure is equalized so there is no longer a higher external pressure to cause other feeders to pipe. In practice, this means that only one feeder should be used on each “feeding zone” within an iron casting; if multiple feeders are placed on the same zone of a casting, then typically one feeder will begin piping while the other feeders will not. Often, porosity will be seen at the contact point of non-piping feeders.

With alloys such as steel, solidification is strongly directional; a relatively strong solid skin rapidly forms which over time increases in thickness towards the thermal center. When blind feeders are used in steel castings, it is essential that atmospheric cores are employed to allow a passage for atmospheric pressure to act on the internal liquid. In effect the atmospheric core creates the surface puncture and allows atmospheric pressure to act on the liquid interior of the feeder(s) for an extended time. In this circumstance, multiple feeders may effectively be used within the same zone of the casting.

The requirement for a single feeder within a single zone of the casting is probably the design rule which is violated most often within iron foundries. We often see designs where two or more feeders are feeding the same zone within a casting, and the resulting casting exhibits porosity, often at the contact point of one of the feeders. The tendency of many foundry engineers is to add more feeders to try and resolve the porosity issue; in fact, this is exactly the wrong approach and will worsen the situation.

In order to correctly design a feeder system for iron castings, it is necessary to be able to analyze the cast shape and determine the location and size of feed zones within the casting. We must answer the question: Is this casting composed of a single feed zone, or are there multiple zones and, if so, what is the location and size of each zone? In order to make this determination, we introduce the concept of the **Transfer Modulus**.

Feed zones within the casting are defined by knowing where within the casting it is possible for liquid metal to flow from one point to another in response to expansion pressures. If there is no possibility of metal flowing from one area of the casting to another as expansion begins, then each of these areas forms a separate feed zone and each may require its own correctly-designed feeder (but no more than one).

Such an analysis of a casting begins with consideration of the Casting Modulus. This is defined as the volume:surface area ratio of various areas of the casting, and has been used for many years to estimate the order of solidification of different parts of the casting. The Casting Modulus ($M_c$) allows us to estimate which part of the casting will solidify first and which will solidify last. In steel castings, this information is immediately useful to indicate where feeders should be placed and what size they should be (the Modulus of the feeder should be greater than the Modulus of the casting). In iron castings, the Casting Modulus is used to estimate when expansion will begin, expressed as a percentage of complete solidification.

Prior to development of computers and software, calculation of $M_c$ was tedious and time-consuming; it required the foundry engineer to estimate volumes and surface areas by approximating various parts of the casting to relatively simple shapes. With modern casting simulation software, solidification of a casting can be simulated, often in a matter of minutes. The result data from this simulation can be converted to Modulus values within the casting. This means that Modulus data is now available at every point within a 3D representation of the casting; this also means that the Modulus data is more accurate, as effects such as local superheating of the mold material are accurately taken into account by the simulation, which is not possible with manual methods.

With the Modulus data for the casting, as well as the chemistry and temperature data, the point at which expansion begins can be calculated. Castings which have a higher Modulus (heavy section castings) will begin to expand earlier and will undergo more expansion than castings with low Modulus (light section castings). This point at which expansion begins is expressed as a percent of full solidification and is often referred to as the **Shrinkage Time** (**ST**) point.

Knowing the ST point for the iron in a casting, it is possible to calculate an equivalent Modulus value which then corresponds to the Modulus at which contraction of the iron stops and expansion begins. This Modulus value is known as the **Transfer Modulus ($M_{TR}$)**, because it defines for us the areas of the casting where liquid metal transfer is possible. The calculation of $M_{TR}$ is as follows:

$$\mathbf{M_{TR} = SQR\ (\ ST\ /100)\ *\ M_C}$$

By post processing (or plotting) the value of $M_{TR}$ in our casting simulation, we are able to visualize the feed zone(s) within the casting and determine whether the entire casting is a single feed zone ($M_{TR}$ is continuous throughout the casting) or whether there are multiple zones ($M_{TR}$ is discontinuous). This then allows us to determine the number of required feeders, using the rule of one feeder per feed zone.

The value of $M_{TR}$ can be understood as representing the Modulus value below which feeding of the casting in the traditional way (from feeders) is no longer effective, and the iron becomes self-feeding due to expansion. $M_{TR}$ is thus critical in designing the feeding system for the casting. The basic premise in all design work for feeding iron castings is that the expansion pressure must be controlled. This means that, assuming the mold is rigid enough, all contacts with the casting (gates and riser contacts) should essentially be solid enough to ensure that the expansion pressure is contained within the casting after the onset of the graphite expansion. This leads to another simple rule: The Modulus of the feeder contact neck should be equal to $M_{TR.}$ This ensures that feeding of the liquid contraction will be able to occur, and also that the expansion pressure will be contained within the casting due to freezing of the feeder contact at just the correct point in solidification.

If the mold is soft and is unable to resist the pressure of expansion, then some allowance must be made to relieve that portion of the pressure which the mold is unable to resist. This is generally done by sizing the feeder neck contacts so that the expansion pressure is allowed to backfill the feeder; in this case the feeder neck must be designed for a Modulus value greater than $M_{TR}$. In general, for successful production of iron castings, the foundry should attempt to ensure that molds are as rigid as possible given the constraints of the production machinery employed. For larger castings, this typically will mean chemically-bonded sand in steel flasks with top weights and parting-line clamps.

## CASE STUDY 1

As an example of both the incorrect and the correct feeding approach, we consider first of the all the ductile iron control arm as shown in Figure 1.

***Figure 1. Ductile iron control arm casting.***

Figure 2 shows the location of this casting in the production vehicle.

***Figure 2. Location of the casting in the vehicle.***

The foundry originally approached the feeding design for this iron casting by placing two symmetrical feeders as shown in Figure 3. This was, perhaps, understandable as the two sections to which these feeders were attached are the heaviest sections of the casting.

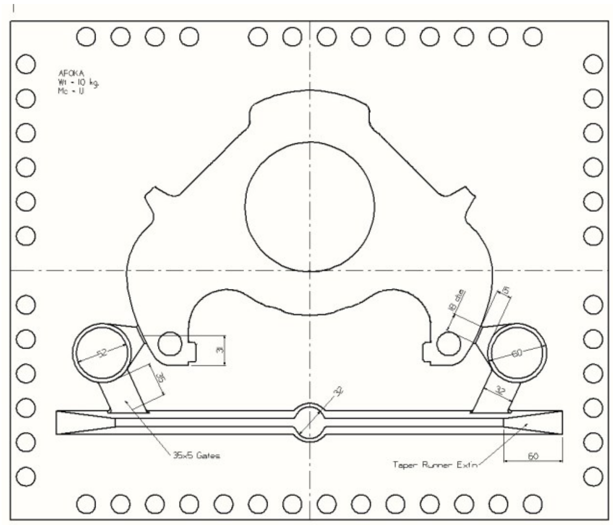

***Figure 3. Original pattern layout and feeder design.***

During initial production of this casting, it was found that porosity occurred at one feeder contact on a consistent basis, as shown in Figure 4. The porosity was not always at the same contact, but on almost all castings one contact showed evidence of porosity and the other did not. No acceptable castings were produced with this pattern design.

***Figure 4. Feeder contacts with original design (2 feeders).***

In order to resolve this problem, it was decided to analyze this casting using the approach described previously to determine the feeding requirements. First, a solidification simulation of the casting without gating or feeders was performed. The results of this simulation are shown in the plot of Solidification Time (in minutes) in Figure 5.

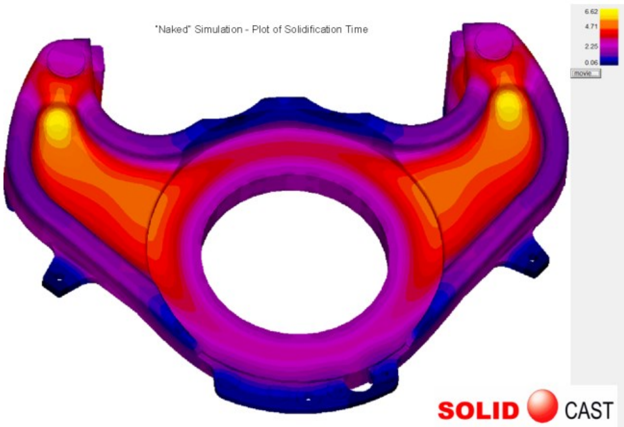


***Figure 5. Plot of solidification time: Simulation of casting without feeders.***

The result data from the simulation is now converted to Modulus data so that the feeding calculations can be performed. Figure 6 shows a plot of the areas of highest Modulus in the casting. From viewing this plot, the foundry engineer might be tempted to conclude that the original feeder design was correct, as there are two areas of high Modulus value in the casting and these are adjacent to the feeder contacts in the original design.

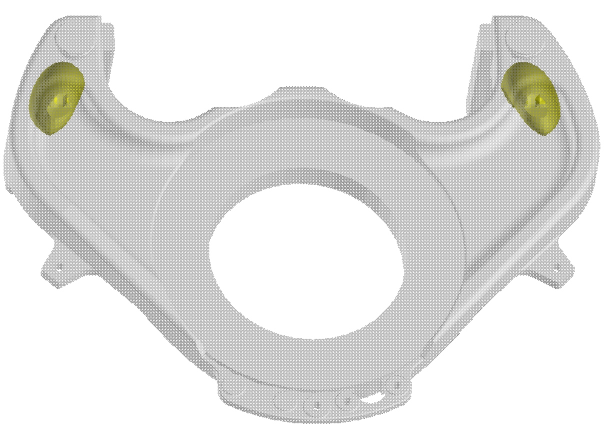

***Figure 6. Areas of high modulus value in the casting.***

However, it is necessary to further analyze this casting to determine the Shrinkage Time and from this the Transfer Modulus ($M_{TR}$) in order to understand the location and size of the feeding zones within the casting. Figure 7 shows the calculation performed within the software of values for both ST and $M_{TR}$.

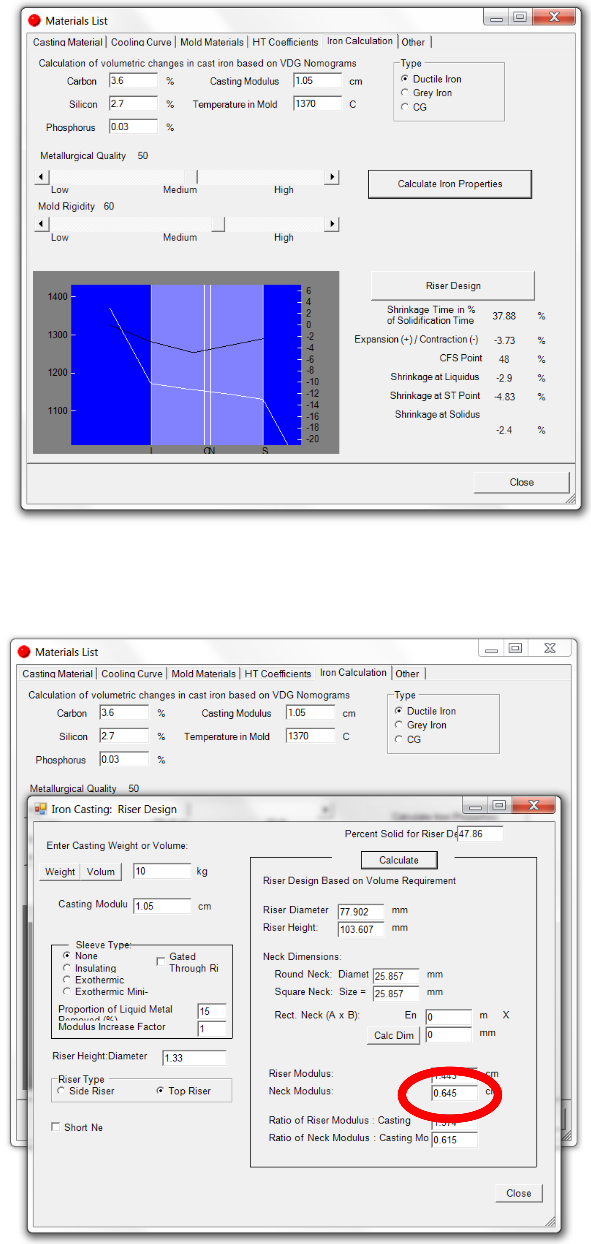


***Figure 7. Calculation of Shrinkage Time and Transfer Modulus for the Casting***

Analysis of the iron characteristics for this casting indicates that the value of the Transfer Modulus is 0.645 cm. Creating a plot of this value within the casting will indicate the location of feed zone(s); this is shown in Figure 8.

***Figure 8. Plot of transfer modulus of 0.645 cm in the casting.***

Examination of this plot shows us that the entire casting is actually a single feed zone. The areas of higher modulus are connected by a section of the casting in which the Modulus is above the value of $M_{TR}$, thus allowing liquid transport for feeding throughout the casting. This means that only a single feeder should be used on this casting. With the two-feeder design, both feeders were connected to the same zone of the casting; when this is done, typically one feeder will pipe and the other feeder will not pipe, resulting in porosity at the contact of the non-piping feeder.

It should be noted that the computer simulation in this case took 16 minutes to perform, and within less than 5 minutes after that the calculation of ST, $M_{TR}$, and the plot shown in Figure 8 were created. This means that with about 20 minutes of analysis, the correct feeder design was arrived at. Had this been done before the original pattern equipment was created, several months of time involved with production of defective castings would have been avoided. The costs involved were far greater than the cost of the software and training to perform this analysis.

After this information was presented to the foundry, the pattern was revised to reflect a single feeder as shown in Figure 9.

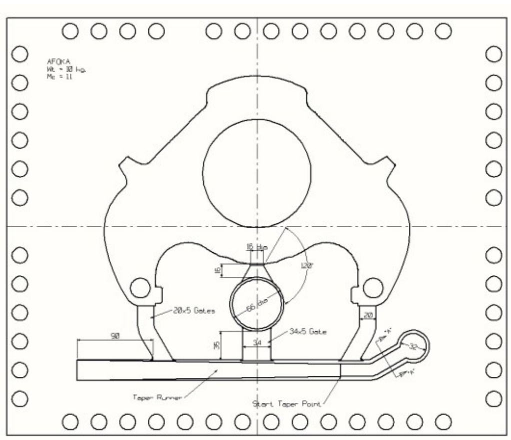


***Figure 9. Revised pattern with single feeder.***

Figure 10 is a photograph of the revised pattern showing a single feeder.

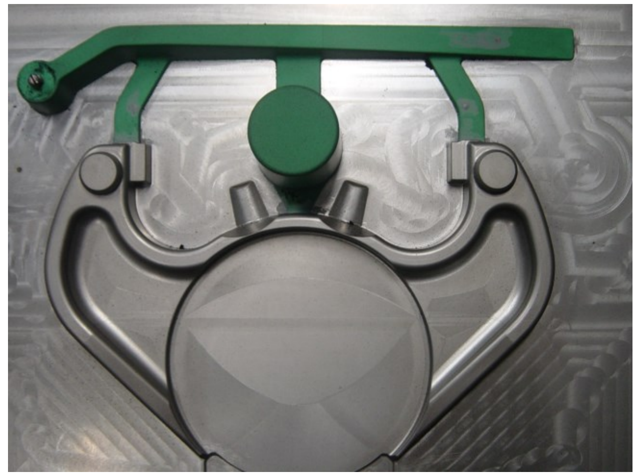

***Figure 10. Photo of revised pattern with single feeder.***

It should be noted that the feeder in this case is not connected to the casting at one of the areas of high Modulus. This illustrates the point that in iron castings, the location of the feeder is not as critical as in steel castings. This is due to the expansion pressure which acts throughout the casting once precipitation of graphite begins.

Finally, Figure 11 shows a photograph of the contact area with a single feeder. In this case there is no porosity at the feeder contact, and no porosity elsewhere within the casting. Thus, a simple and quick analysis of the casting has produced the correct feeder design for making a sound casting.

***Figure 11. Photo of the contact area with a single feeder.***

## CASE STUDY 2

A second example of an incorrect feeding approach is the ductile iron bracket casting shown in Figure 12. Again, the design for production of this casting was performed without adequate consideration of the solidification properties of the iron.

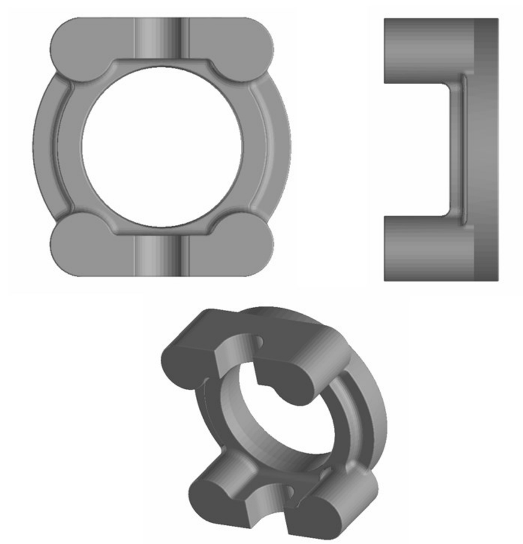

***Figure 12. Ductile iron bracket casting.***

In this case the foundry decided to produce the casting with two top feeders as shown in Figure 13.

***Figure 13. Bracket casting with 2 top feeders: Only 1 feeder has piped.***

Examination of the casting results shows very clearly that one of the feeders shows piping behavior and the other does not. When the non-piping riser was removed from the casting, porosity was visible at the contact surface.

This illustrates an important tool for the iron foundry engineer. Much information can be gained by examining a complete casting with all feeders and gating still attached. In many foundries we see that the feeders and gates are removed before the casting is examined for defects; this practice eliminates some important information which can guide the foundry engineer to the root cause of defects. In this case, the fact that one feeder pipes while the other does not should suggest strongly that both feeders are attached to the same zone within the casting. This can be verified by performing a solidification analysis of the casting and, from that analysis, creating a plot of Transfer Modulus within the casting as shown in Figure 14.

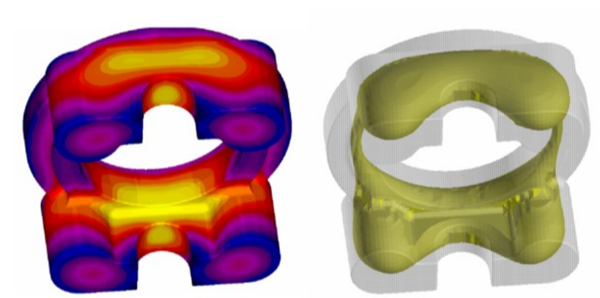

***Figure 14. Solidification time and transfer modulus plots in the bracket casting.***

The calculated value for of $M_{TR}$ in this casting is 0.612 cm. The plot of $M_{TR}$ illustrates very clearly that the entire casting consists of a single feed zone and thus only a single feeder should be used to produce the casting. In this case, the complete analysis required less than 15 minutes of time.

## CASE STUDY 3

A third example involves a 210 Kg ductile iron casting used as a bearing connector for a wind power generator. This casting is in the shape of a large ring as shown in Figure 15.

***Figure 15. Ductile iron bearing connector (210 Kg).***

The foundry involved in producing this casting approached feeding design as a steel casting rather than an iron casting. Figure 16 shows two alternate feeder designs which were being used to produce this casting. The original design specified five feeders with insulating sleeves. When the results of this design were unsatisfactory, the design was changed to include six feeders.

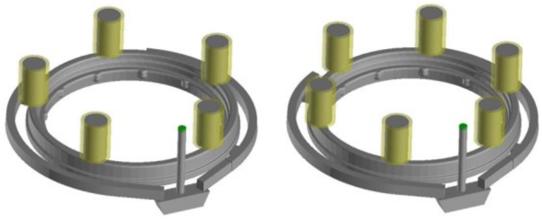

***Figure 16.  Original design with 5 feeders and redesigned process with 6 feeders.***

This is typical of the approach to design and problem solving that one might encounter in a steel foundry; if a casting cannot be successfully produced with a given set of feeders, then the next decision is to add more feeders. In actuality, this approach did not resolve the problem, instead the quality of the casting was worse.  This one casting represented the most costly scrap problem of all production castings in the foundry.

Examination of the defective casting showed that porosity was exposed on the top surface of the casting after machining 6 mm of iron off the surface, as shown in Figure 17.

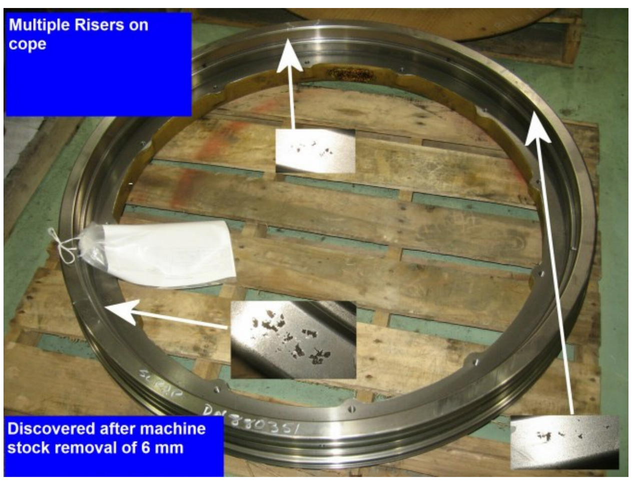


***Figure 17.  Appearance of porosity on machined surface.***

Close-up inspection of the areas of porosity showed what appeared to be primary shrinkage as shown in Figure 18. A very strong clue as to the cause of this porosity is contained in the fact that these defective areas were found at the location of the feeders on top of the casting (which were removed after the casting operation).  This suggests the phenomenon which has been discussed earlier in this paper, that multiple feeders are being used on a single common feed zone and only one feeder is showing piping behavior with porosity formation under the non-piping feeders.

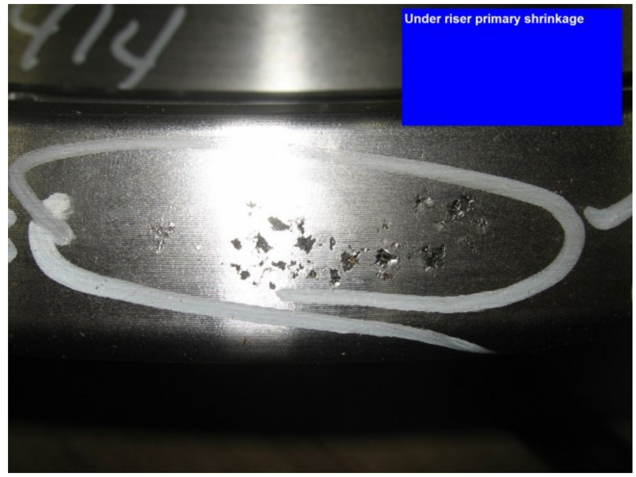


***Figure 18.  Porosity on machined face, under feeder location.***

An analysis of this casting was performed, involving a solidification simulation and calculation of the $M_{TR}$.  The value of $M_{TR}$ was determined to be 0.96 cm.  A plot of $M_{TR}$ in the casting is seen in Figure 19.

***Figure 19. Plot of $M_{TR}$ at a value of 0.96cm.***

This image shows very clearly that the entire casting consists of a single feed zone, and that only a single feeder should be used on this casting.  The final revised design for this casting is shown in Figure 20.

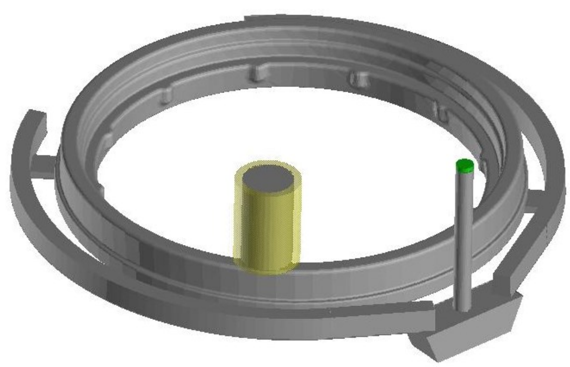

***Figure 20.  Single feeder design.***

When this design was adopted in the foundry and the feeder and contact were sized correctly, the final result was a casting without porosity defects.  It is worth noting that the cores which were originally used by the foundry to create the contact between the feeders and the casting were intended for production of steel castings, where the contact diameter was 50% of the feeder diameter. Consideration of the fact that the Modulus value in the contact should be equal to $M_{TR}$ resulted in a much smaller contact diameter. In this case the foundry produced cores which were specialized for this particular casting to ensure the correct contact size.

It is also worth mentioning that the analysis of this casting to produce the correct feeder design required 15 minutes of time. The foundry could have saved considerable costs over a long period of time had they performed this quick and simple analysis before finalizing the production design for the casting.

## SUMMARY

Understanding the solidification mechanisms of graphitic iron alloys in terms of expansion/contraction behavior, feeding mechanisms and control of expansion pressure is critical to correct design of feeding systems. Quick and simple analysis is available which will help the foundry engineer to design the production process correctly at the beginning of production, thereby avoiding the potential for major costs involved in production of defective castings.