

Determining the Optimum Level of Inoculant Addition by Thermal Analysis – A Case Study

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Introduction

The primary objective of inoculation is to produce carbide-free microstructures. At the same time, the foundry seeks to minimize the shrinkage tendency of the iron. These properties are influenced to a large extent by the type of inoculant and its addition rate to the iron.

Poorly inoculated liquid iron cools to temperatures below the white eutectic. Carbides will form under these conditions. Inadequate inoculation therefore results in carbides and associated shrinkage due to the unavailability of carbon for graphite expansion throughout the solidification range. Simply stated, carbon that preferentially should produce expanding graphite is tied up as dense, non-expanding, hard, and shrinkage promoting carbides.

Over-inoculation is costly and can also result in shrinkage. This is because over-inoculation can cause excessive early graphite growth that may result in a lack of available graphite for expansion at the end of freezing. This in turn leads to the possibility of micro-shrinkage formation. Also, excessive early graphite growth may cause mold wall expansion effects resulting in macro-shrinkage.

These factors mean that it is important for the operating foundry to determine the optimum addition rate of inoculant that takes into consideration chill resistance, shrink protection, and cost of alloying. It can be a balancing act! Over-inoculation, as well as under-inoculation may cause several potential quality issues, and the addition rate of inoculant should ideally be adjusted to each individual casting need.

Thermal analysis is a powerful tool to determine the correct level of inoculant addition to liquid iron that can result in significant cost savings and scrap reductions due to carbides and shrinkage. Also, there exists the possibility that the foundry is using too much or too little inoculant. The optimum inoculant addition rate for one particular casting requirement may not be the optimum addition for another requirement. Special castings may need added protection against shrink, while other castings may need improved protection against chill. Thermal analysis is a useful means to fine-tune and adjust critical inoculant addition rate and also to select the best-suited inoculant material for each individual requirement.

Experimental Work

A series of experiments was conducted in a ductile iron foundry to determine the optimum addition rate of inoculant for their given casting application. The long-time practice at this

foundry has been to inoculate all ductile iron by a fixed 0.7wt% addition of calcium-bearing 50% ferrosilicon inoculant to the pouring ladle. Some studies have shown that a drop in addition rate to 0.4wt% resulted in beneficial effects on process costs without impairing casting quality. The objective of the investigation was to acquire quantitative data through thermal analysis in order to verify this and determine the optimum addition rate of the specific inoculant in use.

The foundry is treating ductile iron by the sandwich process, using a 5% magnesium-bearing ferrosilicon alloy at an addition rate of 1.8wt% and cover steel at an addition rate of 1.3wt%. Treated metal is then transferred into the pouring ladle and inoculant added to the metal stream simultaneously.

In this experiment, four different addition rates of inoculant were tested (0.2%wt, 0.4%wt, 0.6%wt, and 0.8%wt). Thermal analysis samples were taken and cooling curves recorded with the ATAS[®] (Novacast's Adaptive Thermal Analysis System) system immediately after inoculation and approximately every two minutes thereafter for about 15 minutes.

The ATAS[®] system records and generates several numerical parameters. When analyzing the effect of inoculation, this study looked specifically at the effects of four characteristic parameters: TE_{low} , R , $GF1$, and $GF2$. The significance of these terms is explained below.

TE_{low} is the low temperature of eutectic undercooling. A higher TE_{low} value indicates that eutectic undercooling is at a temperature farther from the (white) carbide eutectic and the metal is therefore more resistant to chill than with a lower TE_{low} value. R is the eutectic Recalescence. This value represents the temperature increase from latent heat during eutectic solidification. Higher R values may indicate undesirable, early graphite expansion that increases the risk for wall expansion effects and primary shrinkage. Also, early graphite expansion may reduce the available carbon for later graphite expansion at the end of solidification and thus increase the risk for micro-shrinkage porosity formation. $GF1$ is the ATAS[®] Graphite Factor 1 and it is an indicator of eutectic graphite precipitation rate. A higher $GF1$ is desirable because it indicates more continuous graphite expansion and less overall risk for shrinkage. $GF2$ (Graphite Factor 2) is determined from the first derivative of the cooling curve and describes the degree of late graphite formation. A lower $GF2$ is desirable and indicates late-forming graphite that counteracts shrinkage in the last metal to freeze.

Experimental Results

Figure 1 shows an actual cooling curve taken from the heat made with the 0.4wt% inoculant addition. This sample was taken three minutes after the first sample in that heat. Figure 2 is the first derivative curve associated with Figure 1. These figures are included here to show the locations of the thermal analysis parameters described above. Also, Figures 1 and 2 represent relatively desirable curves; they have a clearly visible small rise in temperature at the beginning of eutectic freezing (low Recalescence, Figure 1) and small final angle in the first derivative (Figure 2) representing $GF2$.

Similarly, Figures 3 and 4 show corresponding curves made with the 0.6wt% inoculant addition. These samples were taken two minutes after the first sample in that heat. The Recalescence is visibly larger and the GF2 angle is visibly wider (inferior) as well. Compared to Figures 1 and 2, these represent inferior solidification conditions.

Figure 5 shows a spread in TE_{low} values over six degrees C for samples taken immediately after inoculation (time 0). TE_{low} drops slightly for all addition rates as a function of time, indicating a certain dissipation of the initial graphitization temperature for all addition rates of inoculant. The 0.4wt% addition rate maintained the highest TE_{low} value during the holding time. Furthermore, the higher addition rates generated lower TE_{low} values consistently as time passed. The conclusion to be drawn from these data is that 0.4wt% is the correct addition rate since it gives the highest TE_{low} as a function of hold time. A secondary observation from this is that adding more inoculant does not necessarily mean that the metal will be more chill-resistant over time.

Figure 6 shows that Recalescence increases with higher addition rate of inoculant. This is consistent with existing theory in that extra inoculant is causing more graphite to come out of solution early in solidification. Lower Recalescence values are desirable and Figure 2 shows that either 0.2wt% or 0.4wt% additions generated lower Recalescence.

Figure 7 shows that Graphite Factor 1 increases in the first 3 to 4 minutes after inoculation for most addition rates of inoculant. For most data points, the 0.4wt% addition rate generate the highest GF1 values. After about 5 minutes, GF1 is falling weakly throughout the remaining hold time.

Figure 8 shows that Graphite Factor 2 is lowest for the two lowest addition rates of inoculant. This is consistent with the finding that Recalescence is lower for the lower addition rates – i.e. less early graphite means more late graphite formation. In most conditions, later graphite is desirable since it counteracts difficult micro-shrinkage porosity. Note also that Graphite Factor 2 drops in the first three minutes after inoculation for all four addition rates of inoculant. Thereafter, the GF2 remains fairly constant for the remaining hold time.

Conclusions

The experimental ATAS[®] thermal analysis data indicates that a 0.4wt% addition rate of inoculant produces metal that is more resistant to shrinkage porosity formation than either lower or higher addition rates. The 0.4wt% addition rate is also found to be more chill resistant than higher or lower addition rates, especially as time is passing after inoculation. These results confirm that the 0.4wt% addition rate of inoculant is the optimum for this specific foundry condition.

The present work also suggests that adding more inoculant will not necessarily produce a more inoculant fade-resistant iron.

The data also suggest, at least for this foundry, that thermal analysis properties can change dramatically over time after addition of inoculant. Analyses suggest that the metal becomes substantially more resistant to shrinkage formation after 3 to 4 minutes hold time after inoculation.

The foundry has been operating for a year at this lower addition rate now and has seen no increase in the scrap rate from carbides or shrinkage. At the same time, inoculant usage has been reduced by 43%. These facts are clear evidence that thermal analysis can be a powerful tool for documenting improved metallurgical performance and reducing raw material costs, and optimizing additions of alloys.

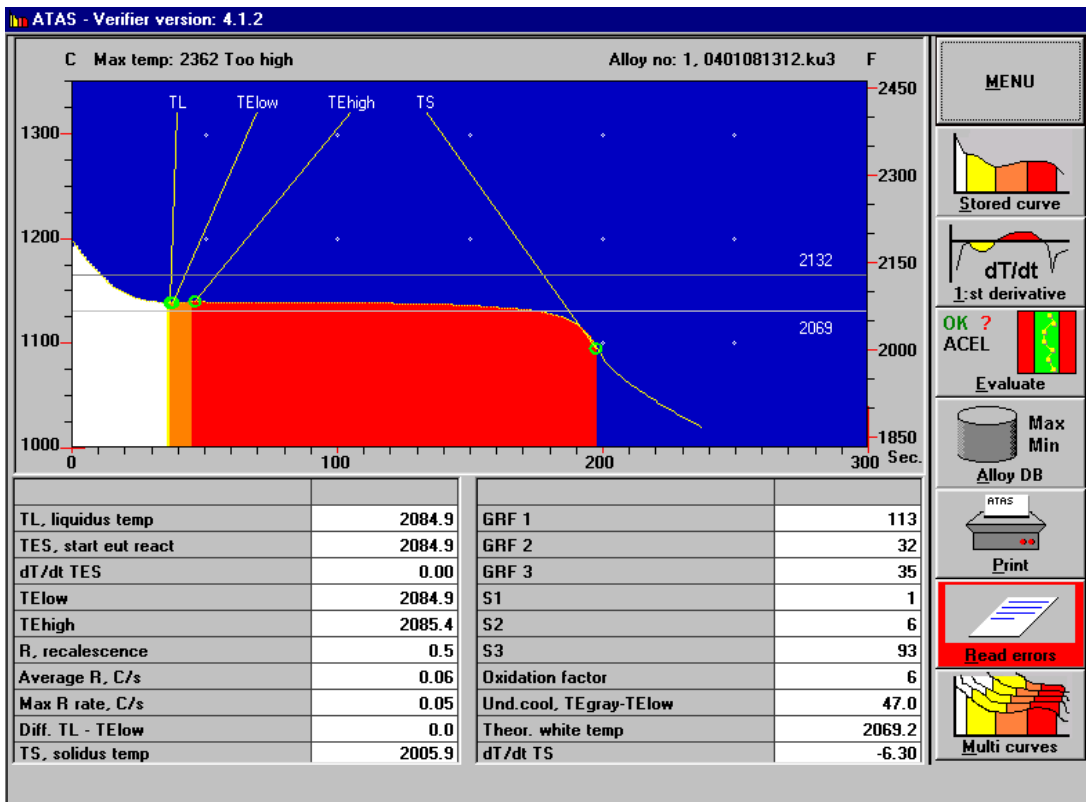


Figure 1: Actual Cooling Curve Taken from Heat Made with 0.4wt% Inoculant

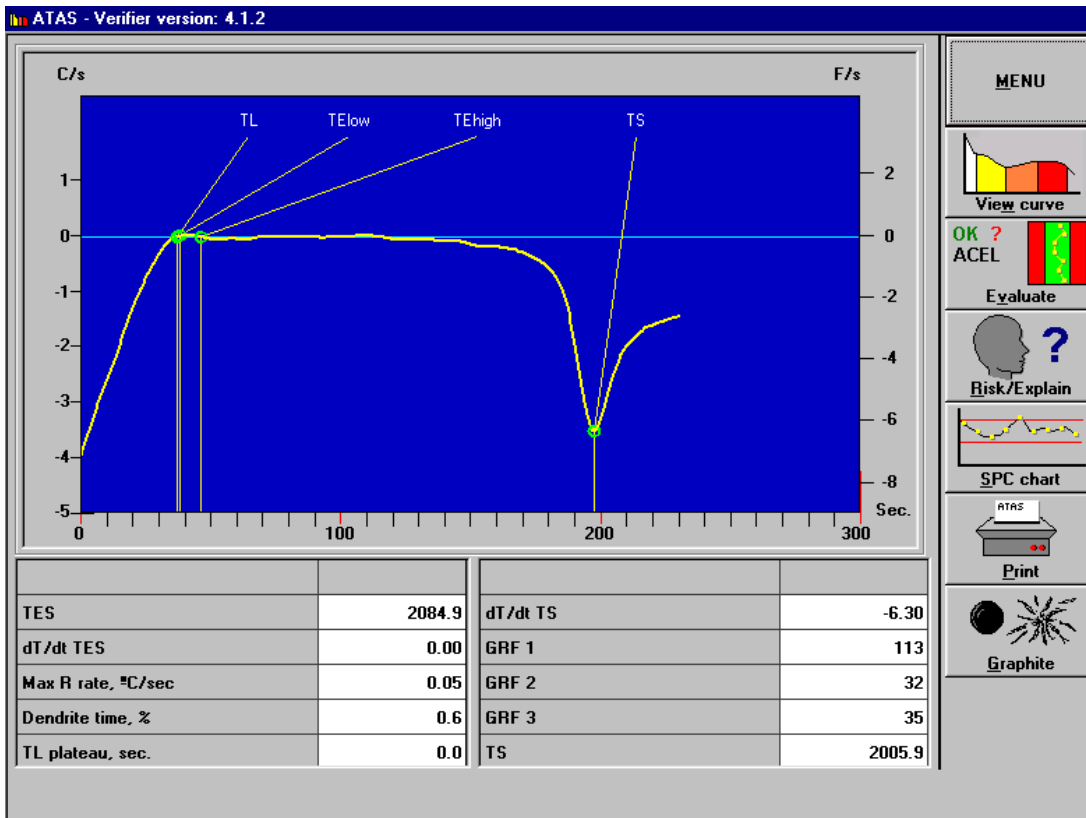


Figure 2: First Derivative Curve Associated with Figure 1

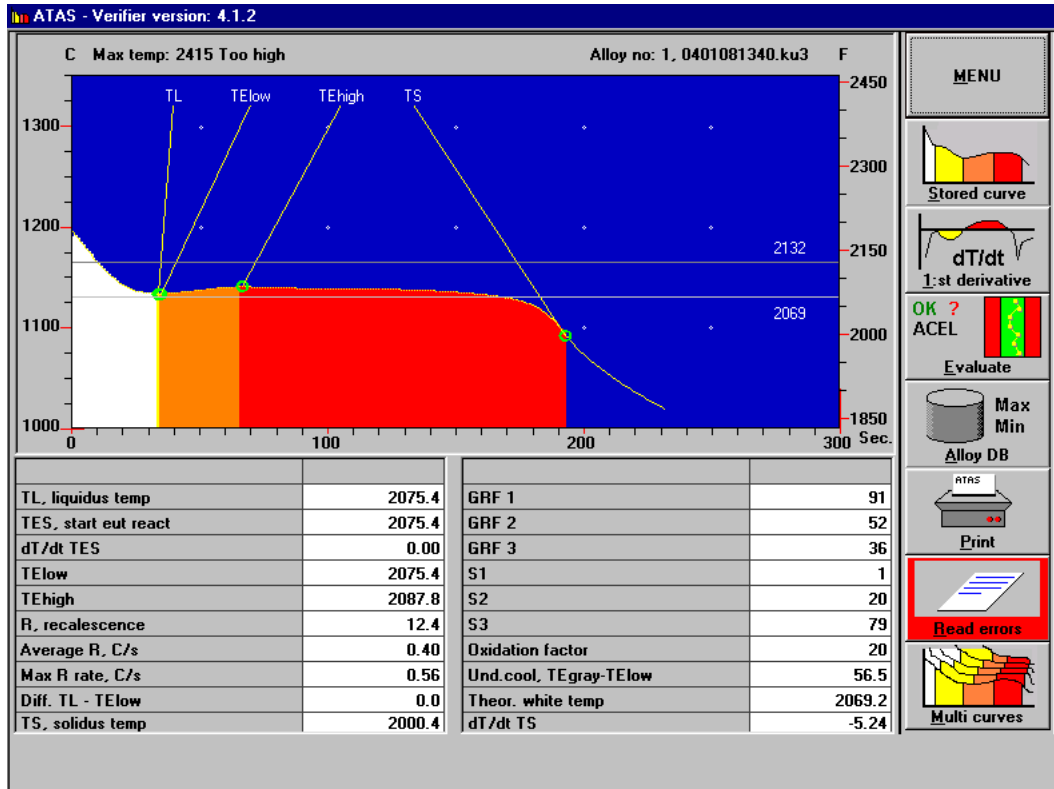


Figure 3: Actual Cooling Curve Taken from Heat Made with 0.6wt% Inoculant

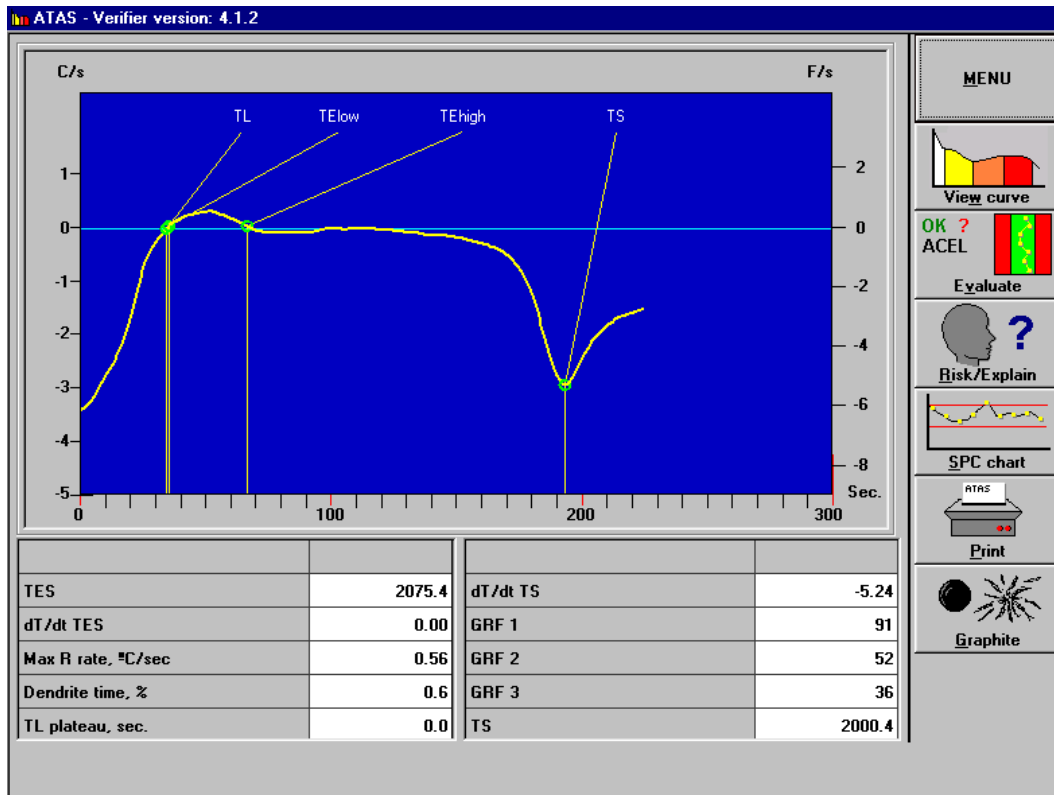


Figure 4: First Derivative Curve Associated with Figure 3

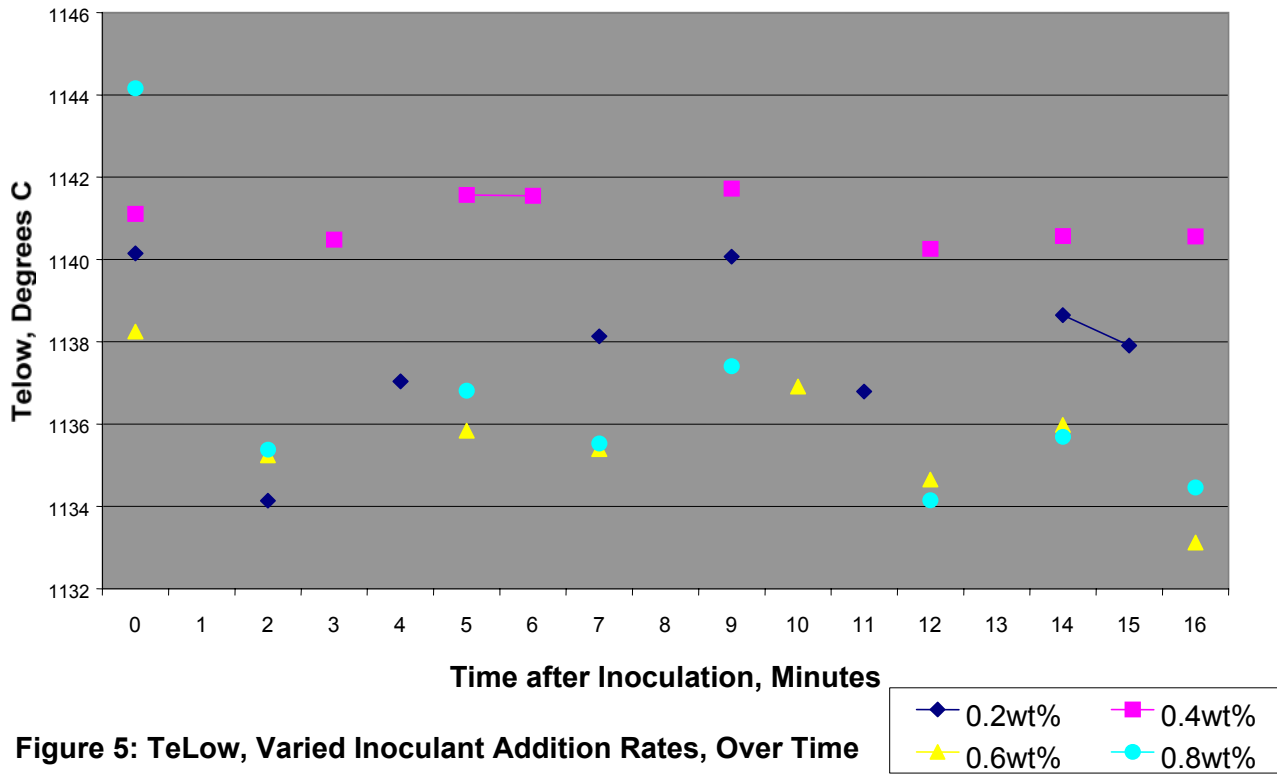


Figure 5: TeLow, Varied Inoculant Addition Rates, Over Time

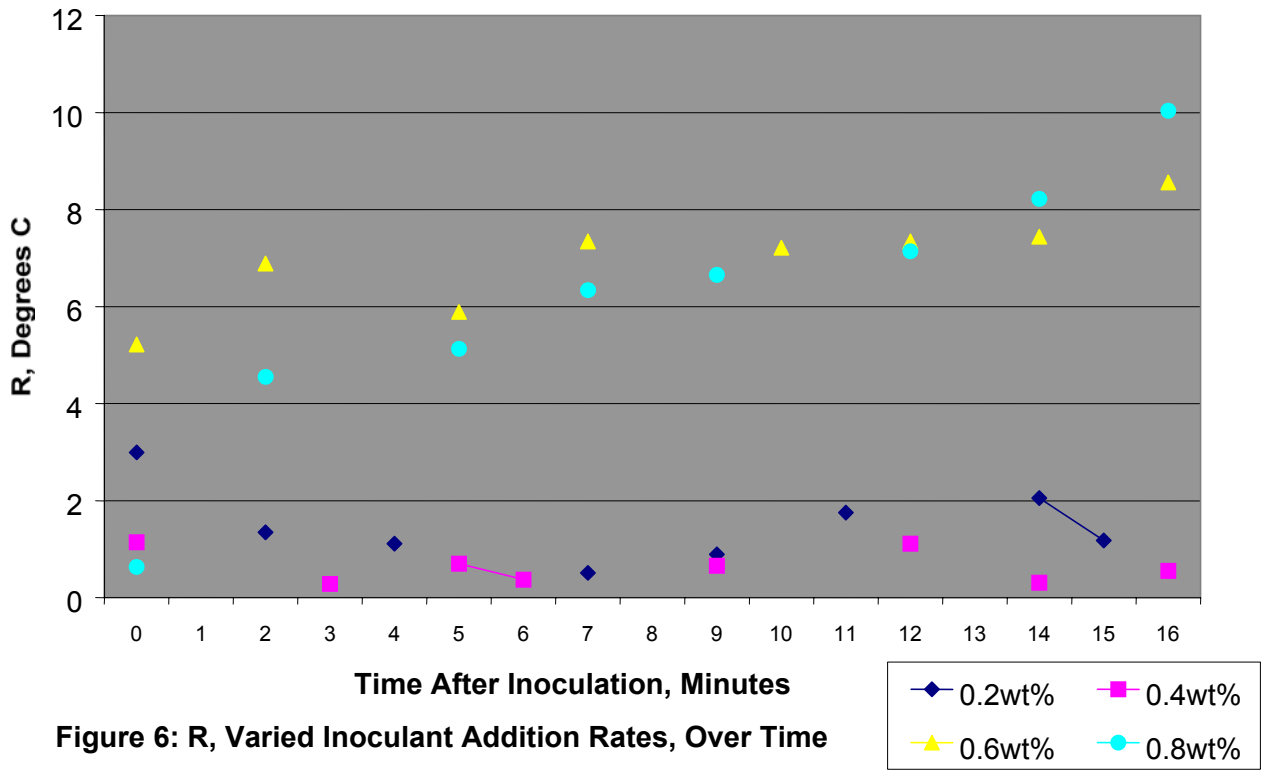


Figure 6: R, Varied Inoculant Addition Rates, Over Time

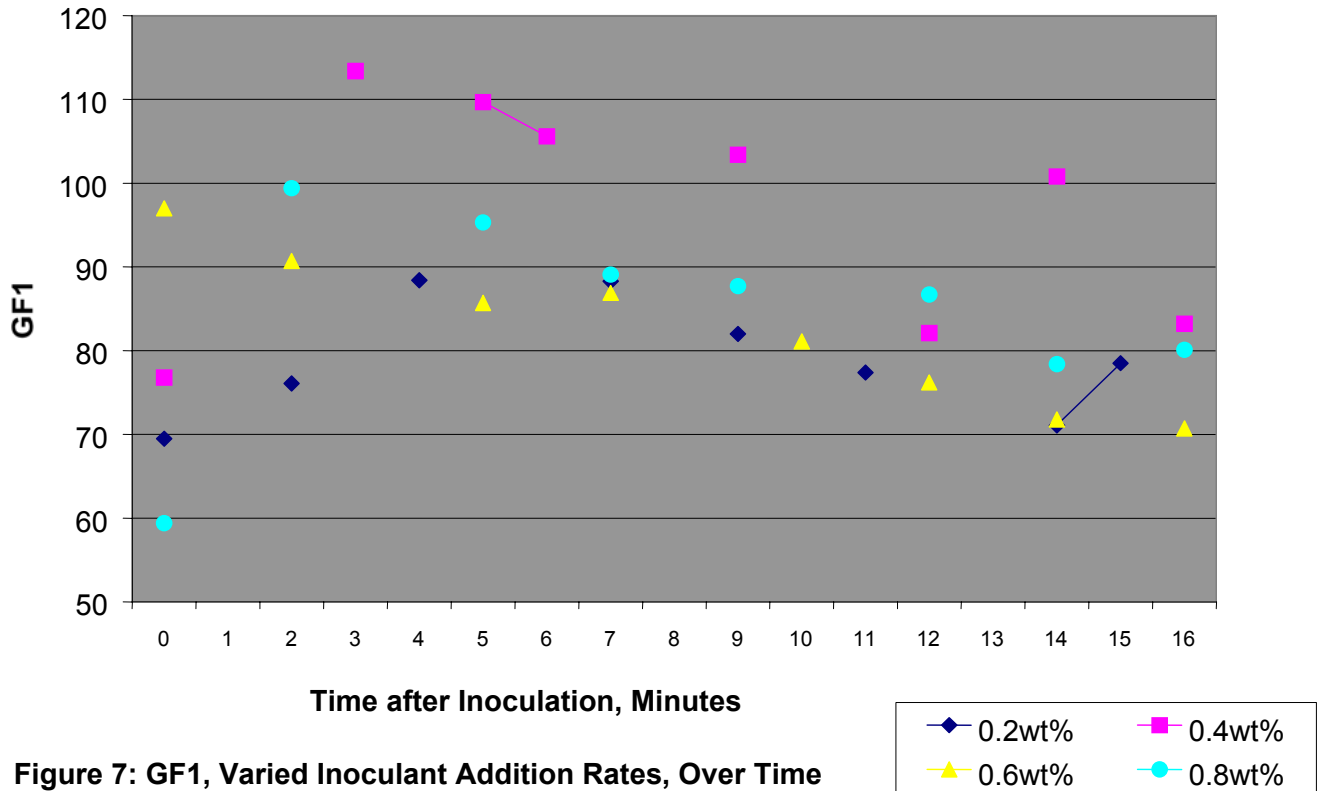


Figure 7: GF1, Varied Inoculant Addition Rates, Over Time

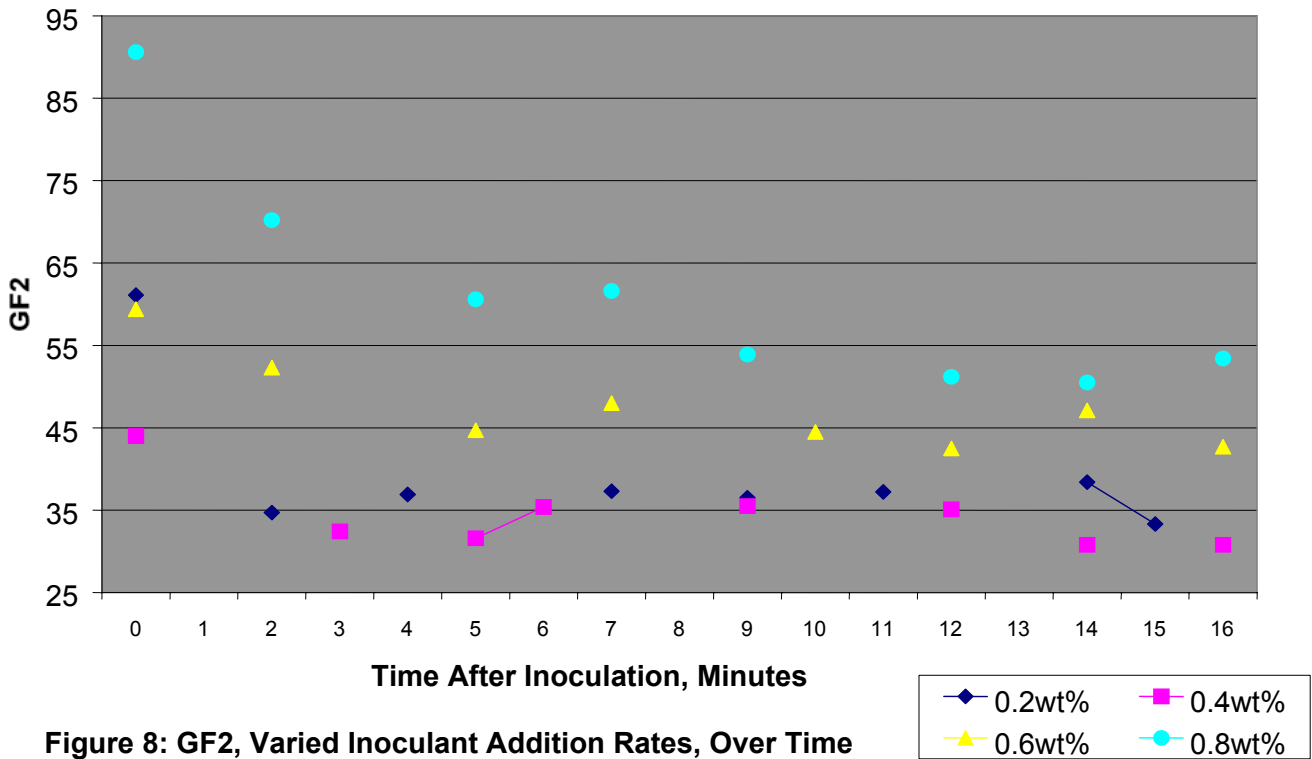


Figure 8: GF2, Varied Inoculant Addition Rates, Over Time