Application of Solidification Modelling in Predicting Alloy Content.

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ABSTRACT

The purpose of this paper is to provide an outline for the process of developing a computer model to predict the alloy content required, thus ensuring the correct heat treatment of both simple and complex castings.

INTRODUCTION

The estimation of required alloy content using casting section can sometimes be difficult, depending on the complexity of the casting geometry. With foundries wanting to use the minimum amount of alloys, or existing Ductile Iron Grades, in an effort to maintain or reduce casting cost, it has become even more important to be able to accurately predict the minimum alloy content which will guarantee full through hardening of the casting.

BACKGROUND

As all castings which require Austempering cannot be considered as having a plate type geometry, using the heaviest casting section for the calculation of alloy content may not always be the most accurate way.

It was thought that the use of modulus (casting cooling rate) rather than casting section would be more precise in the calculation of the required alloy content.

The prediction of modulus was the next problem. The casting modulus can be calculated relatively easily for simple shapes. Complex shapes become more difficult as allowances are required for adjacent changes in casting section, drilled or cored holes, deep pockets, re-entry angles and other areas which may have the effect of changing the cooling rate.

After consideration of these difficulties, it was decided to use an existing solidification modelling program to calculate modulus, and from this calculate alloy requirements.

MODULUS

Casting section is not sufficientlly accurate to describe cooling rate. Cubes, plates and bars with thicknesses of 25mm will all cool at different rates. Modulus more accurately describes cooling rate.

$$\text{Modulus} = \frac{\text{Volume}}{\text{Effective Cooling Surface Area}}$$

SOLIDIFICATION MODELLING

Initially this project started with the concept of modelling the cooling rate of the castings when they were quenched in the salt bath.

Various sized cube shaped castings were poured and then drilled, to allow thermocouples to be placed in the geometric centre of the block. The size and modulus of the blocks are listed in **Figure 1.**

Modulus	Dimensions (Cube)
0.75 (cm)	4.5cm x 4.5cm x 4.5cm
1.00 (cm)	6.0cm x 6.0cm x 6.0cm
1.50 (cm)	9.0cm x 9.0cm x 9.0cm
2.00 (cm)	12.0cm x 12.0cm x 12.0cm
2.50 (cm)	15.0cm x 15.0cm x 15.0cm
3.00 (cm)	18.0cm x 18.0cm x 18.0cm

Figure 1 : Size of Modulus Blocks

These blocks were weighed, then placed on a basket along with some other castings used as balast. The whole load was then weighed. **Figure 2.**

Block Size (mm)	Weight (kg)
4.5cm	0.70kg
6.0cm	1.73kg
9.0cm	5.70kg
12.0cm	13.90kg
15.0cm	26.60kg
18.0cm	45.60kg
Total Basket Weight	**270kg including ballast**

Figure 2 : Block Weight

The basket was loaded into a furnace which was heated to a temperature of 900^{o}C and held for 2 hours. The basket was then quenched into a water saturated salt bath held at a temperature of 375^{o}C.

This thermal information was captured using Type K thermocouples connected to a 10 channel Data Logger at 1 second intervals. **Figure 2 & 3.**

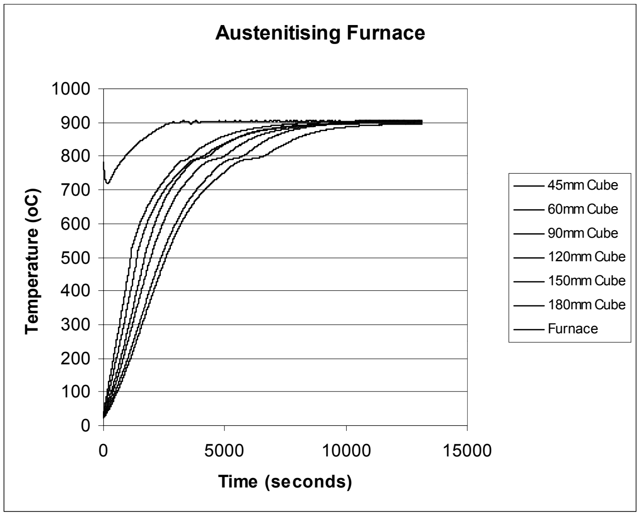

Figure 2 : Heating to 900°C (Time vs Temperature °C)

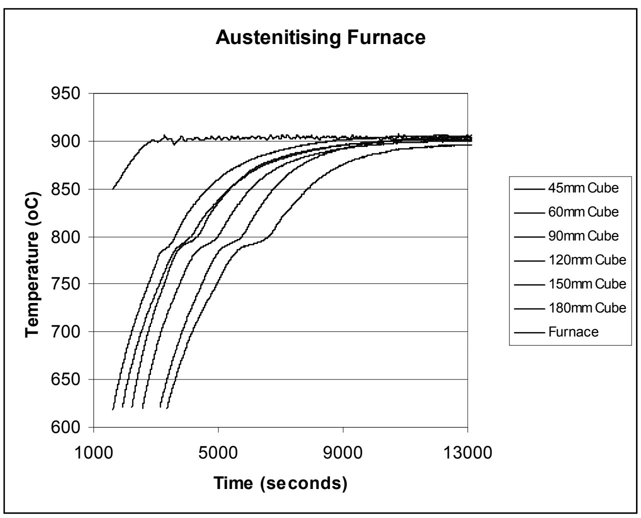

Figure 3: Arrest at Upper Critical Temperature

Figure 2 & 3 shows the thermal arrest for the upper critical temperature to be at 794°C for the analysis of these test blocks.

%C	%Si	%Mn	%Cu	%Ni	%Mo
3.65	2.56	0.31	0.74	0.21	0.03

Critical
Temperature (C°) = 730 + 28 x (%Si) – 25 x (%Mn)

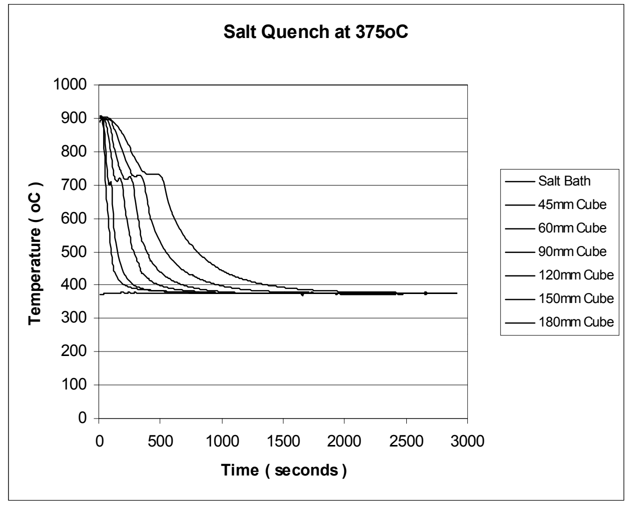

Figure 4 : Salt Quench at 375°C
(Time vs Temperature oC)

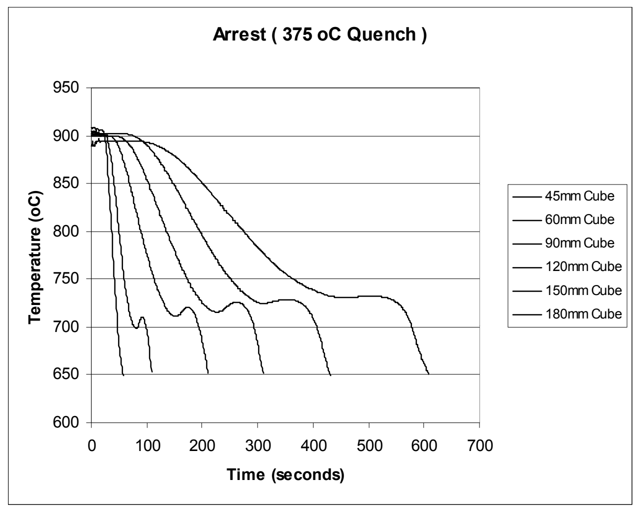

Figure 5 : Arrest during Salt Quench

Figure 4 & 5 show thermal arrest at various temperatures and for an increased length of time, dependant on block size.

Some problems encounted with the concept of using a casting solidification modelling program to model cooling in salt were:

1. Allowing for the length and temperature of the arrest depended on knowing the modulus prior to actually calculating the modulus.

2. A constant cooling rate was used.
The salt temperature in the model would have to be set at a constant temperature. In practice, deep pockets and cored areas have a lower salt flow over their surfaces. This could not be allowed for easily in our existing modelling program.

3. The correct thermal coefficients in a casting solidification model would be needed to accurately predict cooling in the salt.

It was decided to use the solidification time, as calculated by the solidification model as the variable in caculating the required alloy content.

An advantage of modelling the solidification of the casting is that slow cooling areas would be similar in both the mould and on quenching in the salt bath.

Modeling of shapes and sizes with calculated modulii could be used to generate solidification times. From these data a formula could be generated which would calculate the casting modulus from its predicted solidification time. **Figure 6.**

	Shape		
Modulus (cm)	**Cube** (side length)	**Plate** (thickness)	**Round** (diameter)
0.75	4.5cm	1.5cm	3.0cm
1.00	6.0cm	2.0cm	4.4cm
1.50	9.0cm	3.0cm	6.6cm
2.00	12.0cm	4.0cm	9.0cm
2.50	15.0cm	5.0cm	11.0cm
3.00	18.0cm	6.0cm	13.0cm
3.50	21.0cm	7.0cm	15.2cm
4.00	24.0cm	8.0cm	17.2cm
4.50	27.0cm	9.0cm	19.5cm
5.00	30.0cm	10.0cm	21.7cm
5.50	33.0cm	11.0cm	23.8cm
6.00	36.0cm	12.0cm	26.0cm
6.50	39.0cm	13.0cm	28.2cm
7.00	42.0cm	14.0cm	30.3cm

Figure 6 : Modulus vs Shape and Size

Cube - length x width x height
Plate - thickness x length x width (length & width 10x thickness)
Round - diameter x length (length 6x diameter)

The different size cubes, plates and round bars were modelled. The solidification times are indicated in **Figure 7.**

	Solidification Time (minutes)		
Modulus	**Cube**	**Plate**	**Round Bar**
0.75	3.46	4.30	3.20
1.00	6.20	8.00	5.80
1.50	14.2	13.2	13.0
2.00	24.7	23.2	23.6
2.50	38.4	34.5	36.1
3.00	57.7	58.4	52.4
3.50	73.6	75.4	71.4
4.00	93.4	96.0	90.0
4.50	118.9	123.2	115.2
5.00	154.4	157.4	142.3
5.50	184.7	190.8	169.9
6.00	216.5	216.3	207.7
6.50	246.6	252.2	238.3
7.00	290.0	294.3	280.3

Figure 7 : Modulus vs Calculated Solidificaion Time

These figures are represented graphically in **Figure 8.**

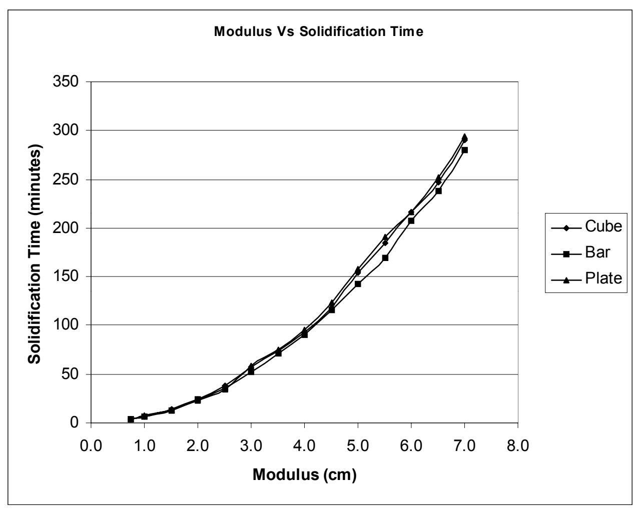

Figure 8 : Modulus vs Calculted Solidification Time

Wanting to allow some safety margin in the calculation the more conservative figures produced by the round bar will be used. **Figure 9.**

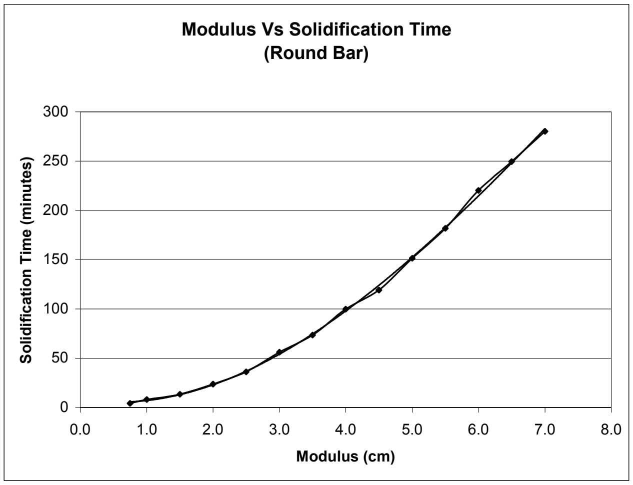

Figure 9 : Modulus vs Calculated Solidification Time of a Round Bar

The equation as follows:

Solidification Time = -0.3914 x **(modulus)**^{3} + 9.9195 x **(modulus)**^{2} - 11.08 x **(modulus)** - 8.5676

The graph is now converted to Solidification Time vs Modulus, as the Modulus is the unknown. **Figure 10.**

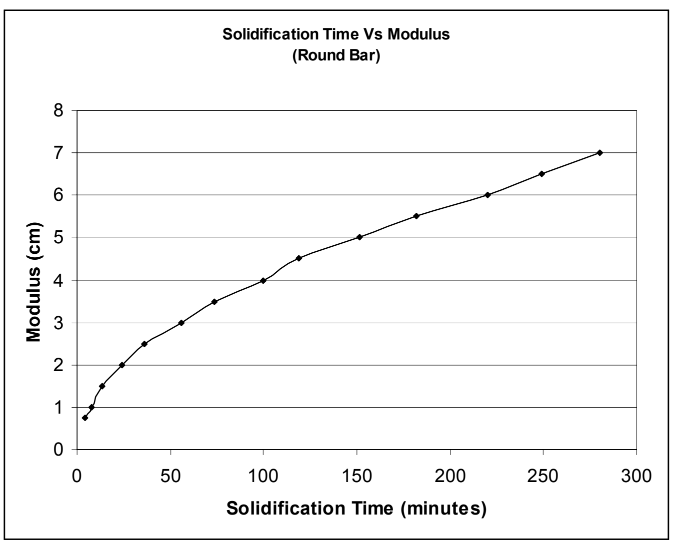

Figure 10 : Solidification Time vs Modulus.

To generate a line of best fit, two formulas have had to be generated. One for 0 to 60 minutes. **Figure 11.** The other one for 61 to 300 minutes. **Figure 12.**

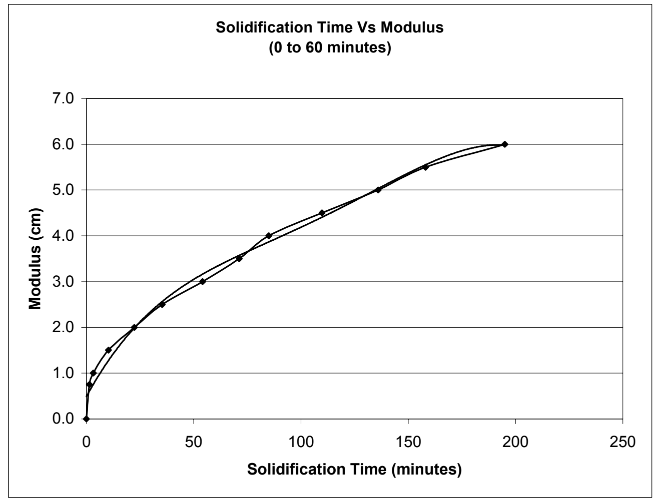

Figure 11 : Solidification Time vs Modulus (0 to 60 minutes)

The equation as follows:

Modulus = (-1 x 10^{-8}) x **(solidification time)**^{4} + (6 x 10^{-6}) x **(solidification time)**^{3} – 0.001 x **(solidification time)**^{2} + 0.00857 x **(solidification time)** + 0.5172

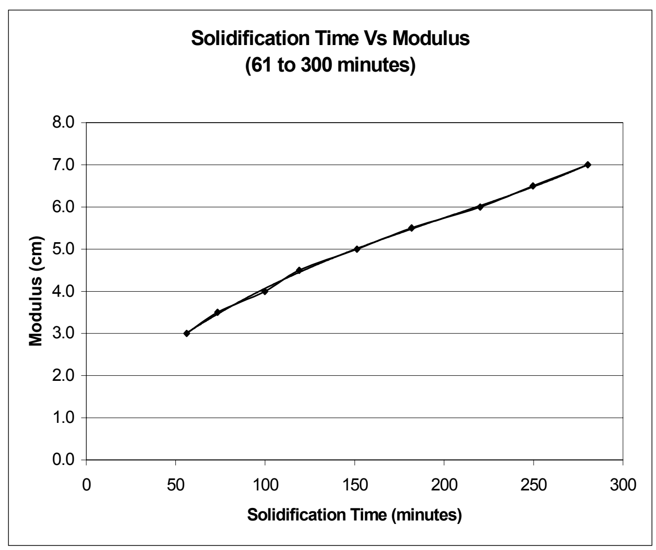

Figure 12 : Solidification Time vs Modulus (61 to 300 minutes)

The equation as follows:

Modulus = (2 x 10^{-10}) x **(solidification time)**^{4} + (9 x 10^{-8}) x **(solidification time)**^{3} – (1 x 10^{-4}) x **(solidification time)**^{2} + 0.0377 x **(solidification time)** + 1.3109

These two formulae are combined and are represented graphically in **Figure 13**.

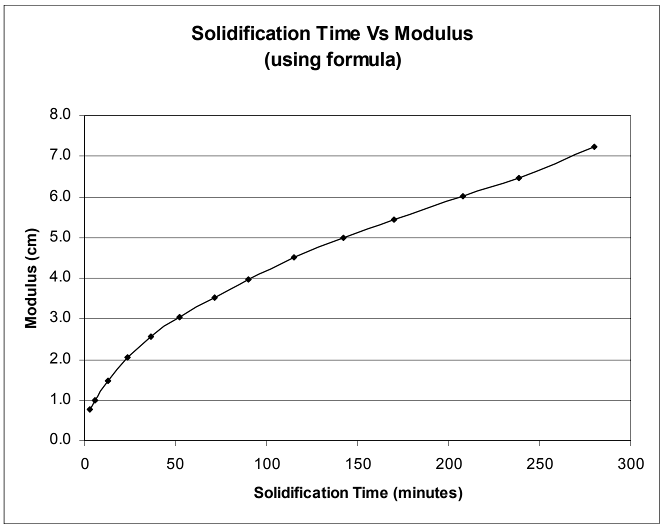

Figure 13 : Solidification Time vs Modulus (using combined formula)

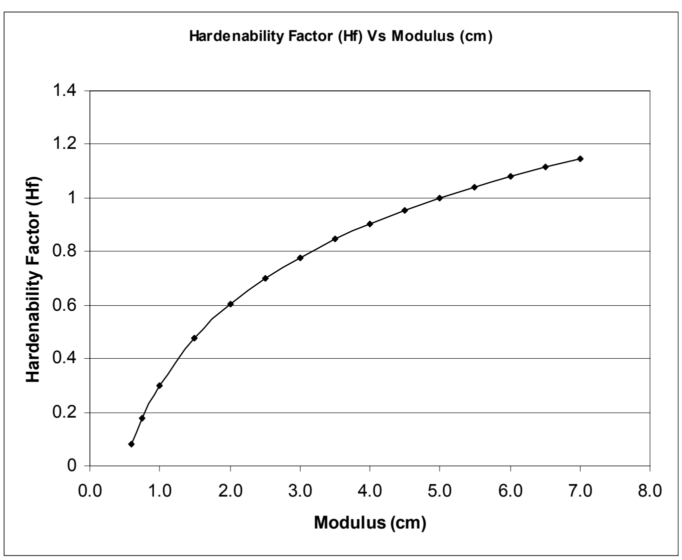

Figure 14 : Modulus vs Hardenability Factor

Having developed a method for converting calculated solidification time into casting modulus **Figure 13**. We can then use **Figure 14** to determine a required hardenability factor.

Using an internally developed Hf formula alloying content can be calculated.

Alloying conent required for various modulii. **Figure 15**. Calculated from solidification time converted to modulus and then using a hardenability factor to predict required alloy additions.

Solidification		Alloy Content			
Time	Modulus	Mn	Cu	Ni	Mo
2.8 min	0.75	0.30	0.19	0.00	0.00
6.1 min	1.00	0.30	0.67	0.00	0.00
22.4 min	2.00	0.30	0.75	0.95	0.00
91.3 min	4.00	0.30	0.75	1.98	0.00
268.3 min	7.00	0.30	0.75	2.20	0.18

Figure 15 : Alloy content for various Modulii.

CONCLUSION

By using a modelling program to calculate the solidification time of cast shapes of known modulii, the solidification time of a casting can then be used to determined its modulus. From this, we are able to predict the minimum alloy content required to ensure full through hardening of the casting during the Austempering process.

Modulus rather than section size should be used in the calculation of Alloy Content and in the determination of Austenitising and Austempering times. Modulus more accurately represents the heating and cooling properties of the casting.

Examples of castings:

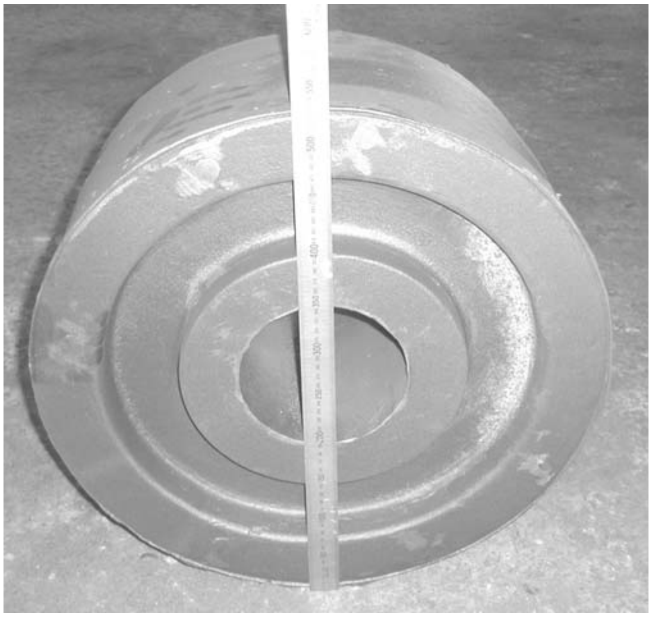

Figure 16 : Roller Casting – 530mm dia x 300mm high

Solidification Time – 152.2 minutes

Modulus – 5.16 cm

Analysis – 0.3%Mn 0.75%Cu 2.20%Ni 0.05%Mo

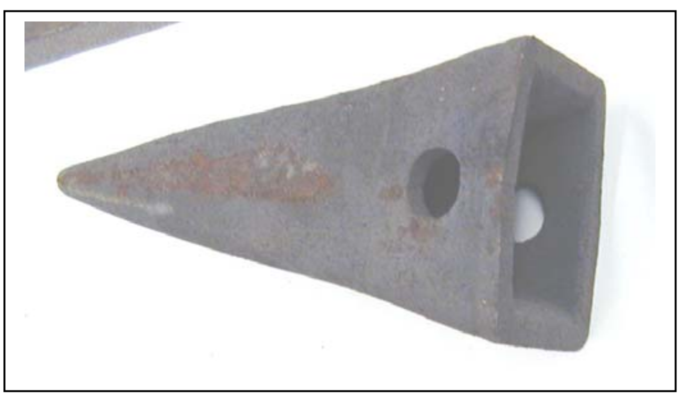

Figure 17: Digger Tooth

Solidification Time -12.1 minutes

Modulus - 1.42

Analysis - 0.3%Mn 0.75%Cu 0.45%Ni

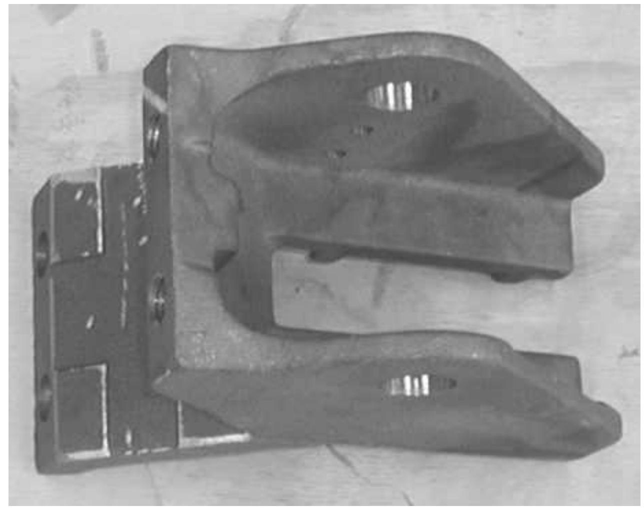

Figure 18 : Tyne Pivot Casting

Solidification Time - 5.3 minutes

Modulus - 0.94 cm

Analysis - 0.3%Mn 0.55%Cu

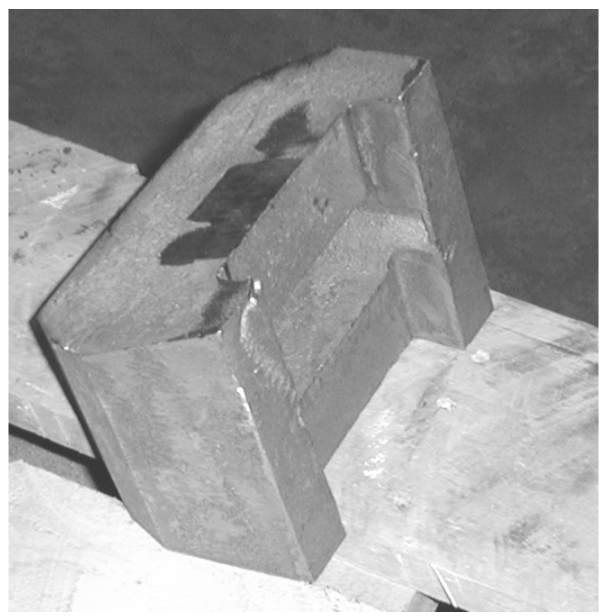

Figure 19: Mulching Hammer

Solidification Time - 15.5 minutes

Modulus - 1.63 cm

Analysis - 0.3%Mn 0.75%Cu 0.65%Ni

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REFERENCES

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ADDITIONAL RESOURCES

ADI Engineering Process & Heat Treatment - internal research.

Applied Process - Internal Research, Hf Alloying Hierarchy.