An Evaluation of Mechanical Properties and Part Quality in Investment Cast Ductile Irons

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Company Overview

- Established over 65 years ago.
- The company operates from a purpose built, modern facility on 141,570 sqft under roof in Melbourne Australia.
- Company values incorporate Safety, Integrity, Accountability, Innovation & Quality.
- 100 staff including engineers, metallurgists, pattern-makers, machinists and technical staff.

Sand and Investment Casting of over 150 high performance alloys from 1g to 300kg
Including Tool-Less Manufacture (Additive Manufactured Prototypes)
Medical, Defense, Aerospace, Space, Automotive, General Engineering

All grades of air melt Iron and Steel, Copper, Nickel, Cobalt, Aluminium

Key Customers Include

BAE SYSTEMS

MARAND PRECISION

NORTHROP GRUMMAN

EOS ELECTRO OPTIC SYSTEMS

ASC

THALES

RHEINMETALL DEFENCE

GM

KENWORTH

Leica BIOSYSTEMS

BOMBARDIER

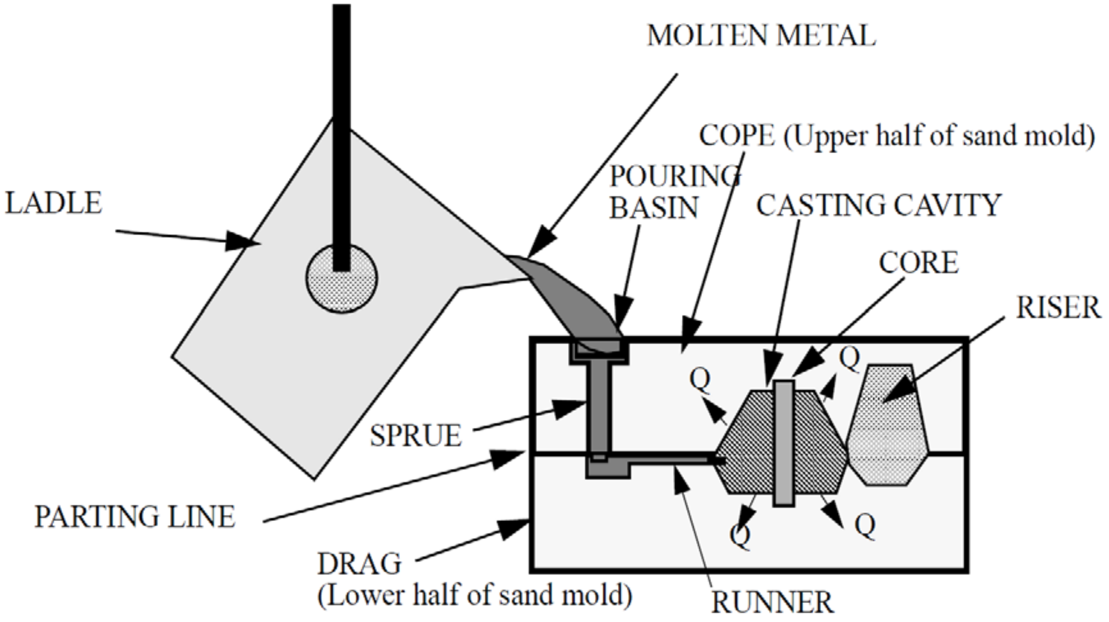
Mahindra Aerospace

AW Bell pty ltd

Todays Presentation

- 1. Overview of Investment Casting Vs. Sand Casting
- 2. Key considerations in producing ductile iron investment castings
- 3. Optimizing Magnesium for surface finish.
- 4. The role of pearlite forming elements on the development of mechanical properties.
- 5. Consideration of some unexpected results
- 6. Control of shell cooling rates.
- 7. Some findings and conclusions.

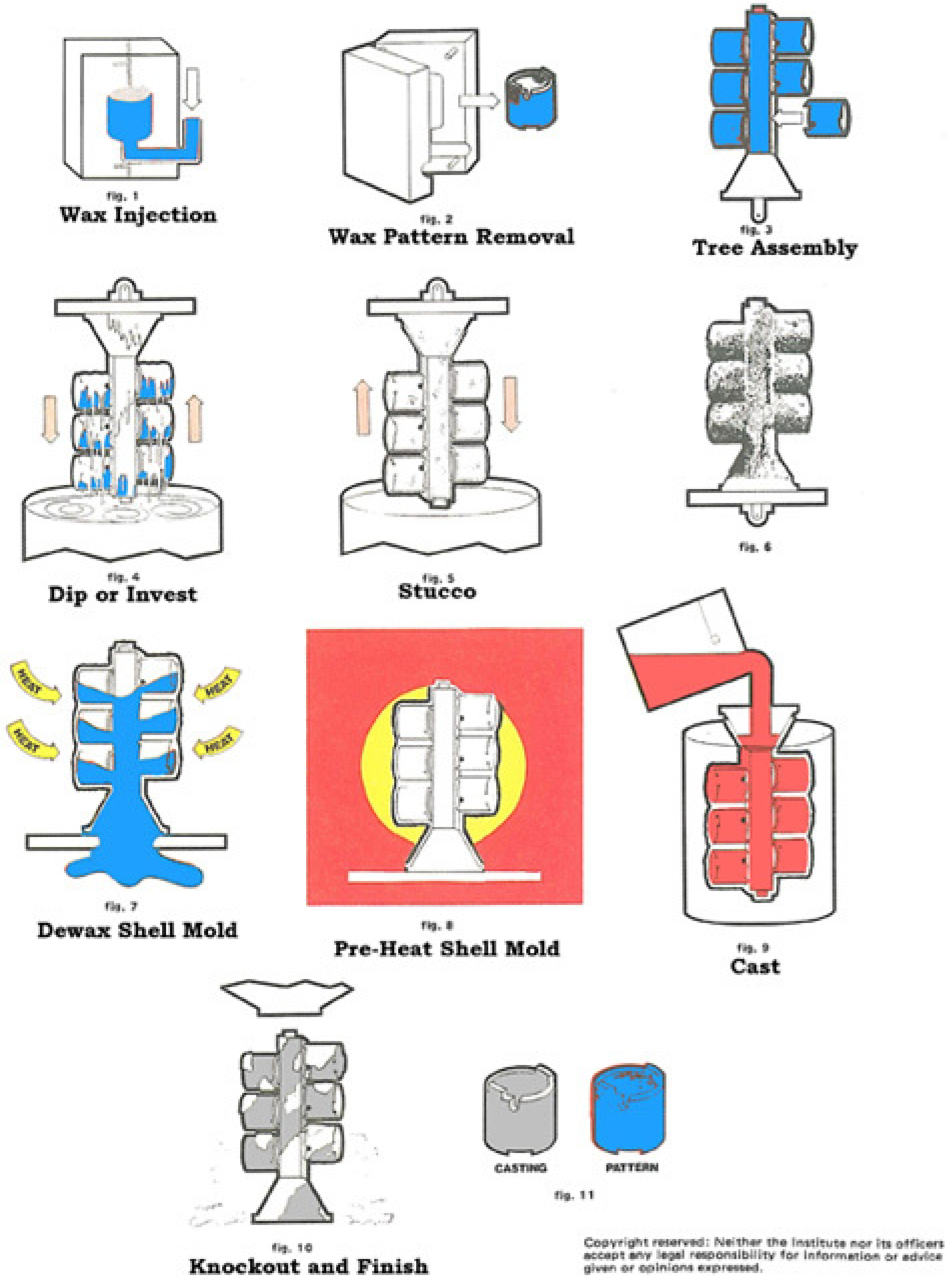
The Sand Casting Process



From: “MetalCasting” by K.B. Rudman

Sand is generally insulating even at low thicknesses, giving consistent & reproducible cooling rates.

Investment Casting Process



Shell is insulating, but typically less than 10mm thick.

Fine prime coats mean exceptional surface detail is possible.

Investment Casting Shell showing prime coat and built up layers at two wall thicknesses

Making Ductile Iron Investment Castings is significantly different to Sand Castings!

Shell has to be strong enough not to crack during eutectic solidification and expansion. Slightly hypoeutectic is preferred but has to be closely controlled. Very fine wall detail must be maintained.

Heat extraction is largely governed by heat transfer across the shell wall to the atmosphere.

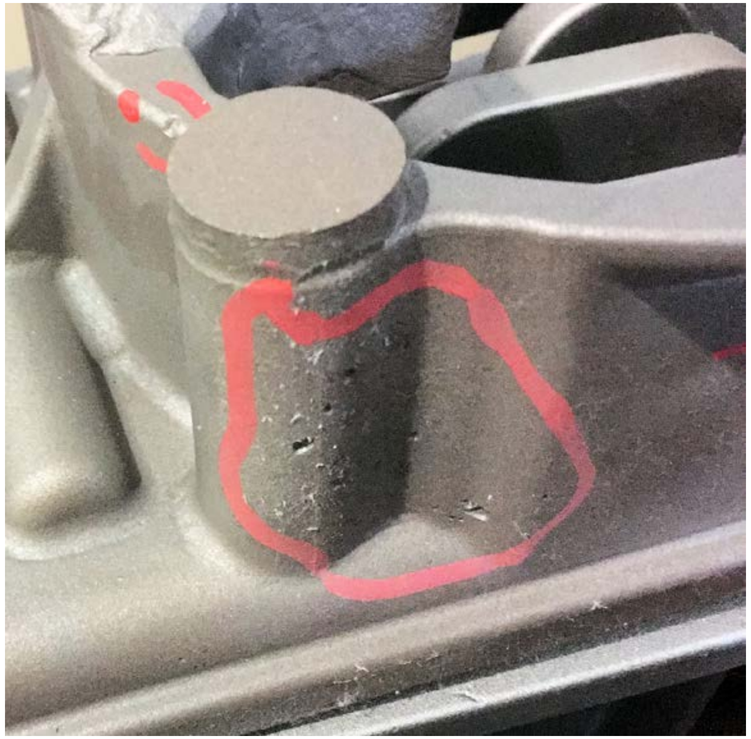
Shells are preheated at typically 700-1000℃.

(Preheat nominally 800℃ in the work presented today)

Investment Casting Process Steps for D.I.

Prepare metal from cut 1020 scrap and CI returns
Tap temperature 1400-1420°C
Shell temperature 700-1000°C
Sandwich method in ladle for magnesium additions with FeSiMg
Pour and allow to cool naturally over 1-2h.
Typical casting weights 20-60kg. (15-50kg most common)
Part wall thicknesses down to around 1mm are possible (with control of shell temperature).
(Note little to no chill is typical)

Some Problems with Magnesium Additions in Investment Cast Ductile Iron



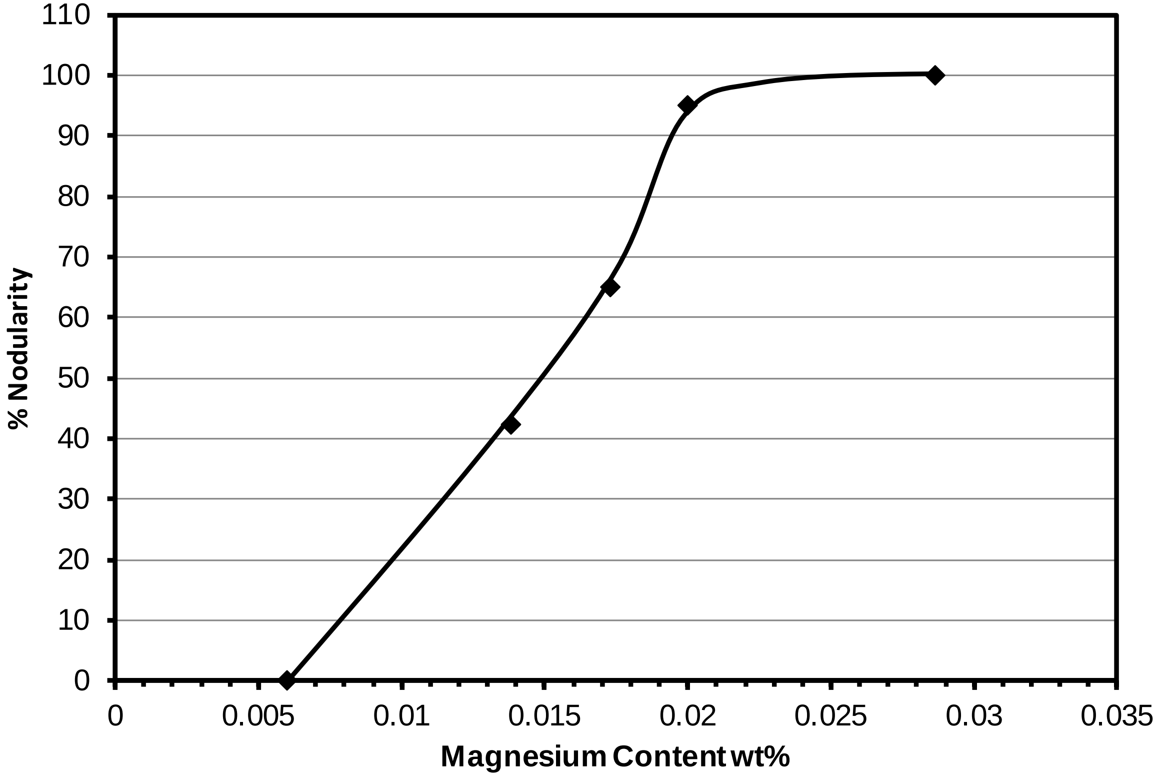
←Mg = 0.048%

Strong tendency to form oxide bifilms at ≥0.04%Mg and when gating not optimized. These oxides do not segregate to slag.

Influences tensile properties when present internally. No evidence of Mg reaction with ceramic shell.

Surface breaking oxides cause NDT failure for Penetrant, Visual inspection or cast tolerances cannot be maintained.

Optimizing Magnesium

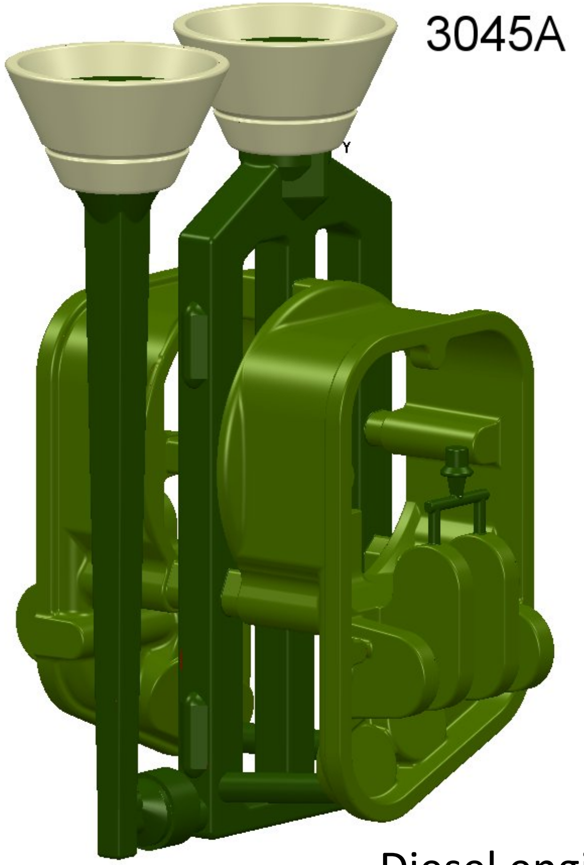


Optimum Mg content is found experimentally to be between 0.02% and 0.04% Mg to avoid bi-films and maintain nodularity. A high aspect ratio ladle (h/d) is required to minimize oxides.

Filters are also required.

Bottom fill gating and filters are always preferred.

Base of Shells



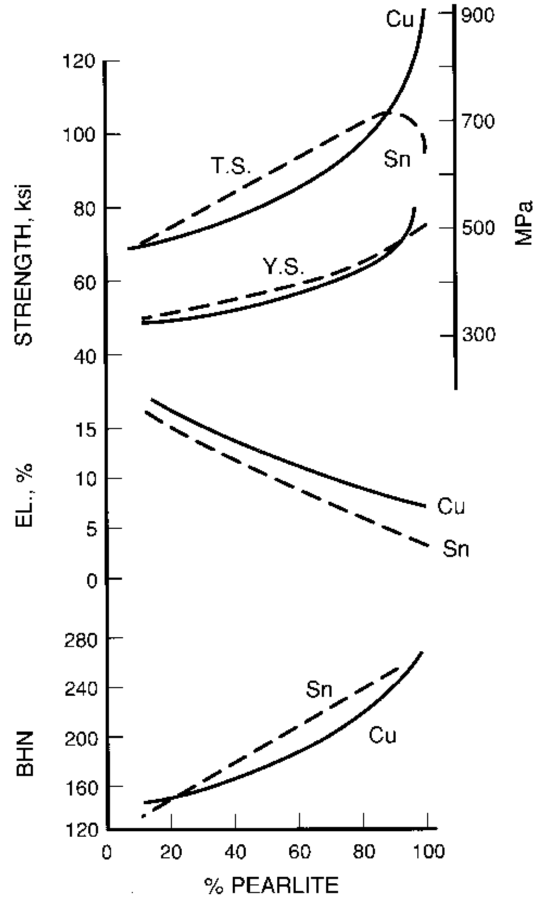
Diesel engine rocker body (42kg)

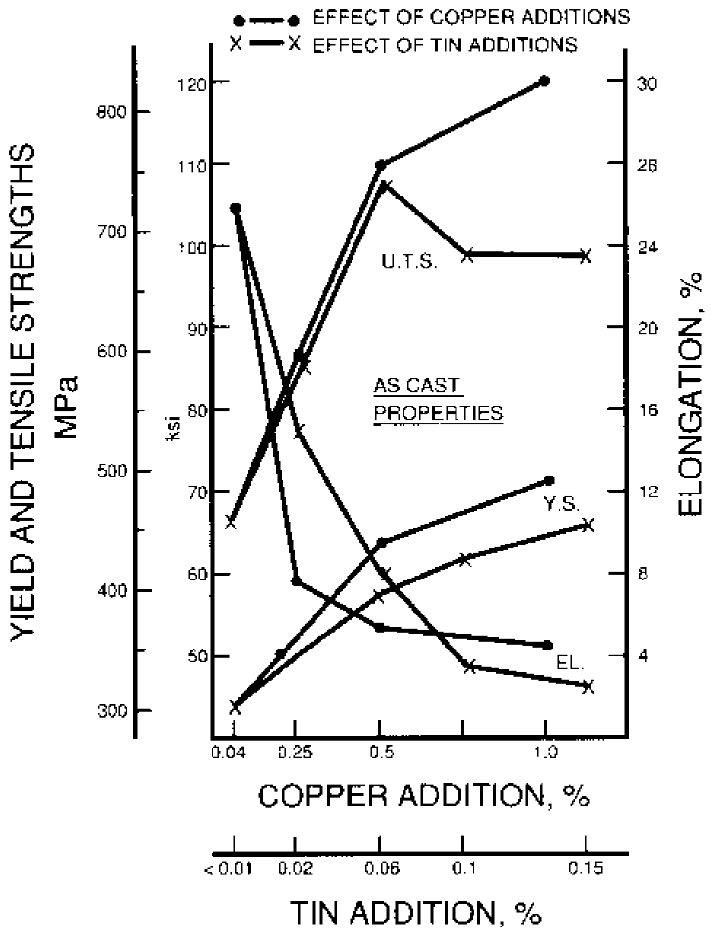
Pearlitizing Elements

- Hypothesis that all pearlite influencing elements may be considered with respect to copper.
- (Herein termed "Copper Equivalent")

- Cu_{eq}= Cu + (Sn×8) + ((Mo+V)×1.61) + (P×1.14) + (Ti×0.9) + (Mn+Ni+Cr)×0.1

This approach should provide an adequate estimate of mechanical properties

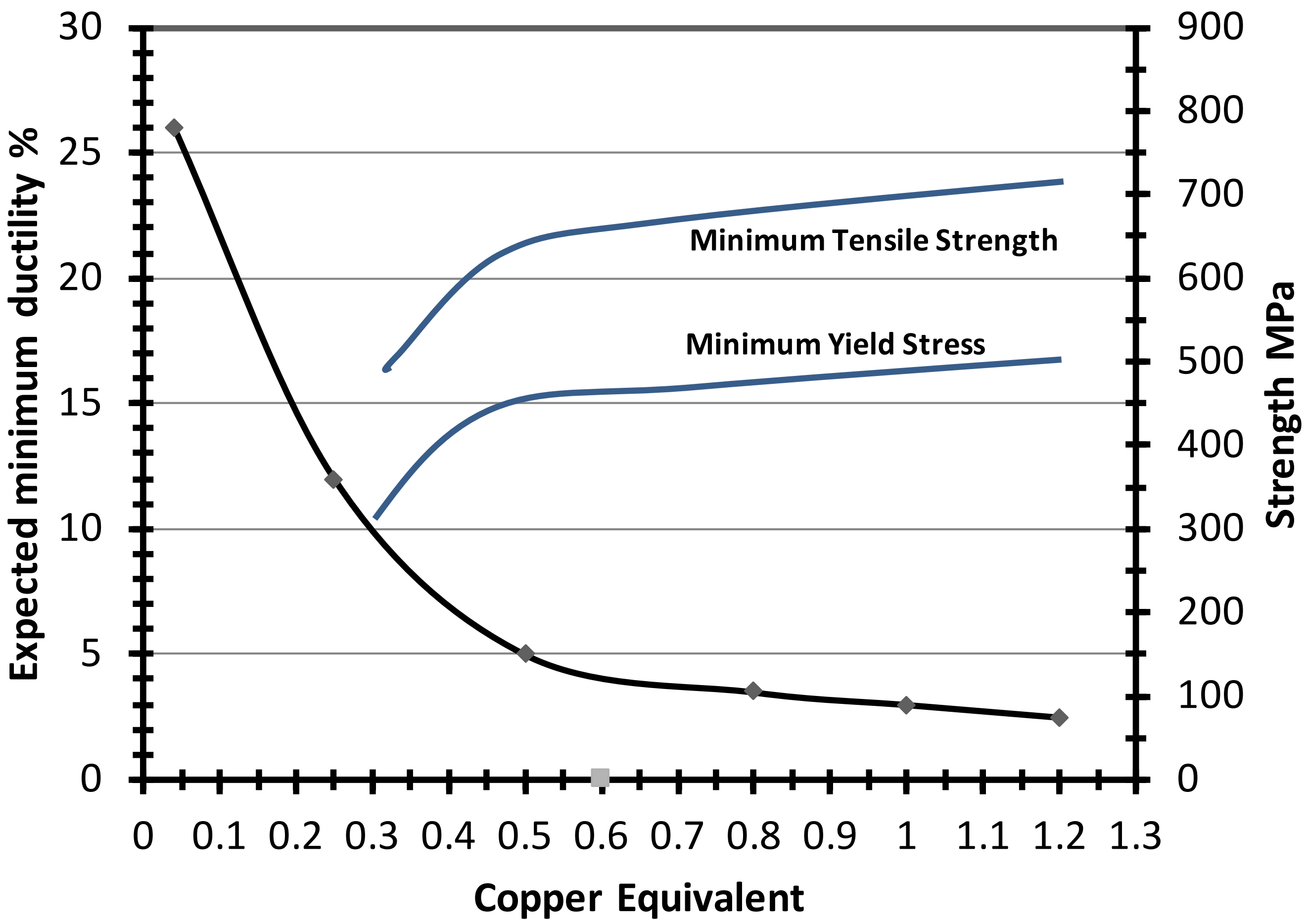




Source: Ductile Iron Data: https://www.ductile.org/ductile-iron-data-2/

Original Predictive Guideline

(Based on literature)



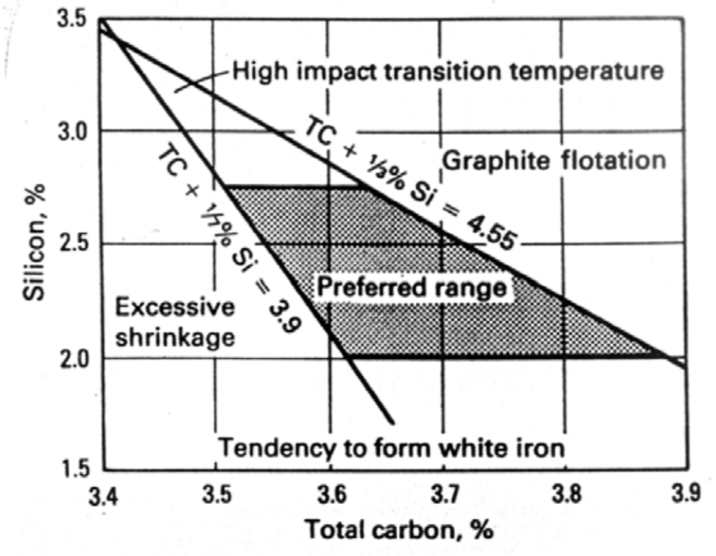
Tensile Testing over batches produced within a 5 year time frame; >100 results, 46 melts, from (mostly) three parts.

	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Sn	Mg
High	3.92	3.08	0.90	<0.02	<0.02	0.315	0.031	0.587	0.75	0.055	0.048
Low	2.96	1.70	0.09	0.009	0.007	0.03	0.001	0.005	0.01	0.002	0.02

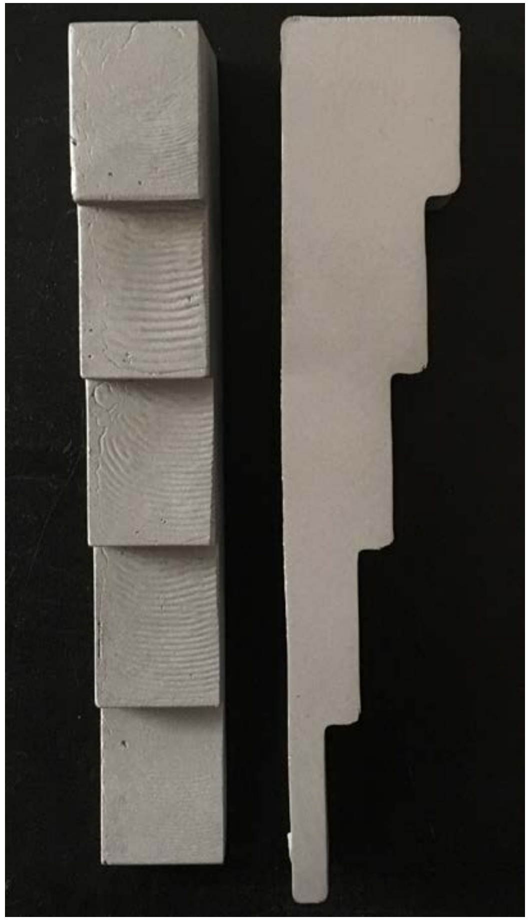
Producing Copper Equivalent values between 0.066 and 1.34.

In general, the compositions fell within the preferred range as per the plot.
The copper equivalent value targeted depended on the grade to be manufactured. (500/7, 550/5, 600/3 etc.)

Carbon and Silicon in Ductile Iron



Microstructures taken from step blocks attached to tree (8mm cut / 16mm in) or from parts.



25mm

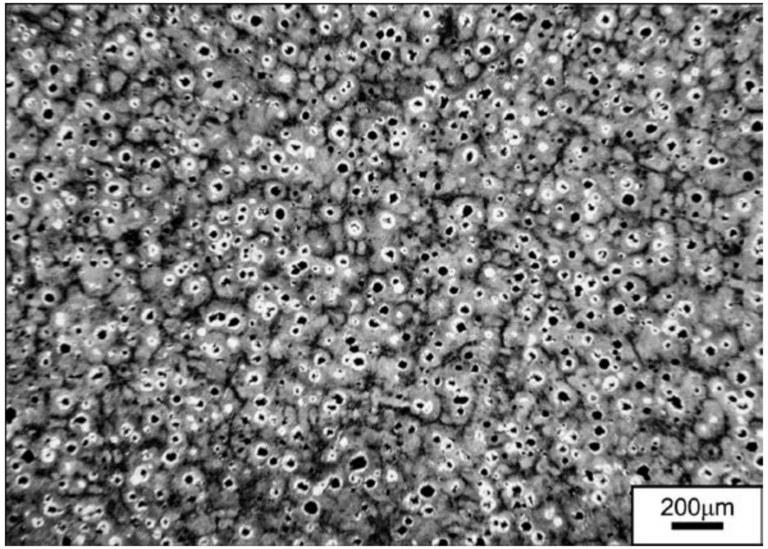
20mm

15mm

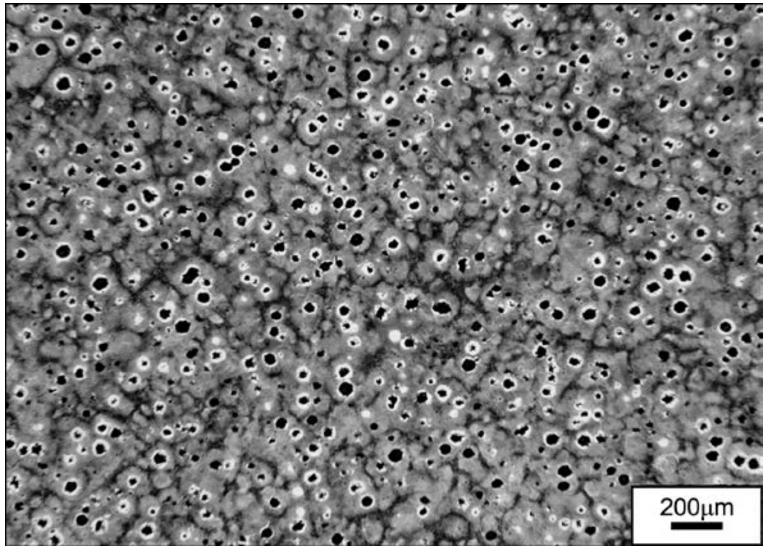
10mm

5mm

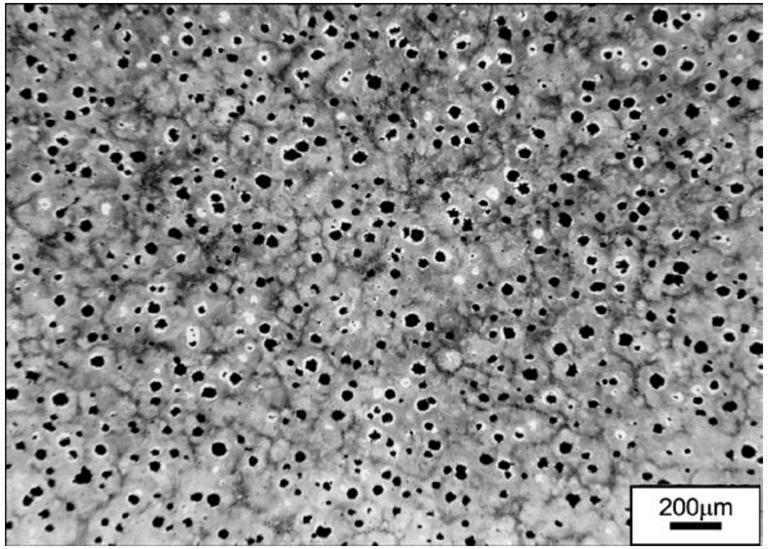
Correlation between the step block and part is excellent



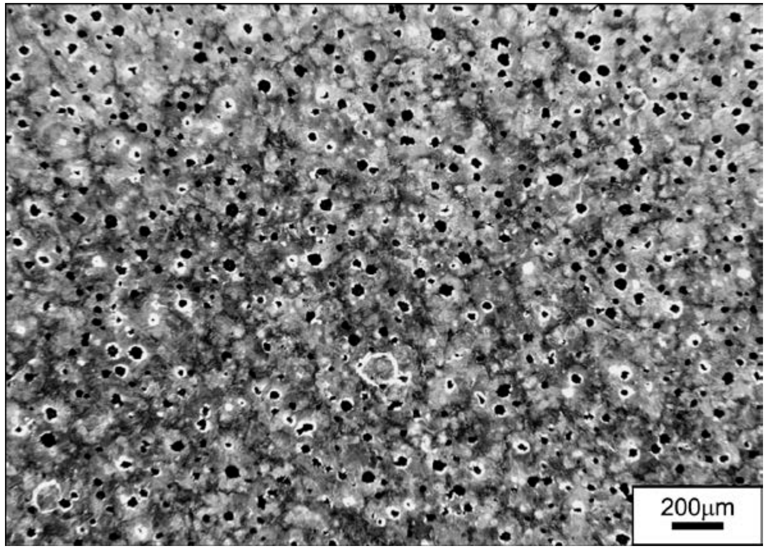
5mm Step



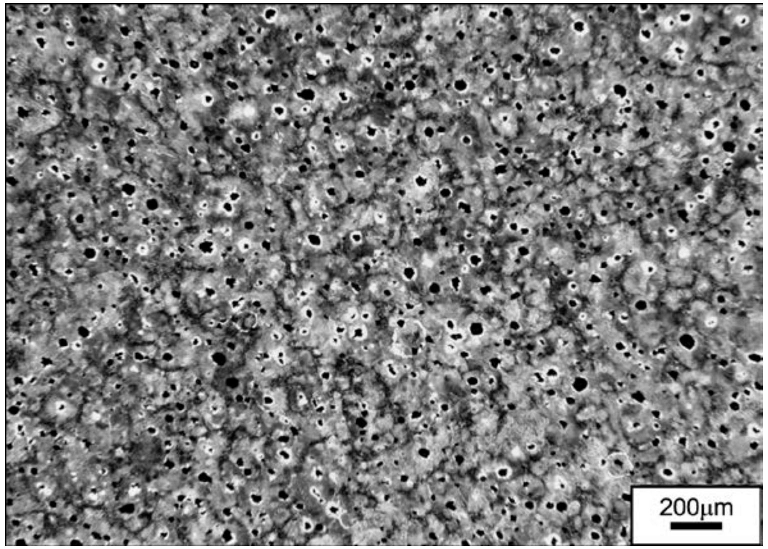
10mm Step



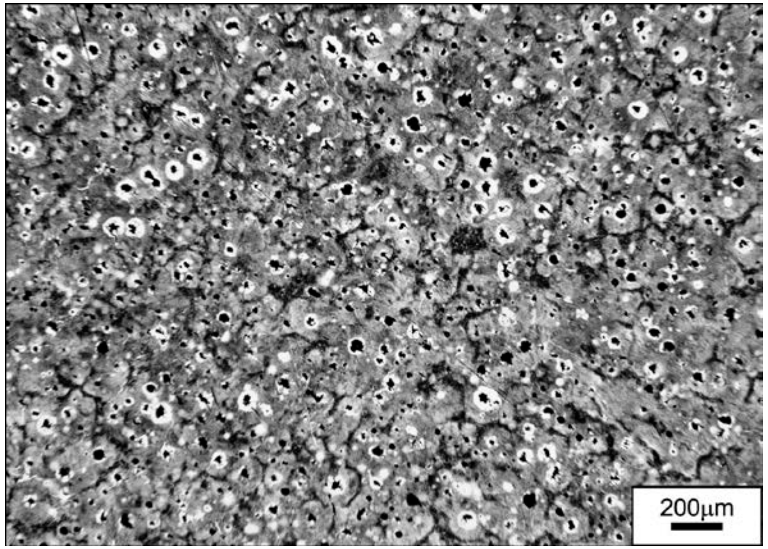
15mm Step



20mm Step



25mm Step

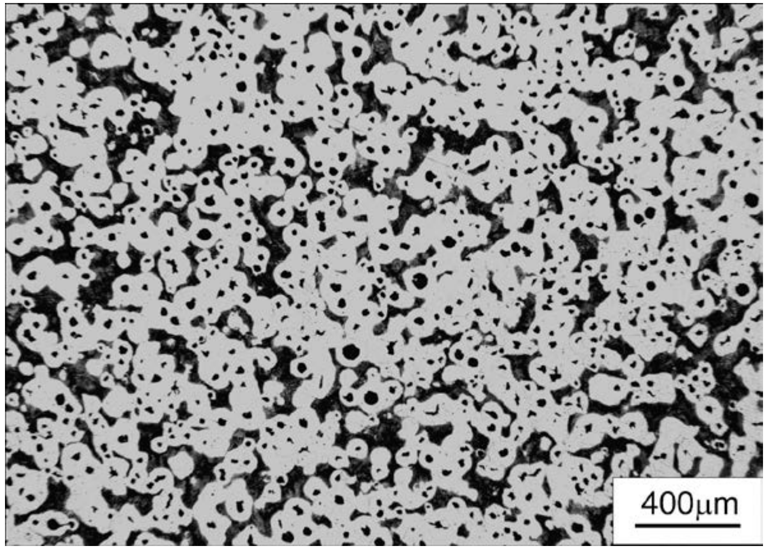


Section of Part

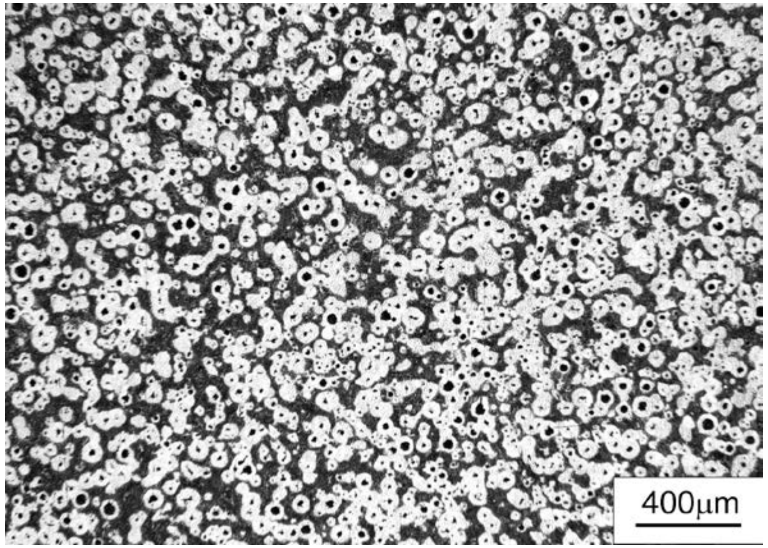
H8132 Body

Microstructures of Alloys with Different Copper Equivalent Values

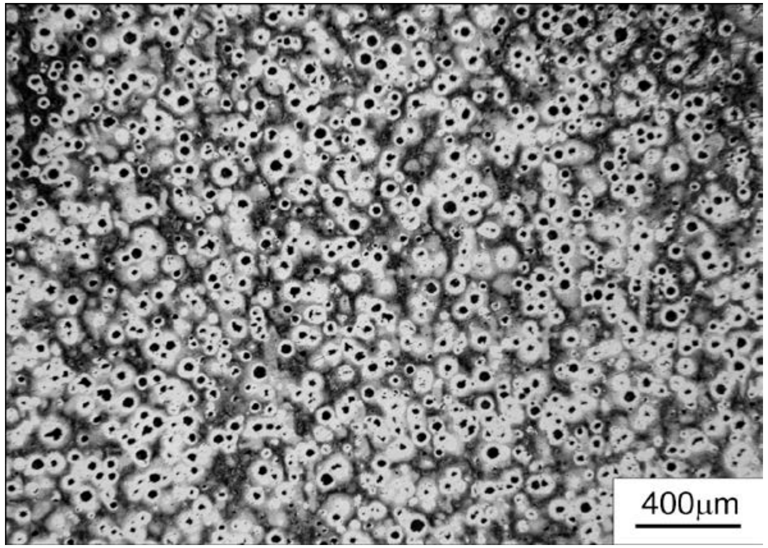
Cu_{eq}=0.066



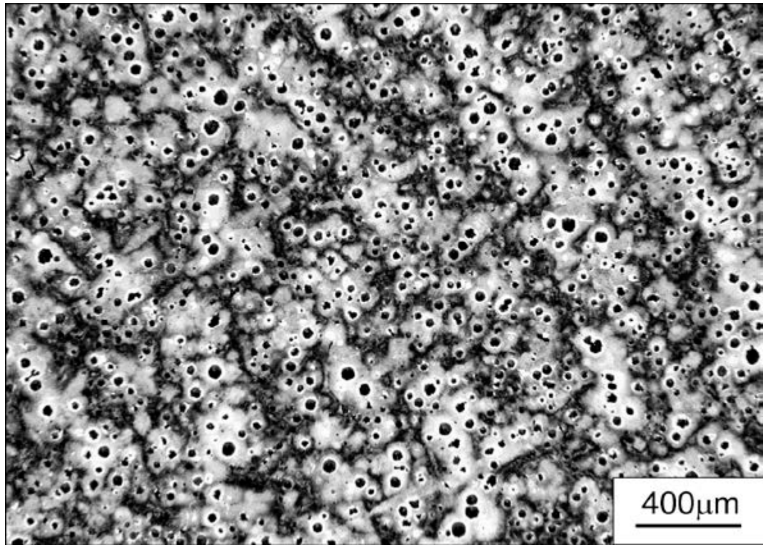
Cu_{eq}=0.106



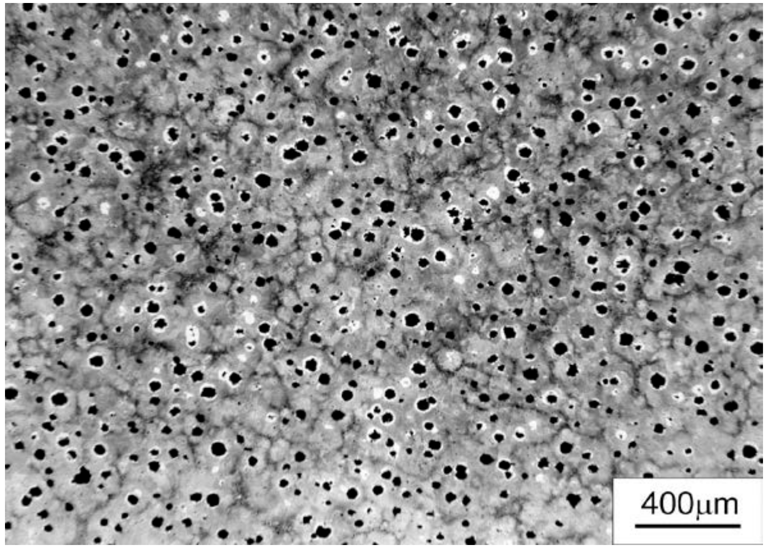
Cu_{eq}=0.35



Cu_{eq}=0.51



Cu_{eq}=1.02

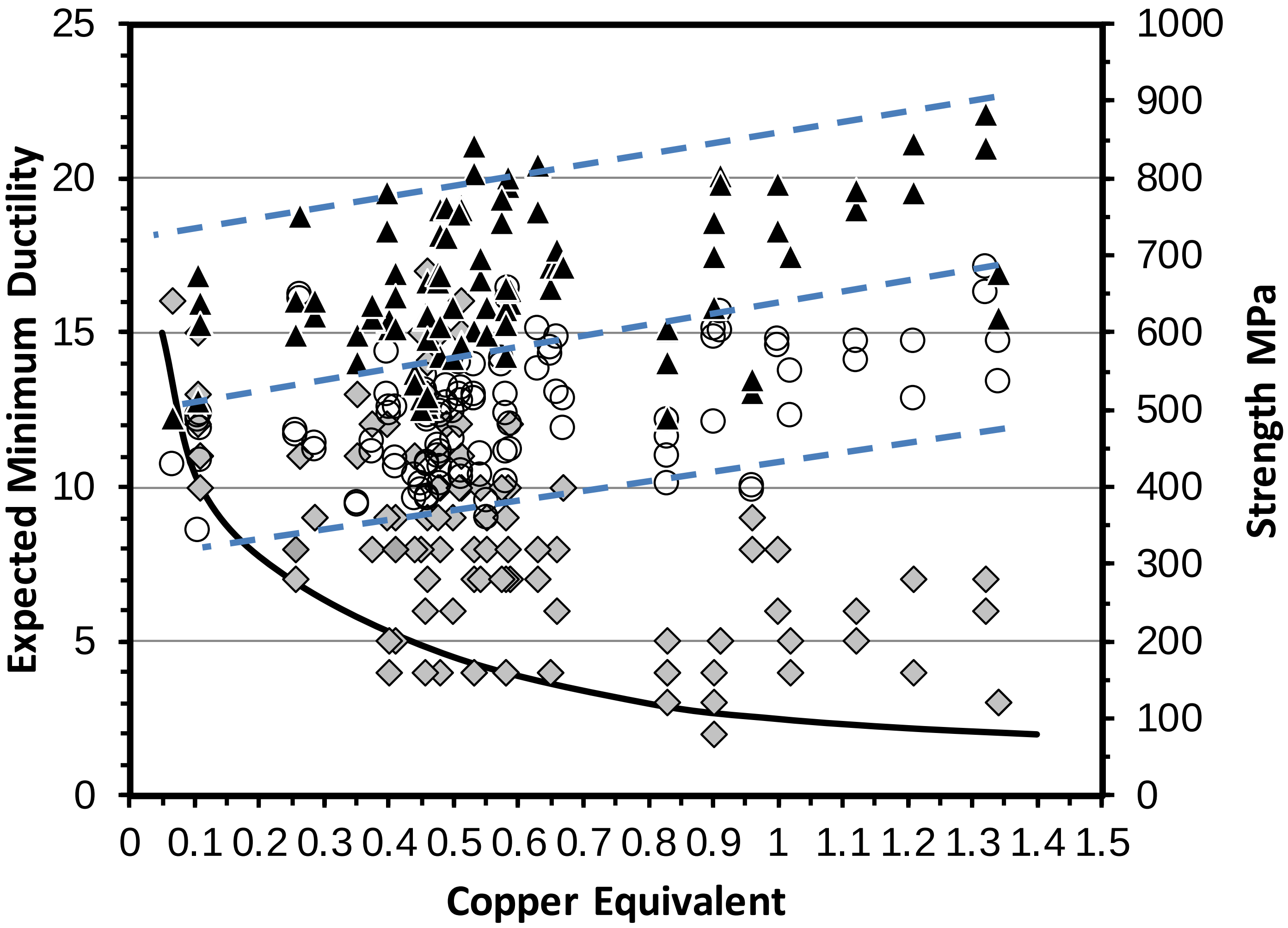


The Hypothesis appears to be valid;

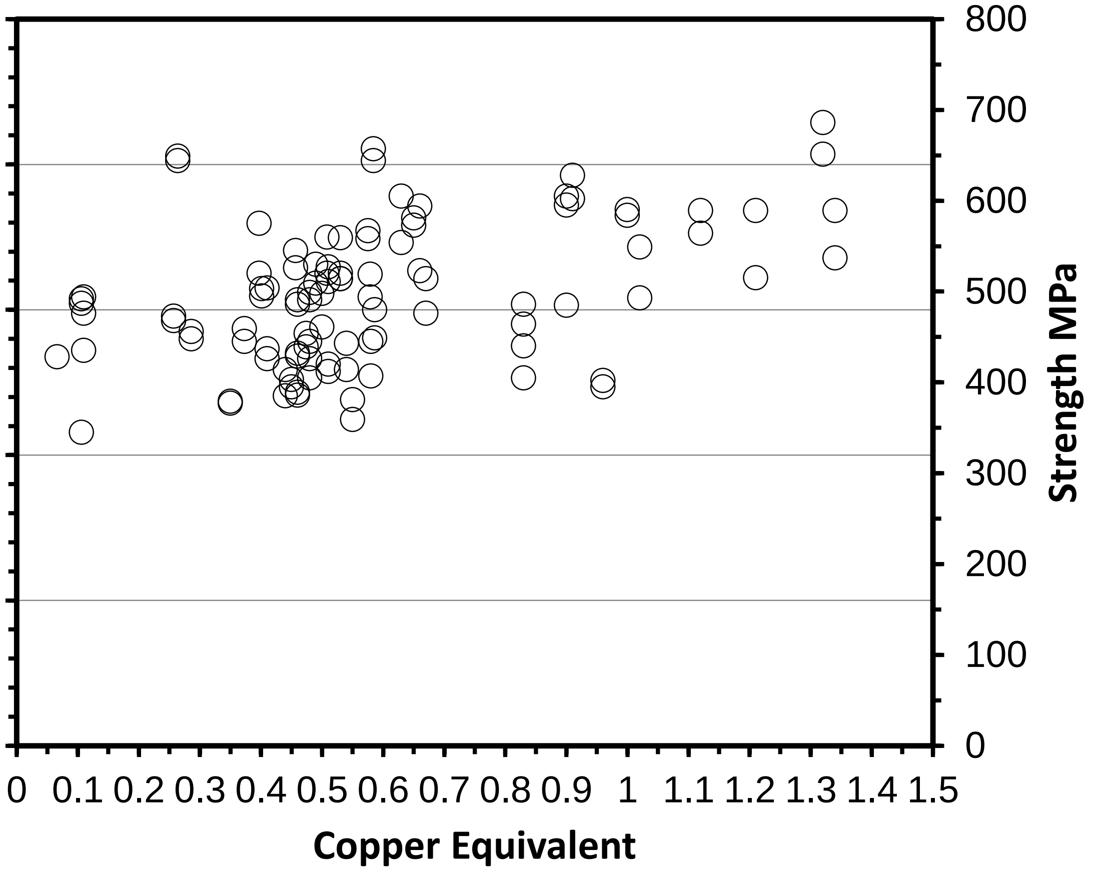
No fully ferritic structure was observed.

There is little difference between Cu_{eq}=0.51 & Cu_{eq}=1.02 (pearlitic) except for the size of the ferrite halo around nodules.

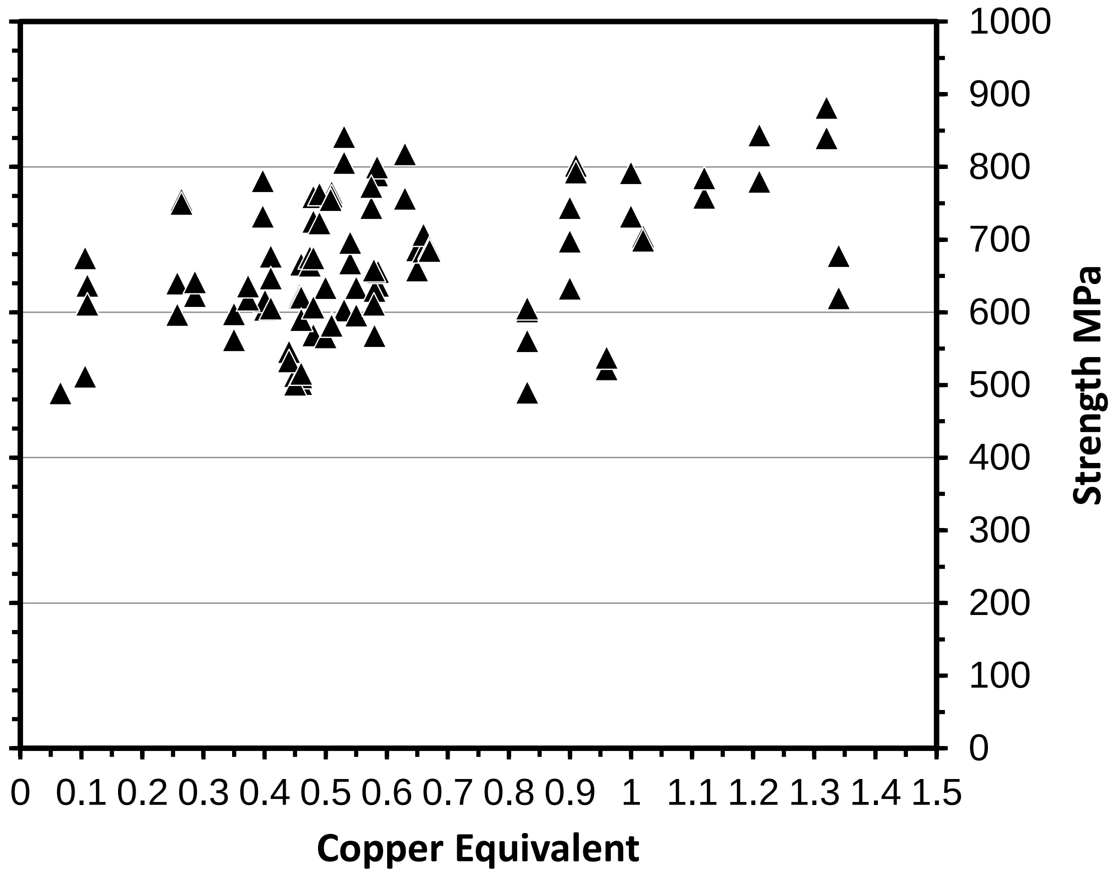
Combined Tensile Test Results



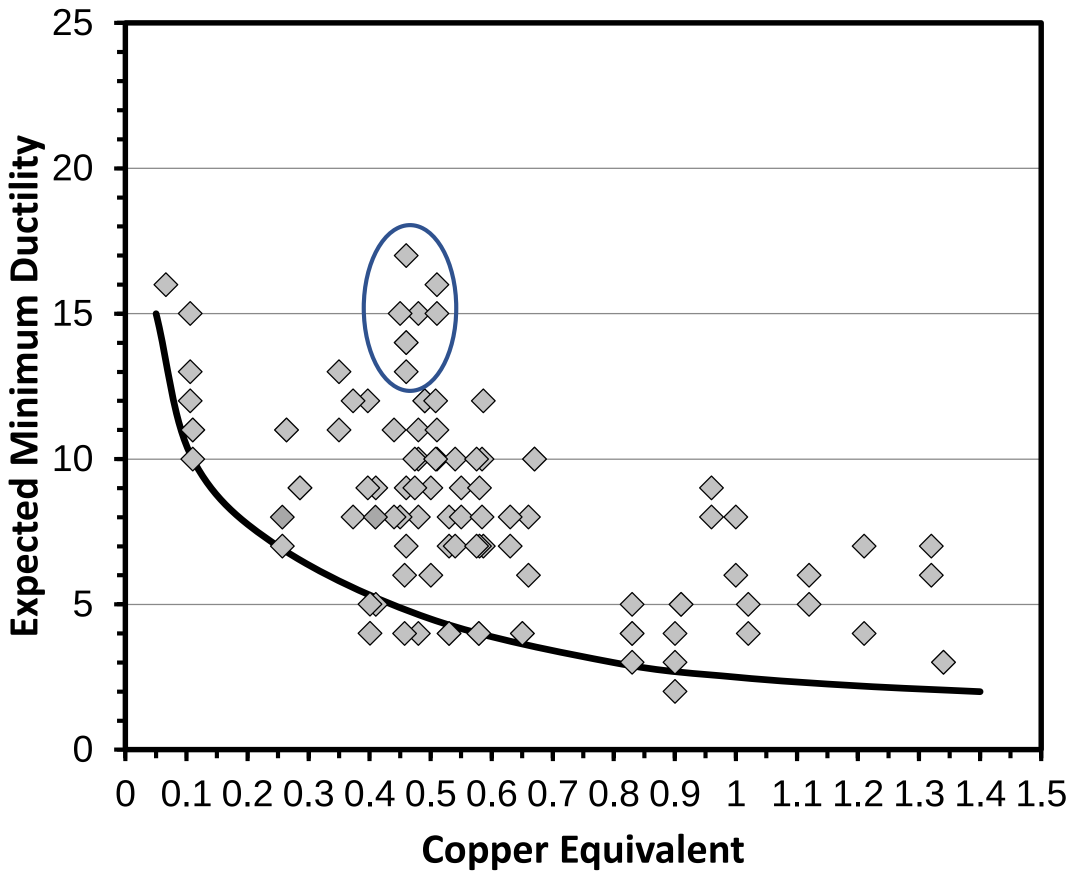
Yield Stress vs. Copper Equivalent



Tensile Strength Vs. Copper Equivalent



Elongation Vs. Copper Equivalent



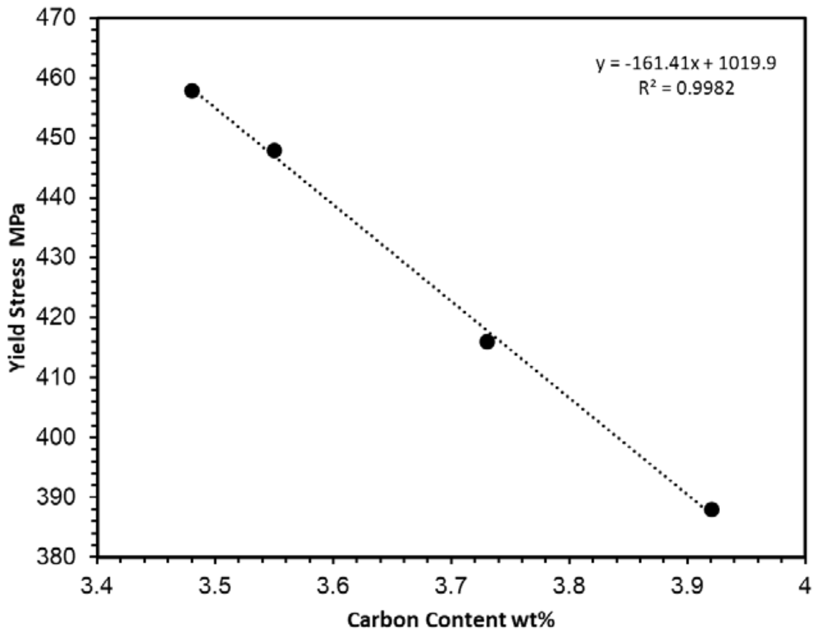
Values below the line exhibited either Magnesium oxide bifilms on the fracture surface, or were found to contain exploded graphite in the microstructure.

Some interesting results were examined in greater detail.

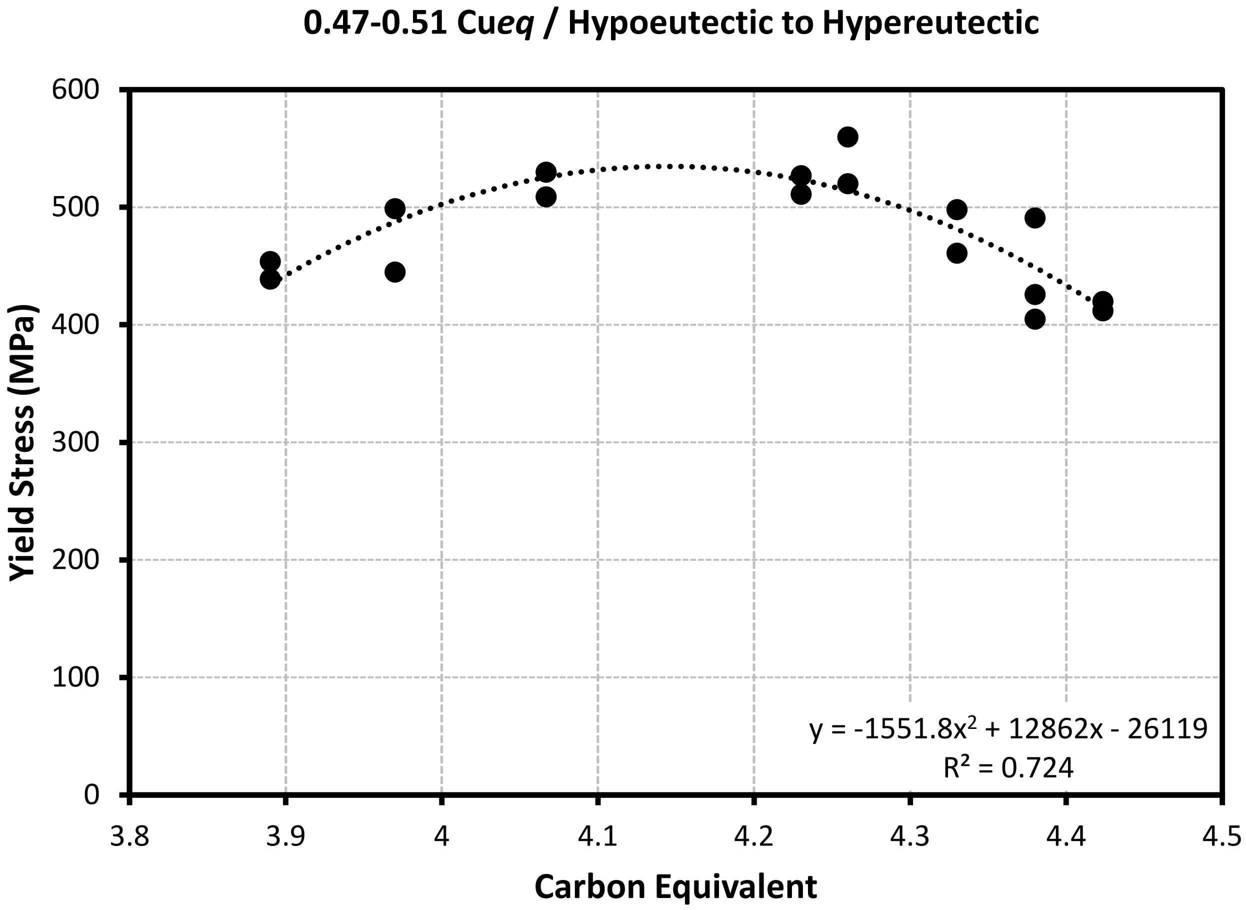
Composition and Properties of the Select Alloys

Alloy	Cu_{eq}	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Ti	Sn	Mg	C_{eq}
1	0.46	3.92	2.19	0.28	0.012	0.006	0.075	0.03	0.22	0.20	0.02	0.014	0.028	4.66
2	0.46	3.48	2.03	0.23	0.013	0.012	0.119	0.018	0.237	0.249	0.02	0.011	0.035	4.16
3	0.48	3.55	2.49	0.39	0.014	0.008	0.232	0.025	0.228	0.183	0.04	0.014	0.030	4.38
4	0.51	3.73	2.08	0.47	0.013	0.010	0.094	0.007	0.214	0.279	0.01	0.014	0.034	4.43

Average	Alloy 1	Alloy 2	Alloy 3	Alloy 4
0.2% Proof Stress (Y.S.)	388 MPa	458 MPa	448 MPa	416 MPa
Tensile Strength	509 MPa	551 MPa	641 MPa	584 MPa
Elongation	15%	14%	13%	16%

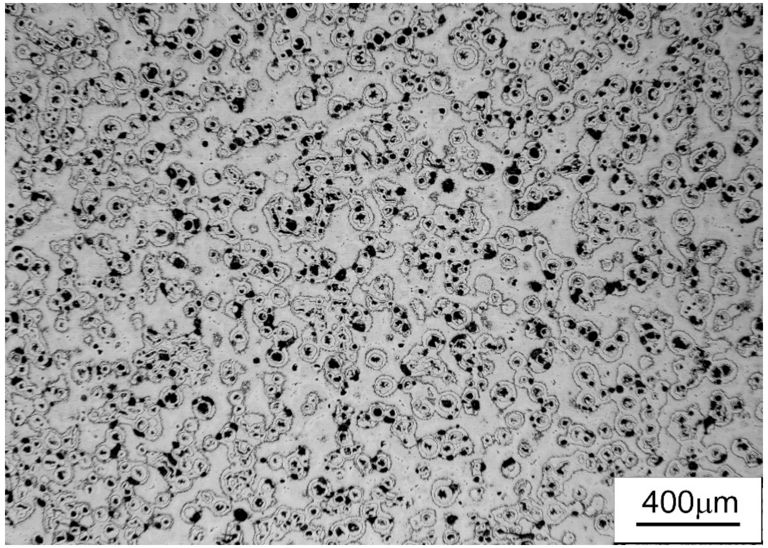


Over ranges of 0.47-0.51 Cu_{eq}; Carbon equivalent has a notable effect on Y.S.

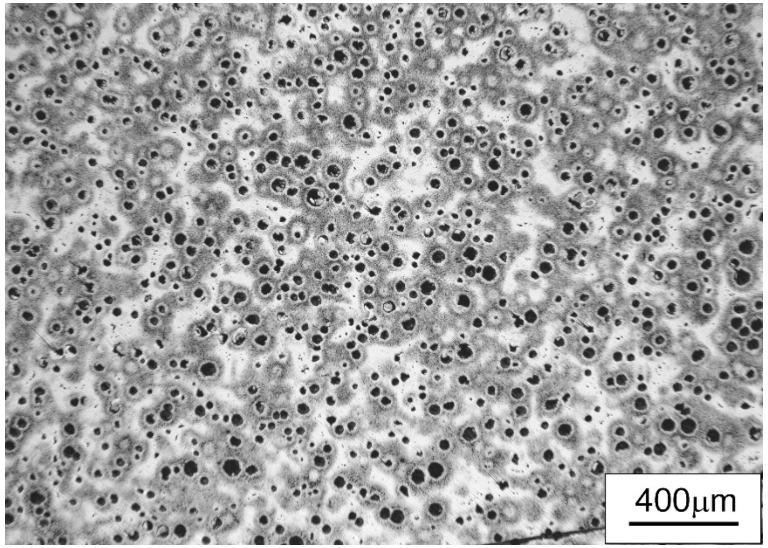


Some Unexpected Results Were Also Found

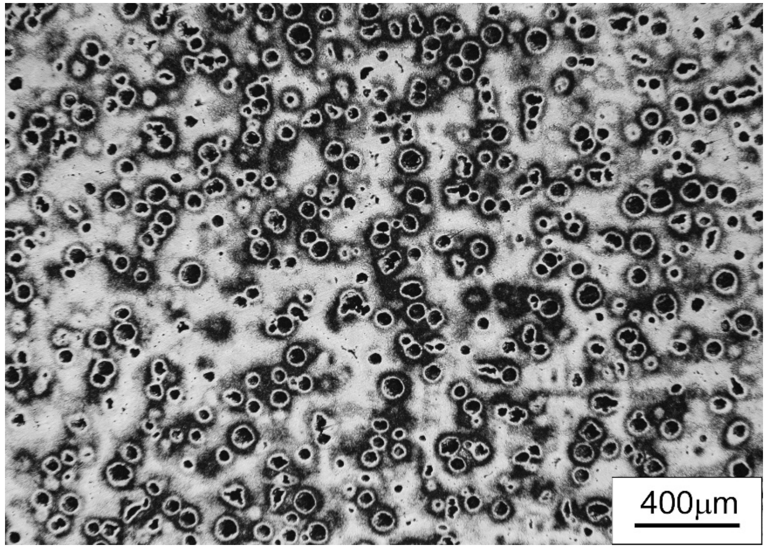
Cu_{eq}=0.11



Cu_{eq}=0.264



Cu_{eq}=0.373

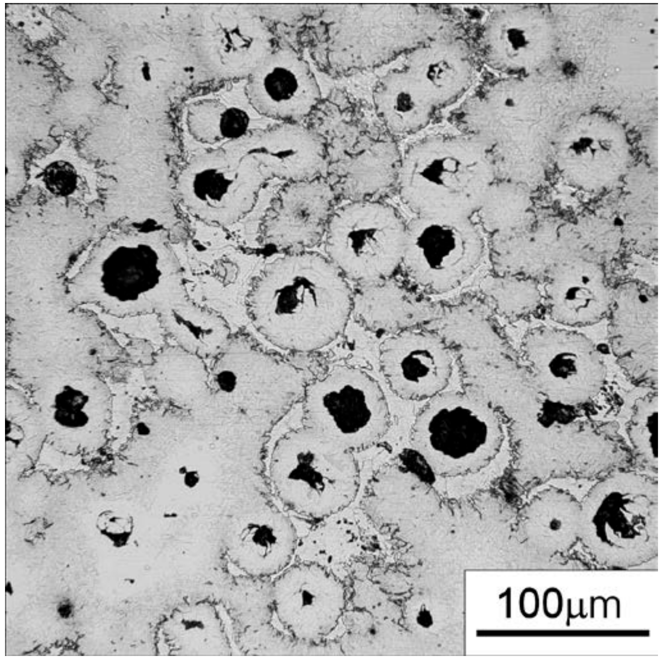


	Cu_{eq}=0.11	Cu_{eq}=0.264	Cu_{eq}=0.373
0.2% Proof Stress	468 MPa	647 MPa	452 MPa
Tensile Strength	620 MPa	753 MPa	627 MPa
Elongation	11%	11%	10%

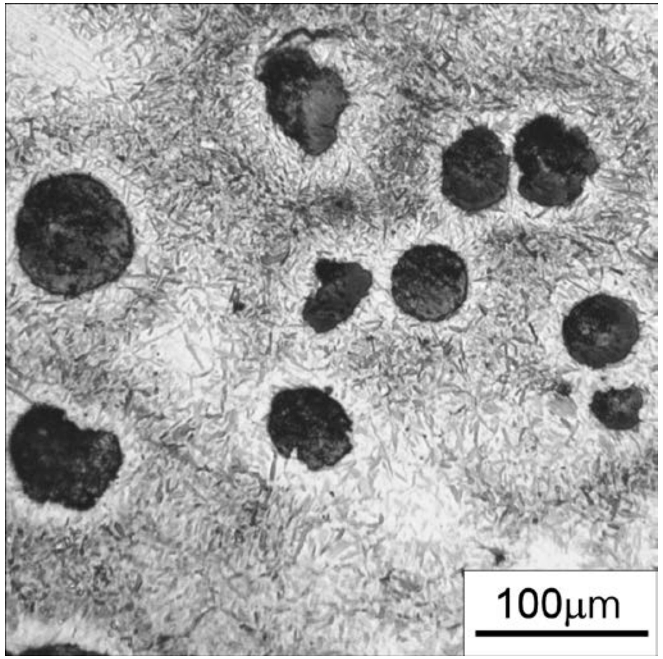
Complex Ausferritic or Bainitic structures may be observed where there should only be ferrite-pearlite;
Copper equivalent relationship to mechanical properties no longer applies.

Some Compositions Forming Different Ausferritic Structures As-Cast

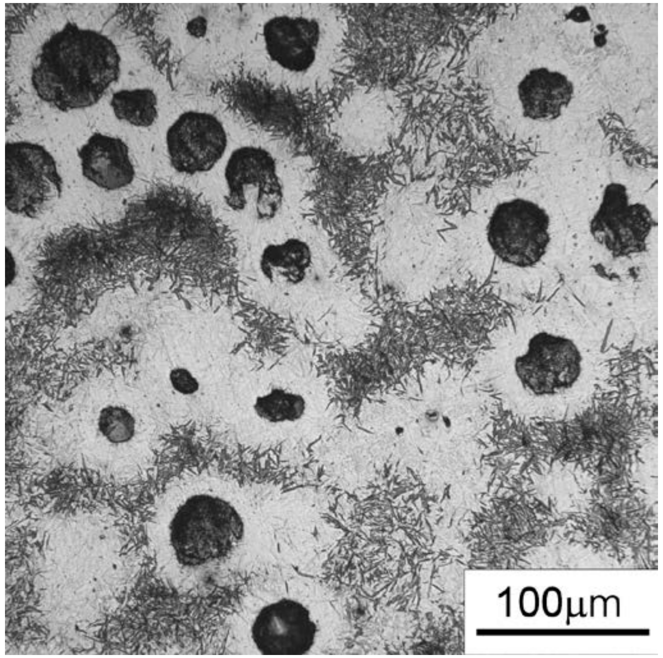
	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Ti	Sn	Mg	C_{eq}
Cu_{eq}=0.11	2.96	3.08	0.156	0.011	0.017	0.061	0.001	0.006	0.01	0.04	0.004	0.034	3.99
Cu_{eq}=0.264	3.91	1.71	0.904	0.015	0.011	0.037	0.005	0.047	0.057	0.008	0.008	0.029	4.49
Cu_{eq}=0.373	3.57	2.13	0.573	0.015	0.018	0.051	0.004	0.182	0.141	0.006	0.014	0.025	4.29



0.11

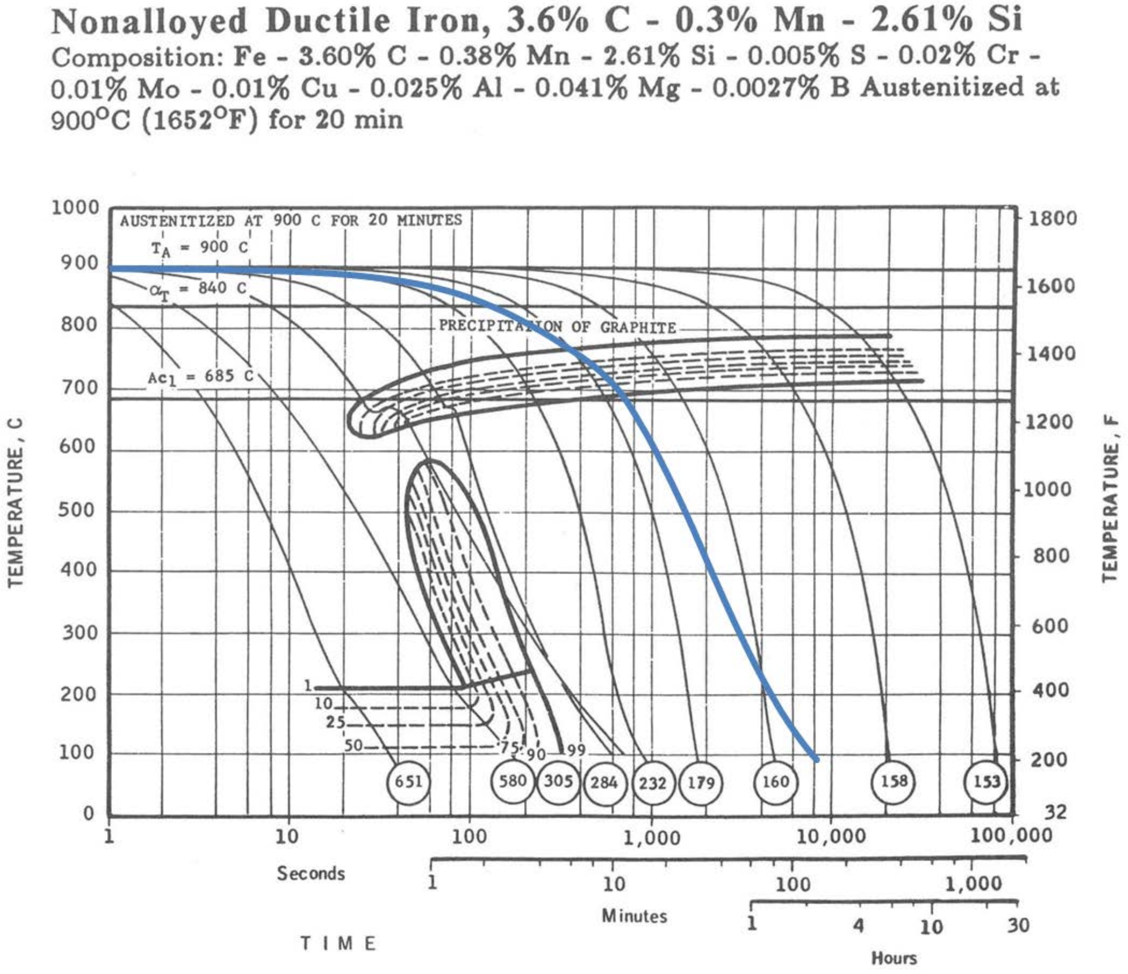


0.264

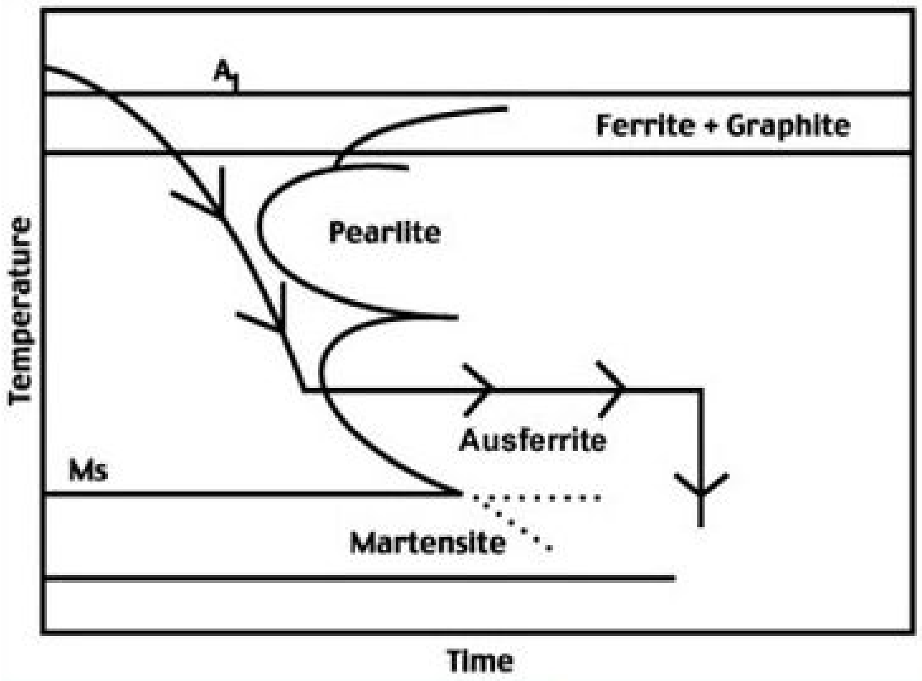


0.373

Typical Cooling Curve Vs. CCT Curve (parts)



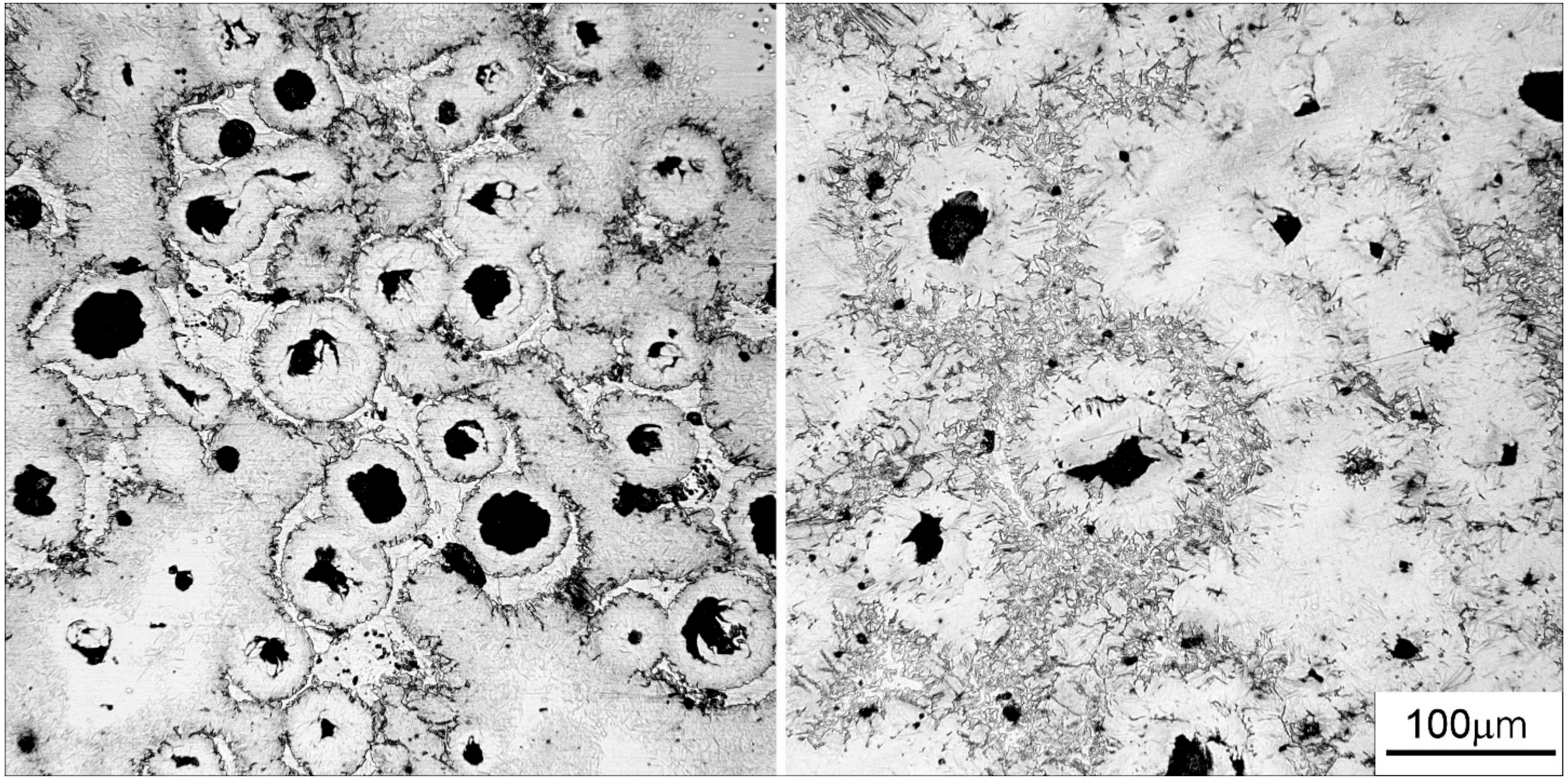
Cooling curve determined by thermocouple insertion into molten metal of shell.



Cooling rate appears to be too slow to form ausferrite or bainite; CCT curve predicts pearlite plus ferrite, not ausferrite.

Some variations with wall thickness were noted but acicular structure was still present

Cu_{eq}=0.11

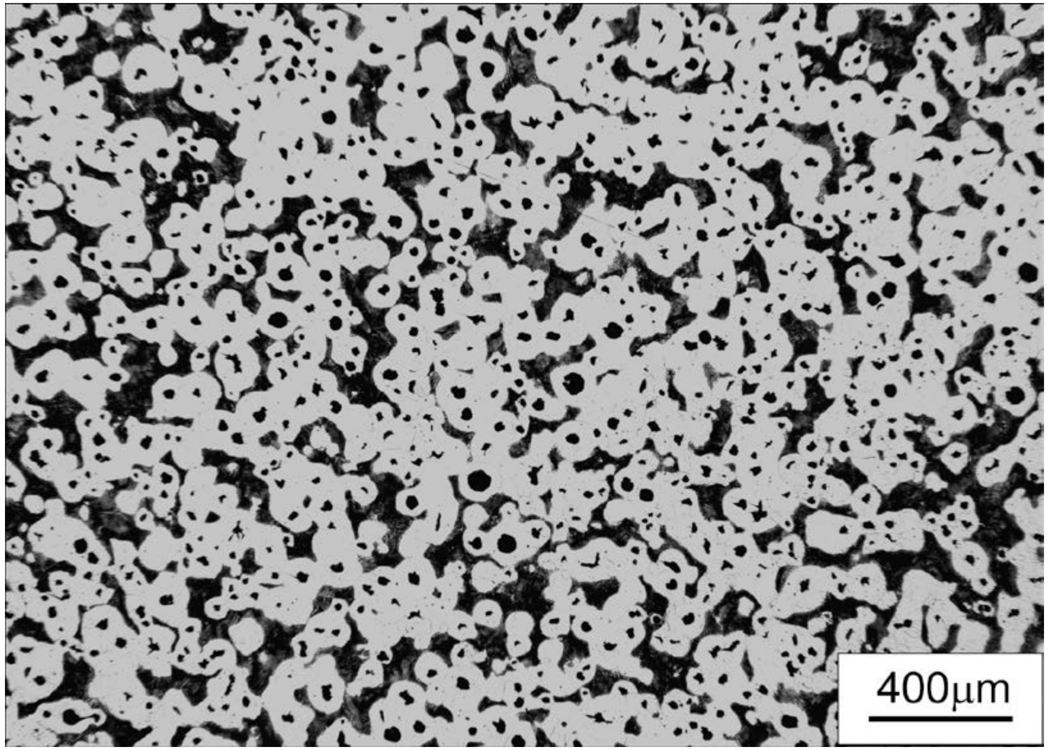


Testbar attached to tree

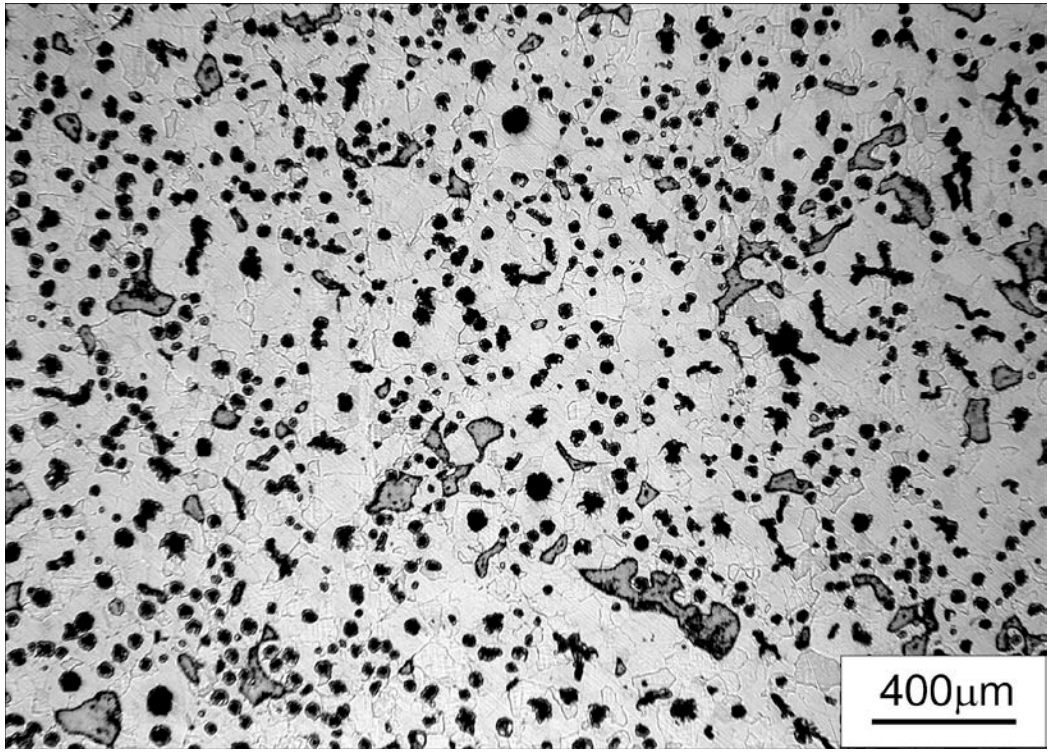
Centre of downsprue / heavier section

A nearly ferritic structure can only be formed using additional insulation:

No additional insulation



With additional insulation (silica wool blanket)



(Two shells cast from the same ladle)

Significant recrystallization in the ferrite has also occurred in the insulated example without separate heat treatment.

Insulated shell to produce ferritic microstructure

Control of the cooling rate to influence microstructure and properties can be accomplished by controlling shell properties and also by controlling the insulating properties of the shell.

Conclusions

- Under normal conditions the concept of Copper Equivalent may be used successfully in investment castings to predict mechanical properties.
- Under some conditions ausferritic structures appear to form instead of ferrite +pearlite, and the relationship between copper equivalent and properties no longer holds true. However, the mechanical properties are usually very good.
- The insulating shell used in investment castings has a very significant effect on the microstructure that forms when producing ductile iron.
- A fully ferritic structure with recrystallized grains is achieved when additional insulation of the ceramic shell is utilized.
- It is hypothesized that the shell wall thickness and its general cooling rate significantly impacts mechanical properties. The mechanical properties of the ductile iron produced may be modified with a combination of chemical composition and ceramic shell manufacturing practice.

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