Development of Thin Wall Cast Invar for Satellite Applications.

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Company Overview

A W Bell is a global supplier of complex metal parts with high mechanical properties to aerospace, defence, space & biomedical industries.

To be the most innovative and customer-focused supplier of quality casting solutions globally.

Company Vision

Today’s Presentation

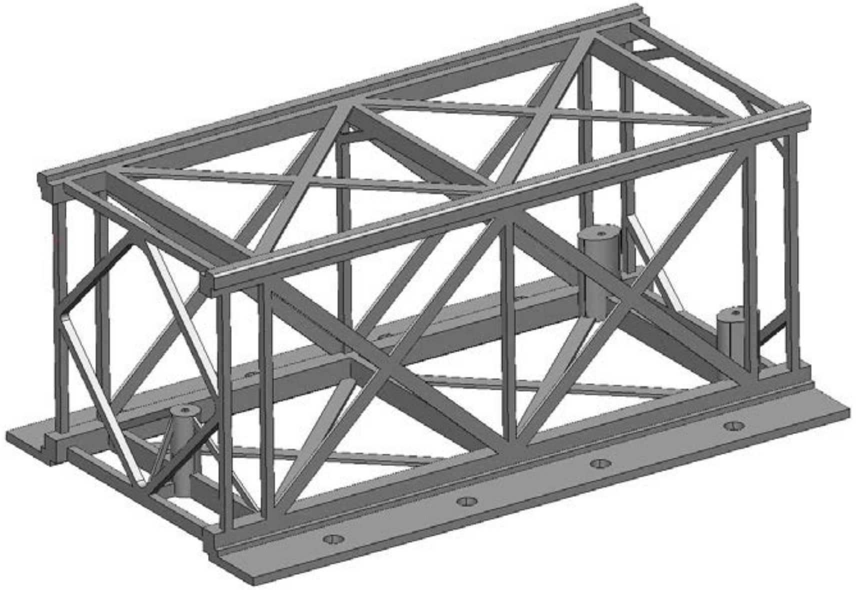
- Cubesats
- Thermal Drift of Sensors
- Why Invar?
- The Invar Effect
- The Invar Effect: Range of Compositions
- Project Scope
- How Thin? Ten Alloys Evaluated
- Hot Tearing
- Microstructures
- Effect of Alloying Elements
- Fluidity Testing
- Satellite Chassis Production

CubeSats

A cubesat is usually defined as being of dimensions that are in multiples of 100mm, often 200mm-300mm long, 100mm to 200mm wide etc.

Cubesats may be employed either singularly or in constellations.

Cannot carry large cooling systems for thermal management.



Cubesat Chassis Design by UNSW Canberra.

Thermal Drift of Sensors in Space

Sensor require high precision or they have to be continually adjusted to account for changes in dimensions with temperature.

Thermal drift is the changes in the normal operational behavior of a device due to changes in ambient temperature. Drift is caused by internal heating of equipment during normal operation or by changes in external ambient temperature.

Parts of a satellite face the sun (*hot*: e.g. 150°C), others are facing space (*cold* e.g. -150°C).

Why Invar?

- Minimal coefficient of thermal expansion over a wide temperature range minimizes thermal drift of sensors and components.
- Discovered in 1896 by Charles-Edouard Guillaume at the International Bureau of Weights and Measures
- The amount of information on casting invar parts is limited (one paragraph in Metals Handbook 1948 ed.; & small amount of information from Howmet)
- Today the major use of Cast Invar is in Carbon Fibre tooling, especially for aerospace.

The Invar Effect

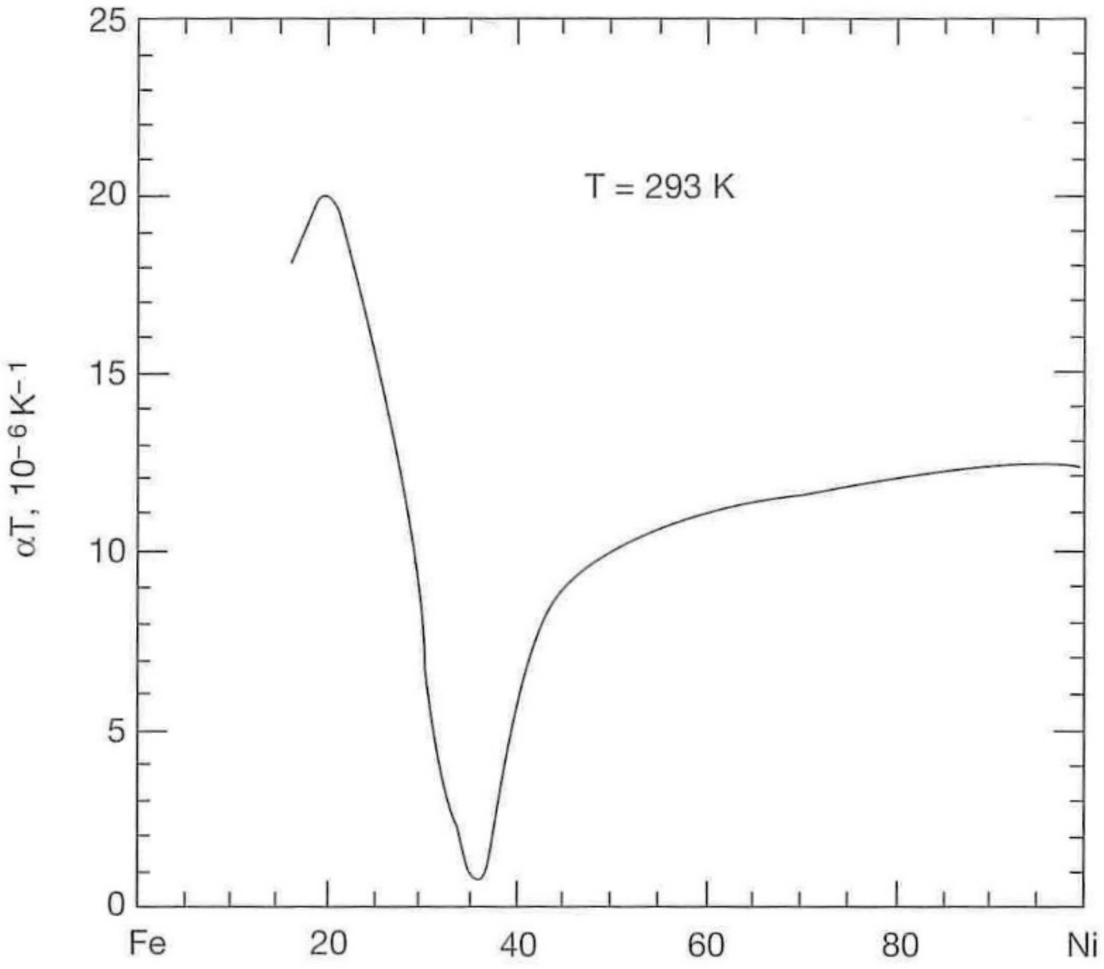
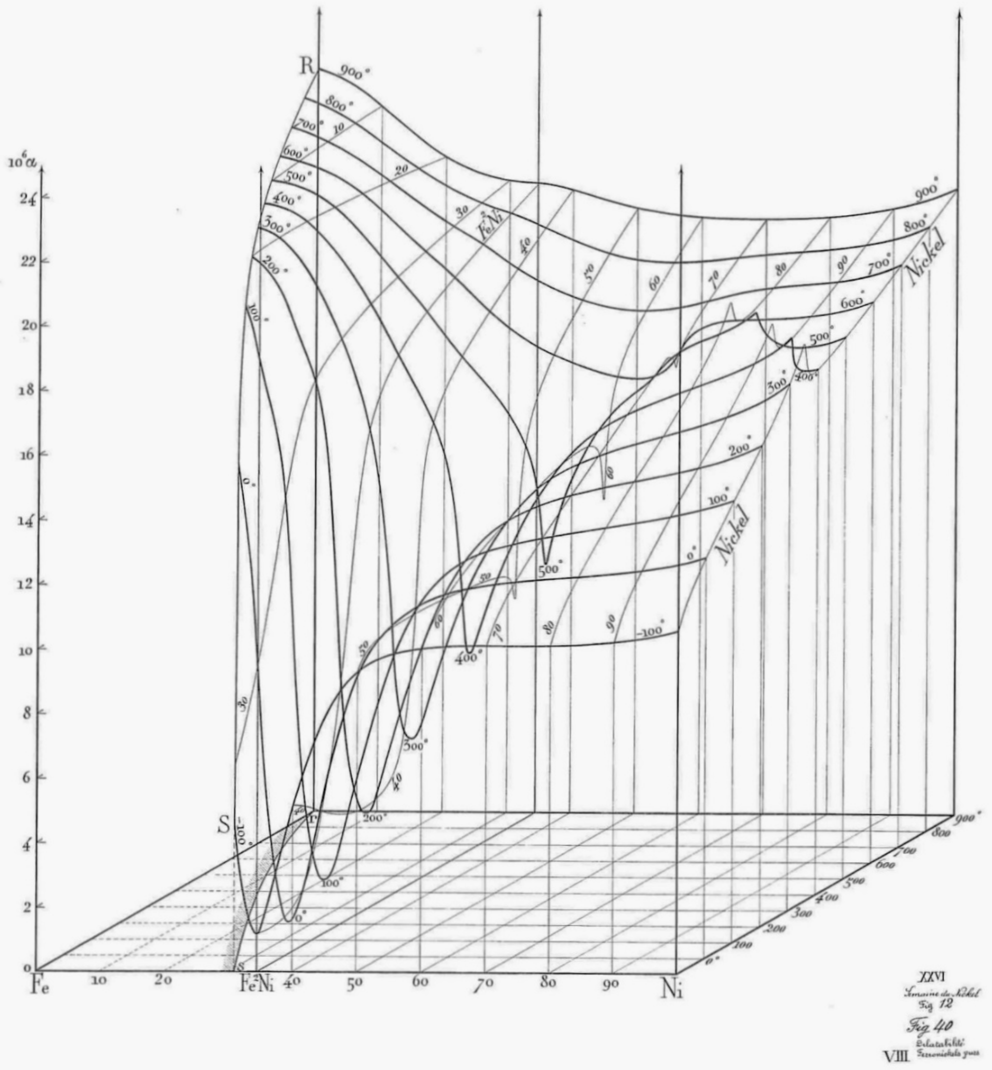


Fig. 2.10. — Variation of the linear thermal expansion coefficient with nickel content in Fe-Ni alloys at room temperature (Masumoto).

The Invar Effect: Range of Compositions



Recherches expérimentales sur les alliages de fer, de nickel et de chrome, Revue de Métallurgie, 1928, Vol. XXV, p. 19.

Three-dimensional expansion coefficient-temperature-composition diagram for austenitic Fe-Ni alloys.

Project Scope

- Project # 11.62, High Altitude Sensor Systems
- "Advanced Manufacture of Cubesat Components"
- UNSW, CSIRO, LaTrobe University, AWBell.
- Evaluate feasibility of manufacturing thin walled Invar from investment castings.
- Alloys were assessed based on their Castability, Coefficient of Thermal Expansion (α), and propensity to form defects.
- A focus was on optimizing thermal expansion over the temperature range -150 to +150°C, suitable for satellite components.

How Thin? Ten Alloys Evaluated

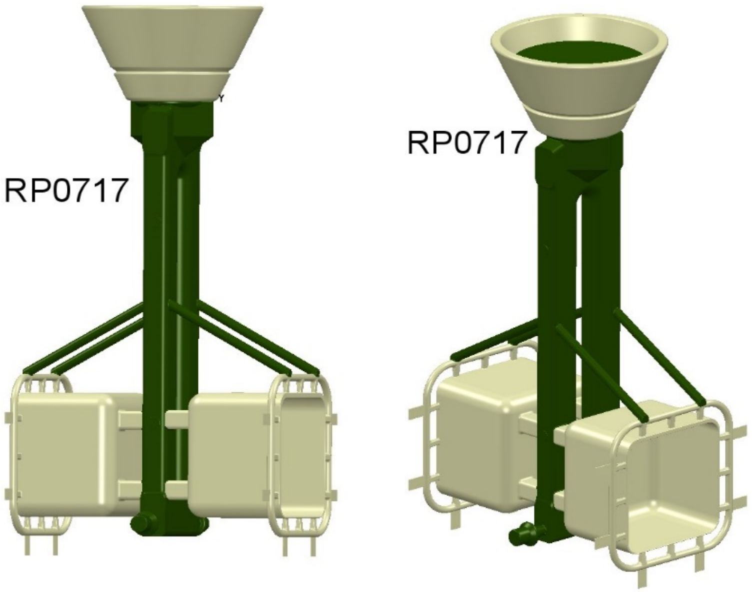
Shell temperature 1000°C, Melt 1660°C

Alloy	Ni	C	Si	Mn	Mo	Cr	S	P
GX3Ni36 specification (ISO 19960)	35.0-37.0	0.05 max	0.5 max	0.5 max	1.0 max	0.25 max	0.02 max	0.03 max
1	35.68	0.027	0.29	0.37	0.73	0.07	<0.01	<0.01
2	35.85	0.080	0.41	0.37	0.71	0.11	<0.01	<0.01
3	36.04	0.116	0.38	0.37	0.73	0.12	<0.01	<0.01
4	35.67	0.075	0.92	0.46	0.90	0.12	<0.01	<0.01
5	35.19	0.072	2.01	0.45	0.88	0.12	<0.01	<0.01
6	34.70	0.075	3.24	0.44	0.89	0.12	<0.01	<0.01
7	36.06	0.074	1.53	1.00	0.77	0.12	<0.01	<0.01
8	35.65	0.09	1.53	1.89	0.77	0.12	<0.01	<0.01
9	35.97	0.10	2.27	1.81	0.72	0.13	<0.01	<0.01
10	36.33	0.10	2.21	2.27	0.71	0.13	<0.01	<0.01
11 (Boeing specification D33028)	37.80	0.02	0.17	0.36	0.00	0.004	<0.01	<0.01

Design of Experiment

- Alloy 1,2,3 would show the effect of C;
- Alloy 2,4,5,6 would show the effect of Si;
- Alloy 7 and 8 would show the effect of Mn when Si was 1.5%
- Alloy 5,9,10 would show the effect of Mn when Si was ≥2%;
- Alloy 11 was commercially available wrought Invar (Boeing Specification D33028 / ASTM F1684-6)

How thin?



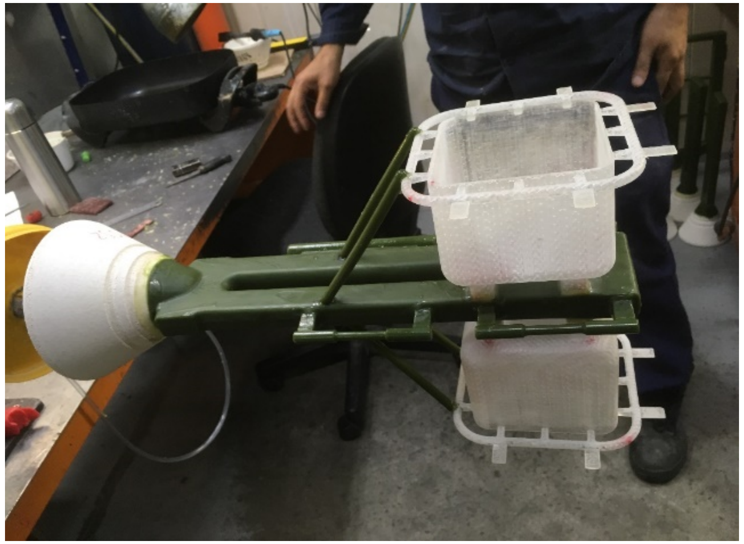
Shell temperature 1000°C, Melt 1660°C
Wall thickness trials 0.8- 6.2mm

Influence of C,Mn,Si,Cr,Mo on castability

C,Mn,Si all improve thin wall filling; Cr for oxidation protection.

The effect of various elements on the mean CTE (α) between 20°C and 100°C.

Element	Si	Mn	Cr	Cu	Co
Δα per percent addition (°C ×10^6)	+1.3	+1.0	+0.8	+0.1	0



Hot tearing Was a Major Issue in Some Alloys

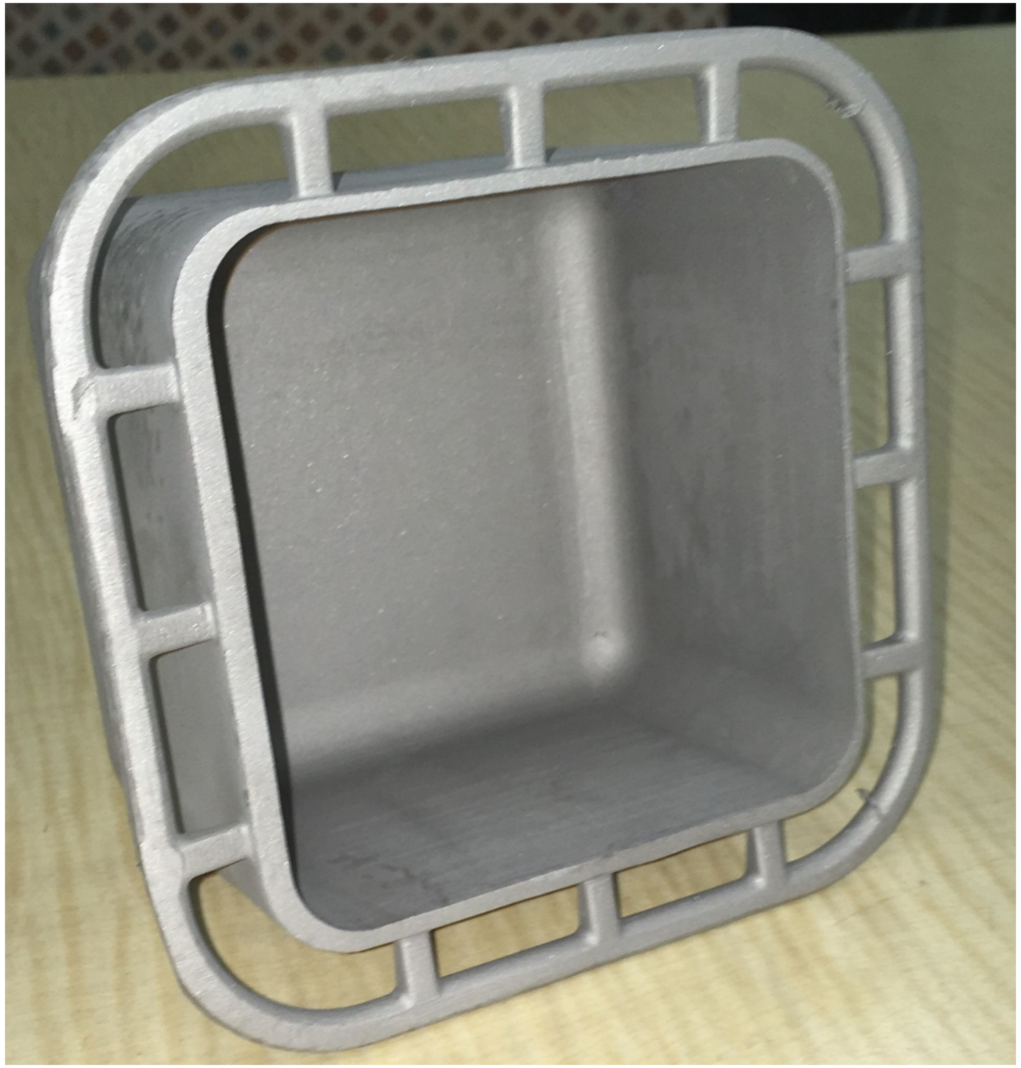
Alloy	Severity of tearing	Ranking
3	Minimal / none	1
1	Minimal / none	2
2	Minimal / None	3
4	Some tearing	4
8	Some tearing	5
9	Some tearing	6
7	Tearing	7
10	Severe	8
6	Severe	9
5	Severe	10

Tearing primarily related to Si and Mn

Alloy 1 was in specification for GX3Ni36

But not in all alloys

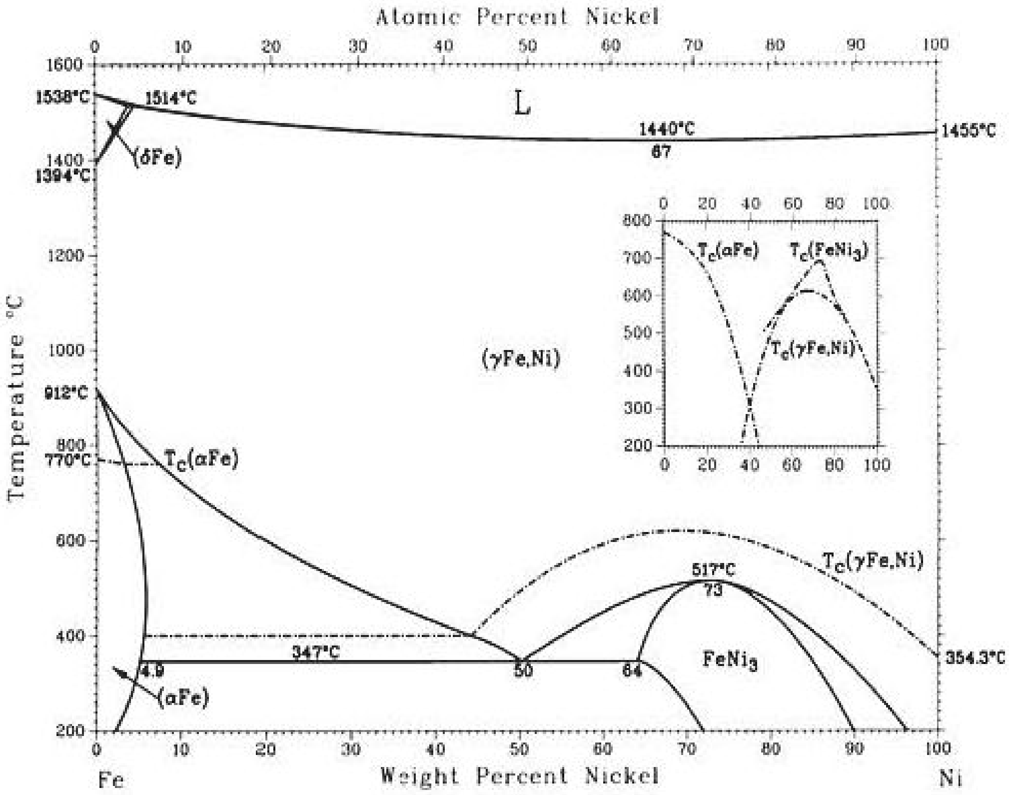
Wall thickness down to ~1mm as-cast.

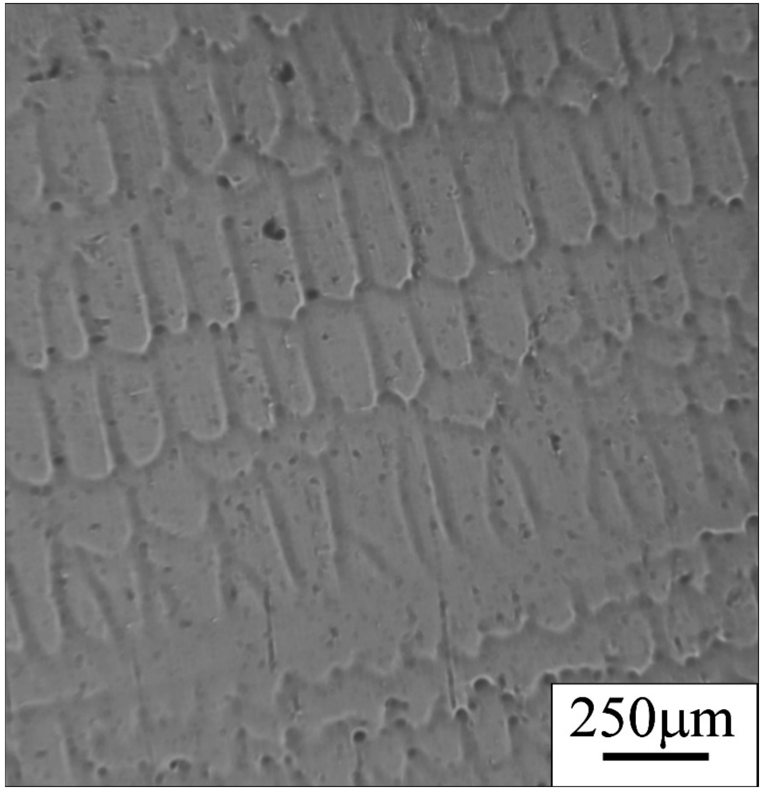


(Test-piece has five different wall dimensions)

Typical Microstructure Alloy 1

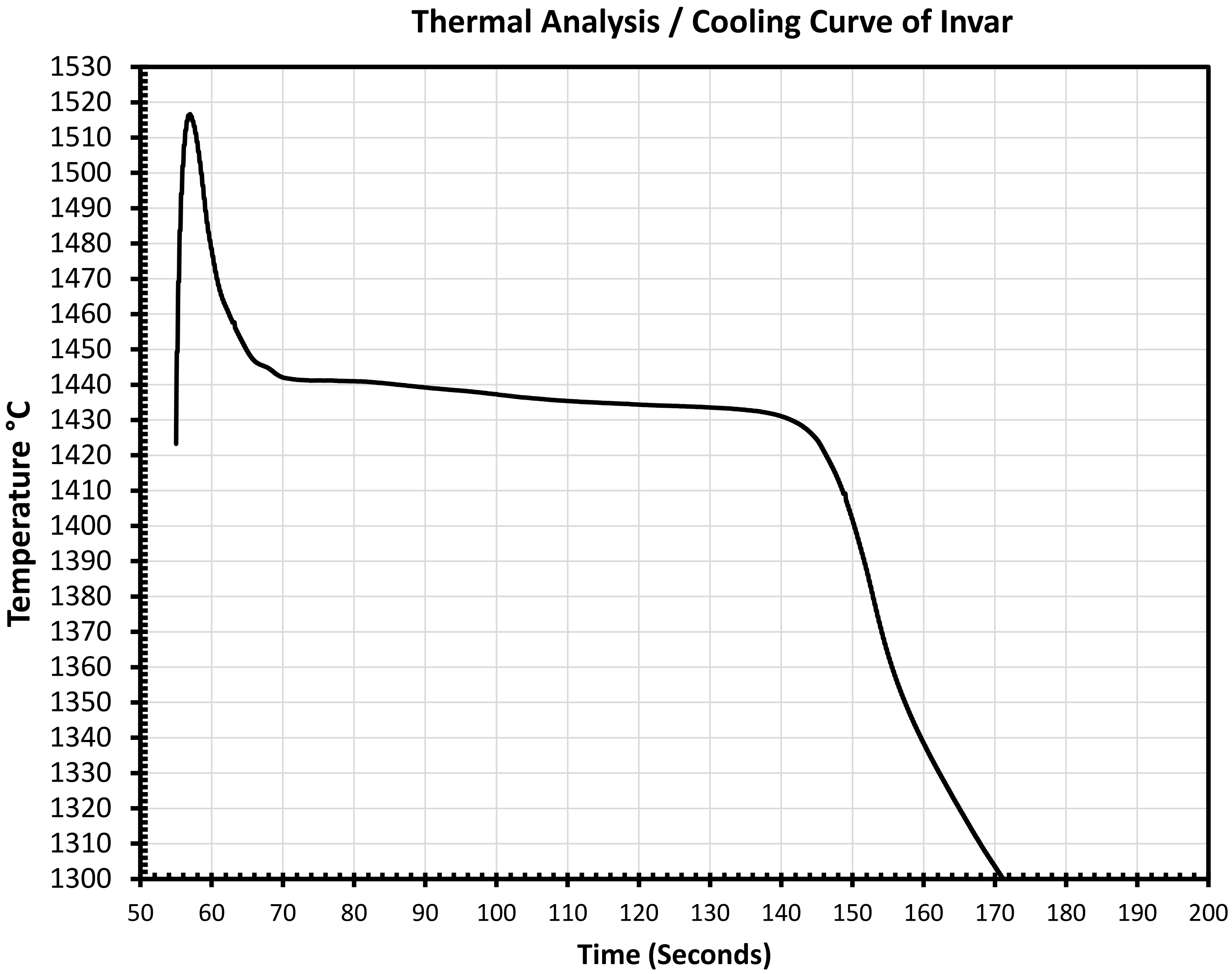
Appears to have a coarse dendritic structure with DAS ~125um



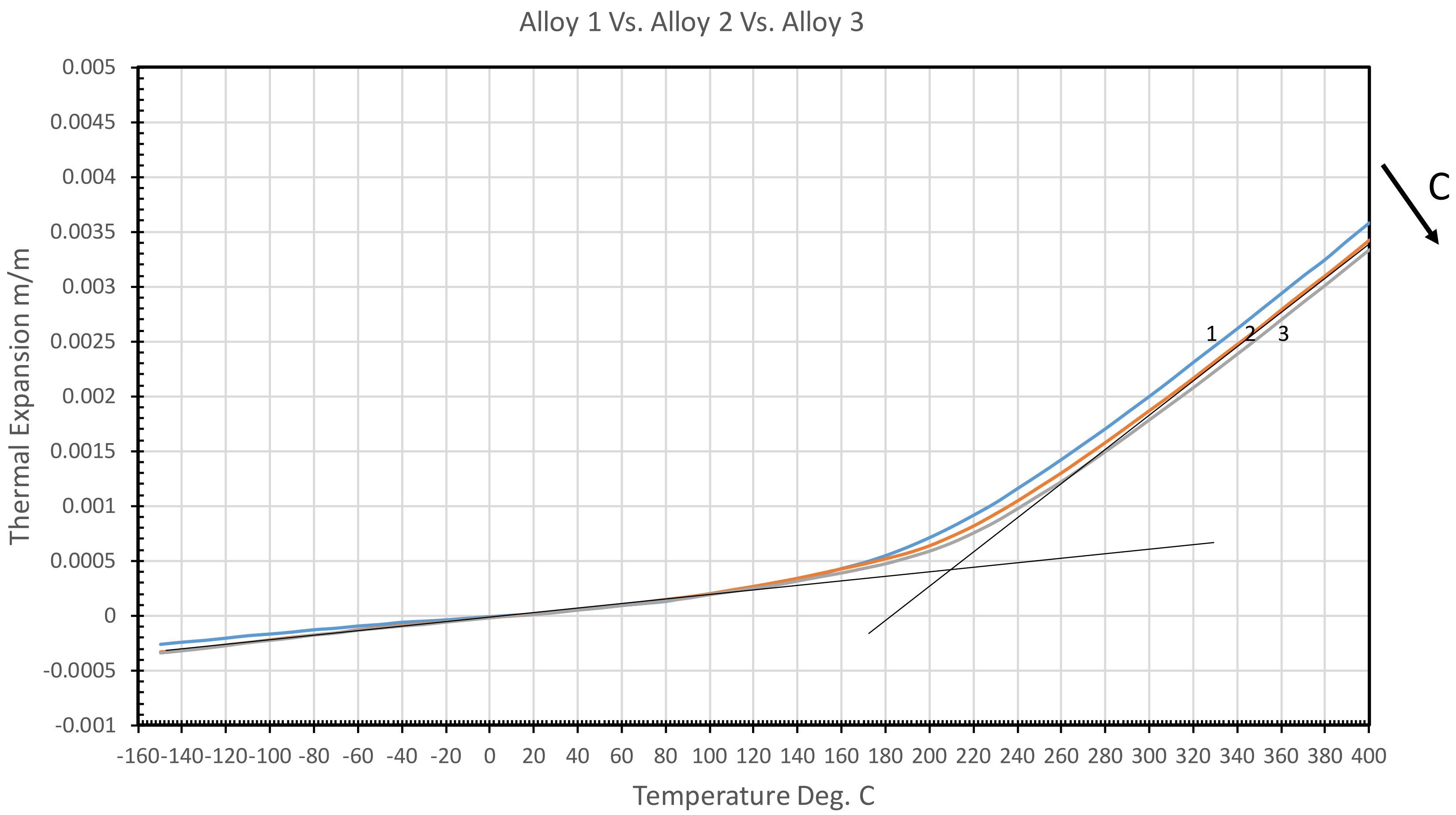


Not necessarily suggested by phase diagram

Thermal Analysis is Consistent with Phase Diagram

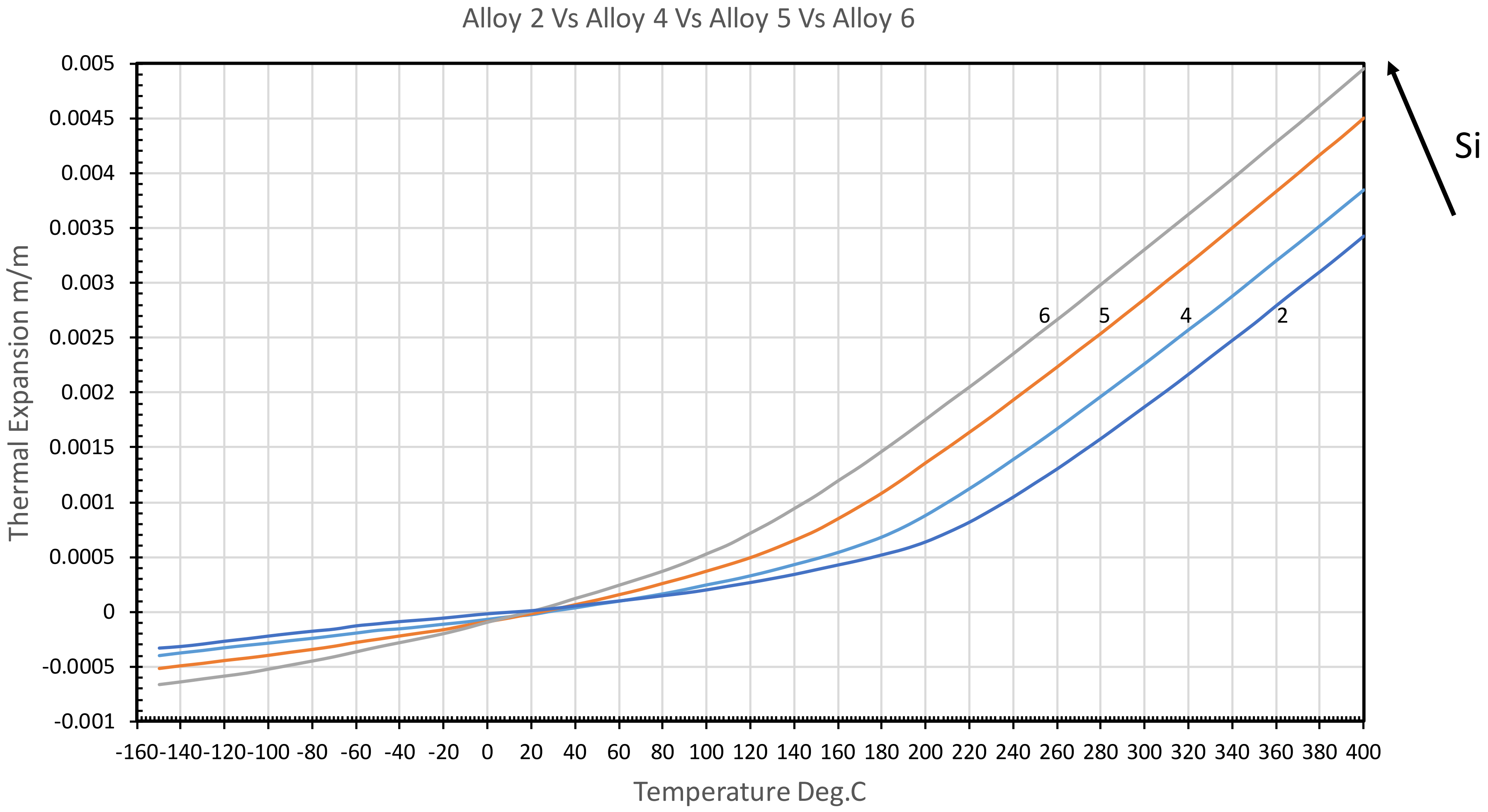


Effect of Carbon

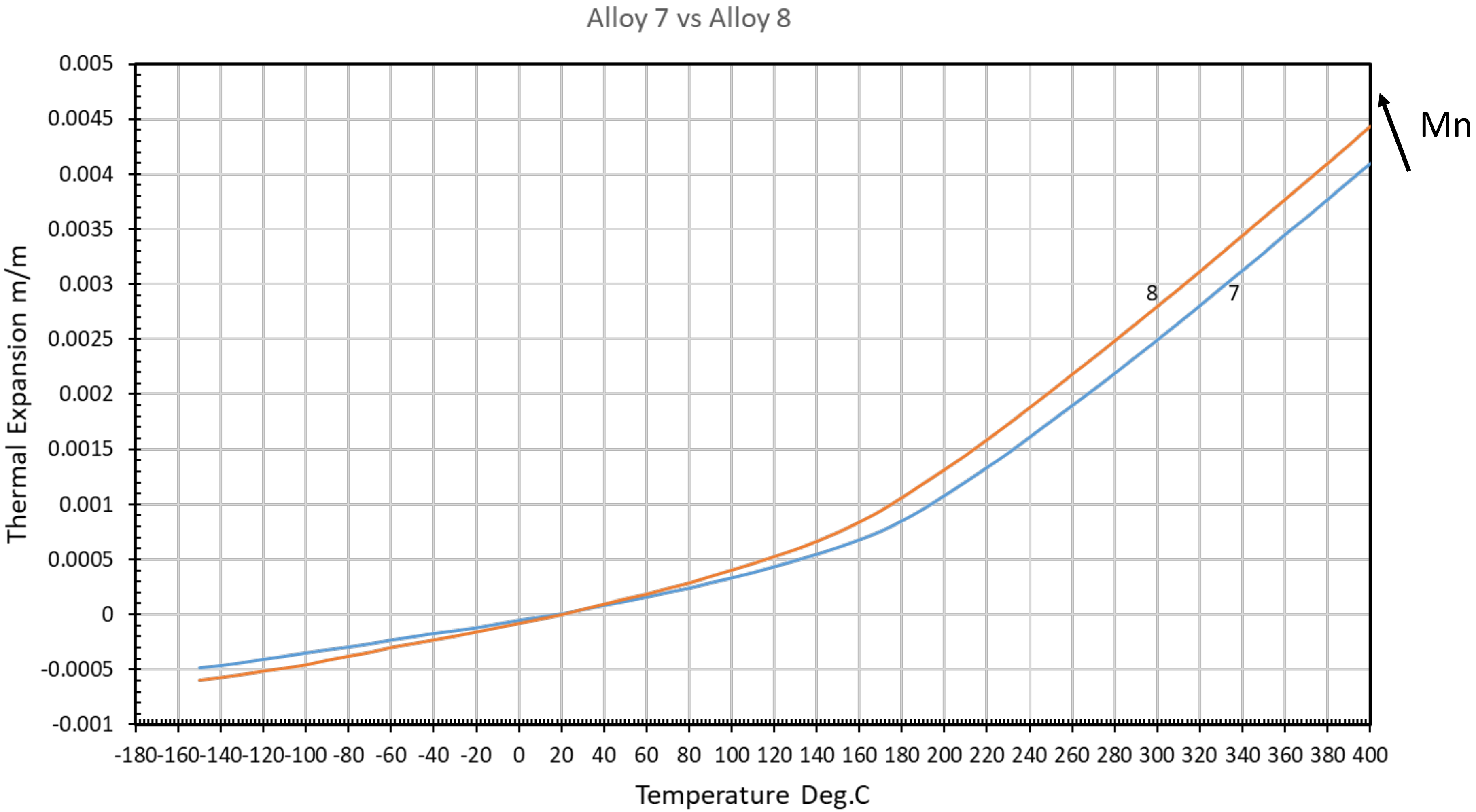


Important Temperatures are the Inflection Point and Curie Temperature

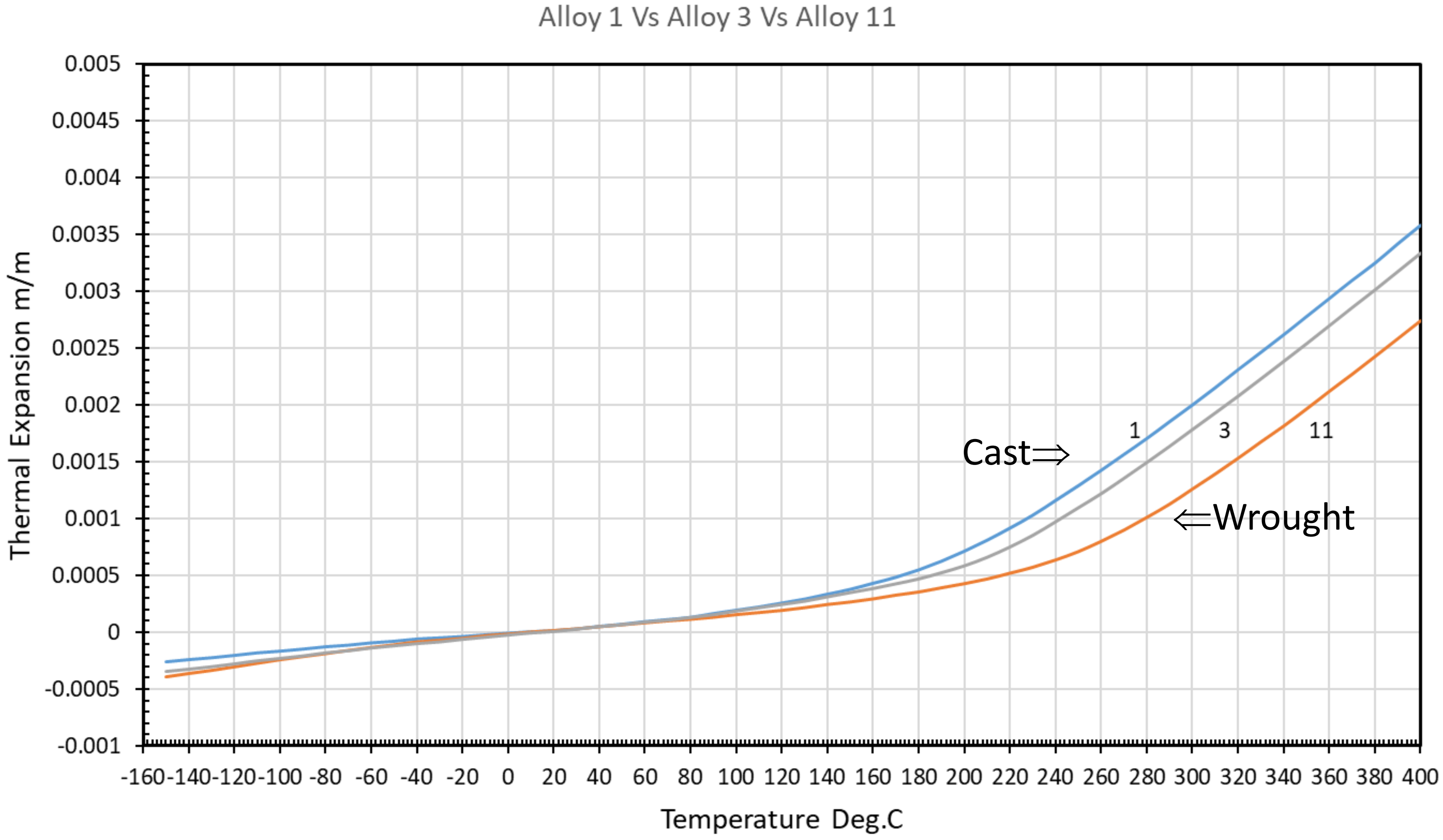
Effect of Silicon



Effect of Manganese



Best cast results versus wrought



Results are excellent over the range of -150 / +150°C

Inflection, Curie Temperature and CTE

Inflection temperature, Estimated curie temperature, and Coefficient of Thermal Expansion over the temperature ranges 20-100°C, or -150 to +150°C.

Alloy	Inflection Temperature	Curie Temperature (estimated)	Coefficient of Thermal Expansion ($\times10^{-6}$) /°C	Coefficient of Thermal Expansion ($\times10^{-6}$) /°C
			20°C to 100°C	-150°C to 150°C
1	195°C	309°C	2.25	2.127
2	207°C	310°C	2.375	2.383
3	215°C	319°C	2.2625	2.31
4	182°C	319°C	3.4	2.947
5	154°C	306°C	4.85	4.19
6	132°C	309°C	6.5625	5.747
7	178°C	300°C	4.1	3.65
8	164°C	296°C	5.0875	4.4867
9	159°C	310°C	5.713	5.043
10	159°C	308°C	5.613	5.107
11	260°C	335°C	1.75	2.1933

Stage 2 Trials

Temperatures and fluidity study

Effect of Nickel on CTE

Mechanical Properties

Demonstrate production capability

Welding

Fluidity was a major unknown

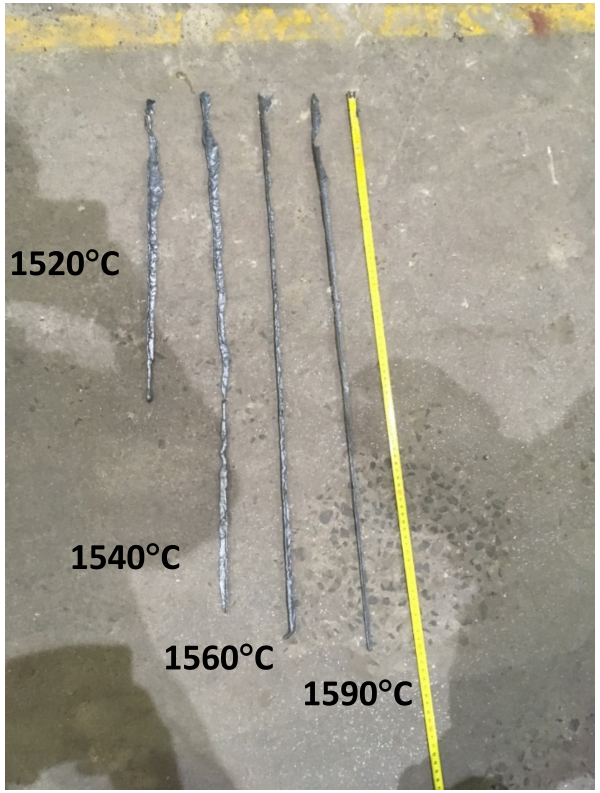
But easily understood!

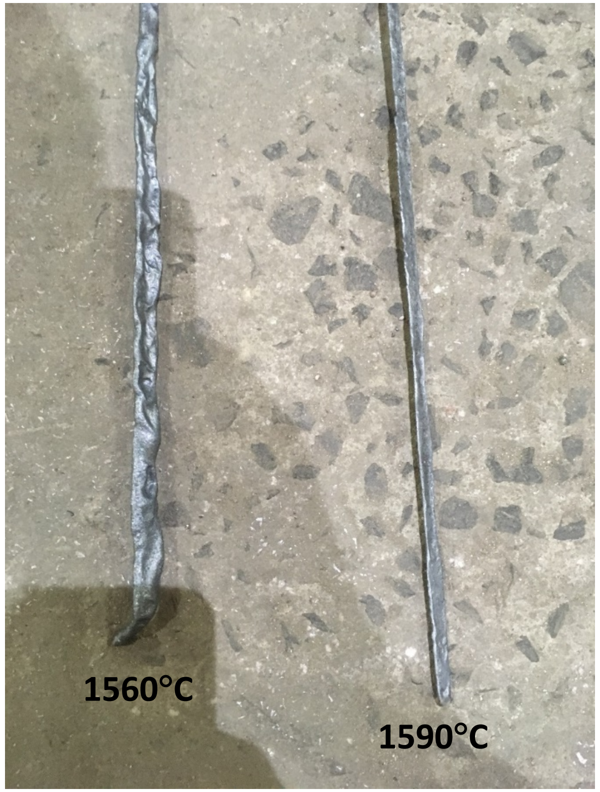
Cast at lowest temperature possible to achieve good fluidity minimizes hot tears.

Video is available on pdf

Fluidity Testing Results

Cast at lowest temperature possible to achieve good fluidity minimized hot tears.





Effect of Nickel

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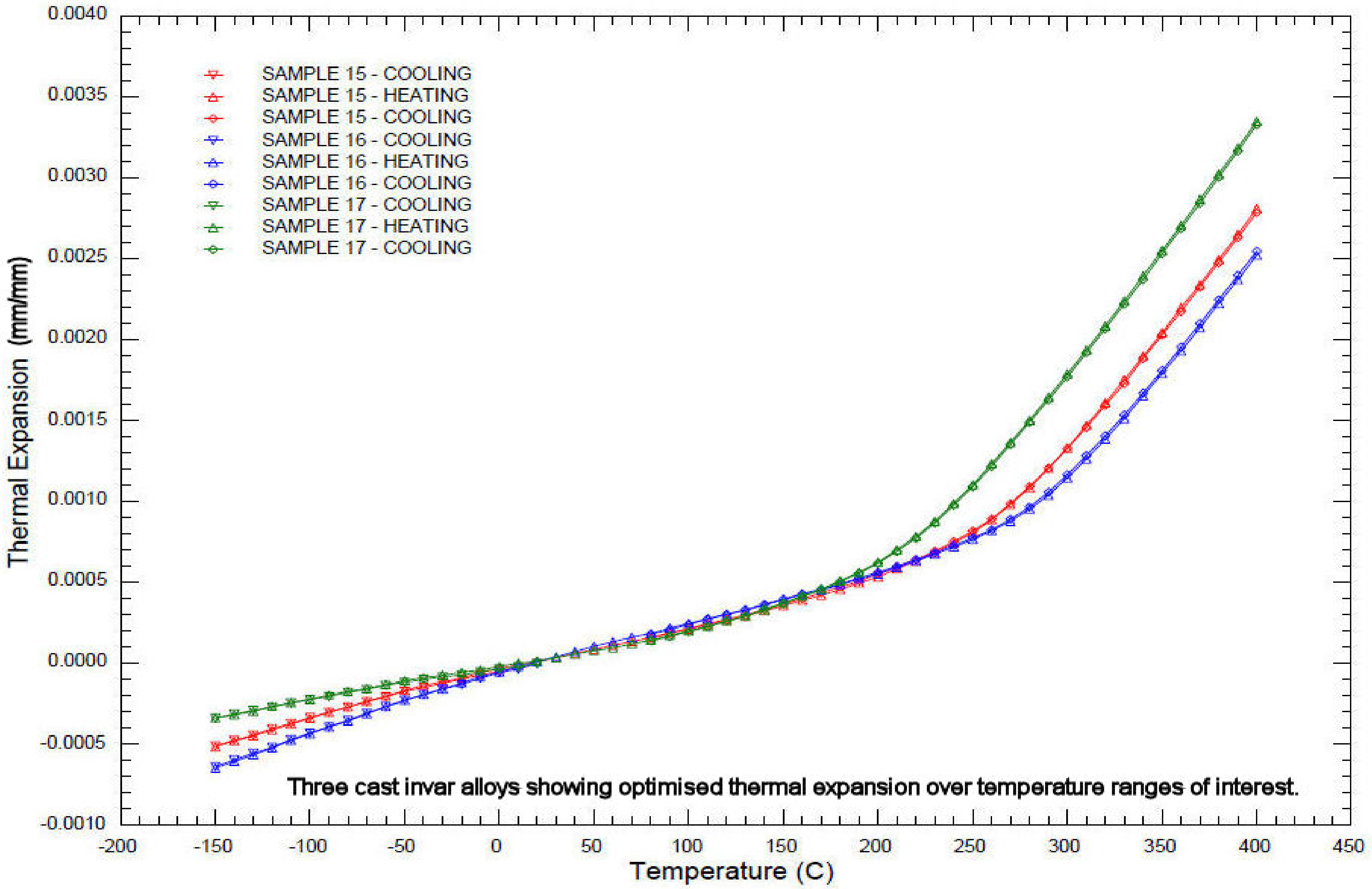
12	36.30	0.020	0.35	0.48	0.77	0.15	<0.01	<0.01
13	36.07	0.024	0.31	0.46	0.65	0.13	<0.01	<0.01
14	37.38	0.023	0.23	0.40	0.63	0.15	<0.01	<0.01
15	38.40	0.022	0.19	0.37	0.62	0.14	<0.01	<0.01
16	39.70	0.021	0.14	0.32	0.61	0.14	<0.01	<0.01
17	36.85	0.022	0.30	0.41	0.69	0.16	<0.01	0.015

Effect of Nickel (CTE) Cast



Three cast invar alloys showing optimised thermal expansion over temperature ranges of interest.

↘ Ni

Ni influences inflection & Curie Temperature

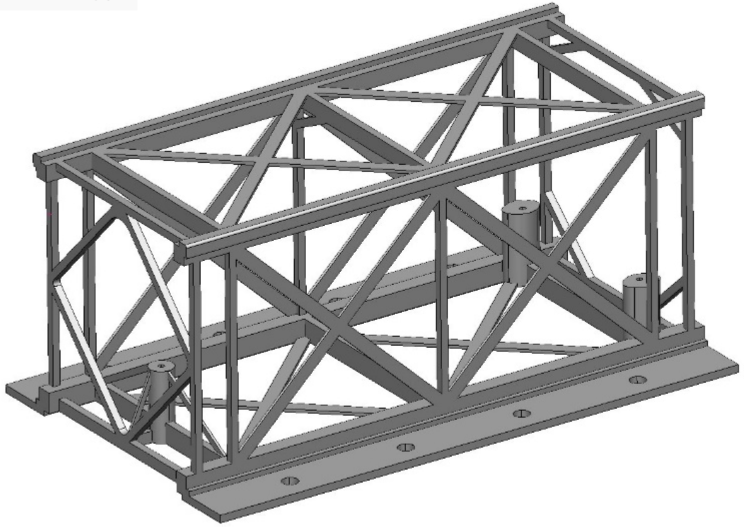
Mechanical Properties (Heat Treated)

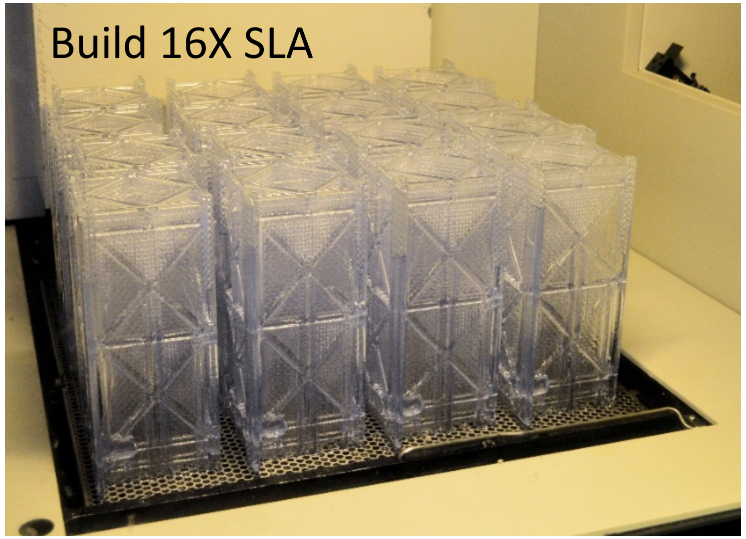
Average tensile properties of Invar containing different levels of Nickel.

Alloy	0.2% Proof Stress (MPa)	Tensile Strength (MPa)	Elongation (%)
GX3Ni36	275min.	395min.	28 min.
12	292	426	38
13	284	418	34
14	294	432	37
15	293	422	34
16	290	429	36
17	288	417	33

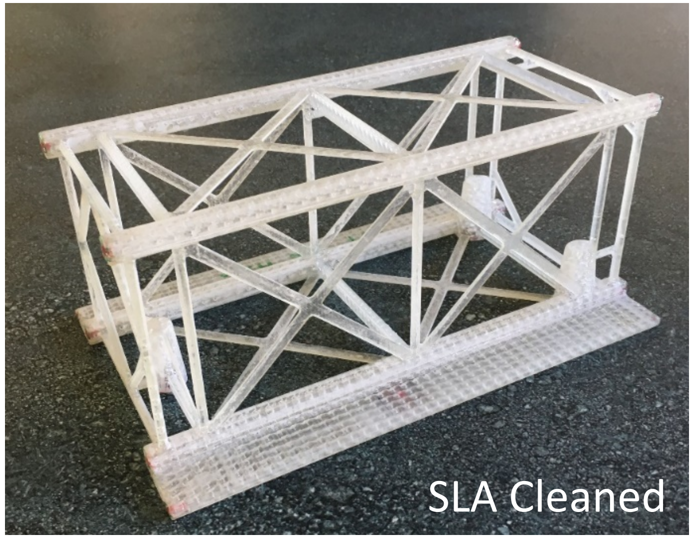
Chassis Production ISO 19960: GX3Ni36

CAD





Build 16X SLA

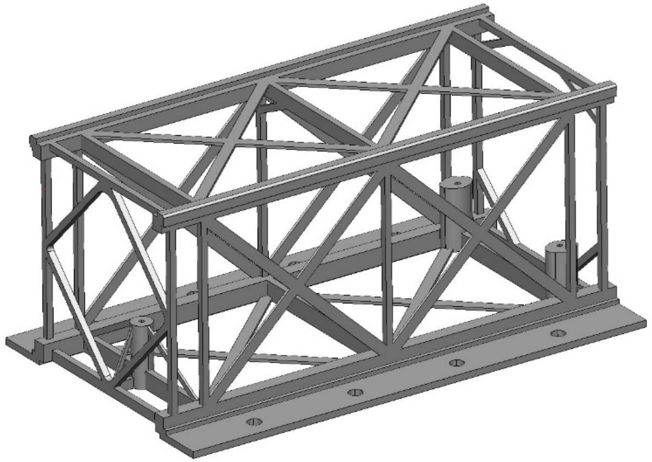


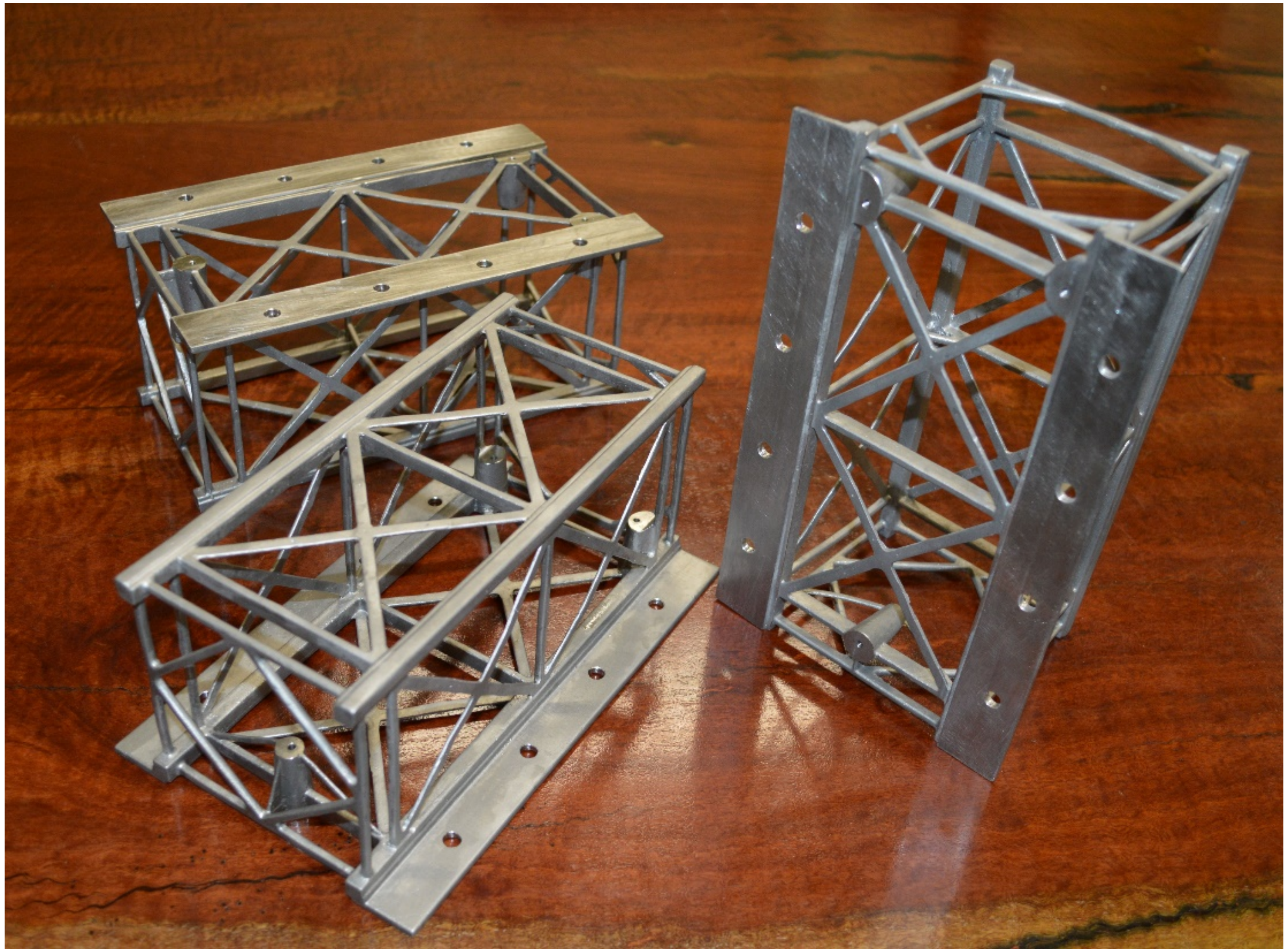
SLA Cleaned

Tree

Cast and Fettle

Cast and Machined Chassis





GX3Ni36 Invar
Cast, Heat Treated
& Machined

AWBell Foundry Team, 2019.

Mike Baker Photography © DMTC Limited 2019

Conclusions

Invar may be successfully melted and cast using standard air melting techniques.

The material is particularly sensitive to the presence of Silicon and Manganese, which contributes to Hot Tearing.

Alloys are less sensitive to increases in Carbon Content

Nickel offsets the Inflection Point and Curie Temperature to higher values, but does not impact castability.

Excellent fluidity may be achieved and wall thickness down to around 1mm are feasible.

Mechanical Properties meet the specification of ISO19960, alloy GX3Ni36.

Commercial feasibility was demonstrated for printing Cube Satellite Chassis direct from CAD data into SLA, then casting Invar.

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