Finite element modelling of the thermal deformation of standards for in process measurement

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Overview

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- Background and aims of the modelling work
- Part 1: Thermal diffusion and displacement modelling
- Part 2: Milling model
- Summary of conclusions and Next steps

Calibration of surface measurement tools

- Calibrating manufacturing tools helps manufacturers make products that are the size and shape that they were designed to be.
- Calibration requires reference standards
- Creating reference standards for surface measurement is challenging:
  - Standard will be affected by the environment (thermal expansion)
  - Process of standard production generates localised heating & deformation (imperfect shaping)

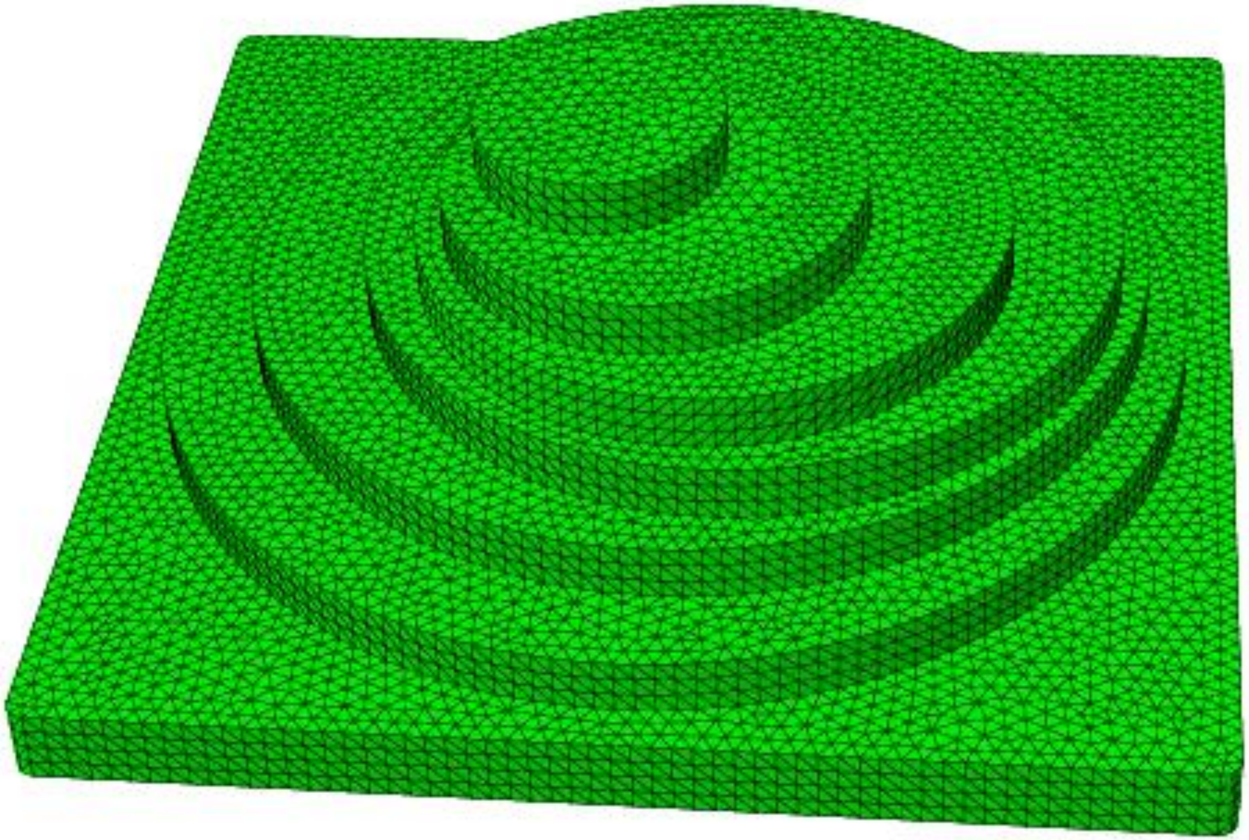
Finite element modelling

- Model
  - Geometry - nodes and elements
  - Properties
- Physics
  - frequently expressed as partial differential equations
- Numerical technique for solution of partial differential equations
  - Can handle general geometries (important because we have complicated shapes)
  - Can solve the heat equation to predict temperature distributions
  - Can solve stress equilibrium equations to predict deformation due to thermal expansion
  - Can use a material removal technique to simulate milling process used to make standards

Aims of the modelling work

- Part 1: Thermal diffusion and displacement modelling
  - Predict how long a standard takes to equilibrate in a changing environment
  - Predict final temperature distribution and deformation when at equilibrium
- Part 2: The milling model
  - Simulate localised heating and deformation caused by milling process

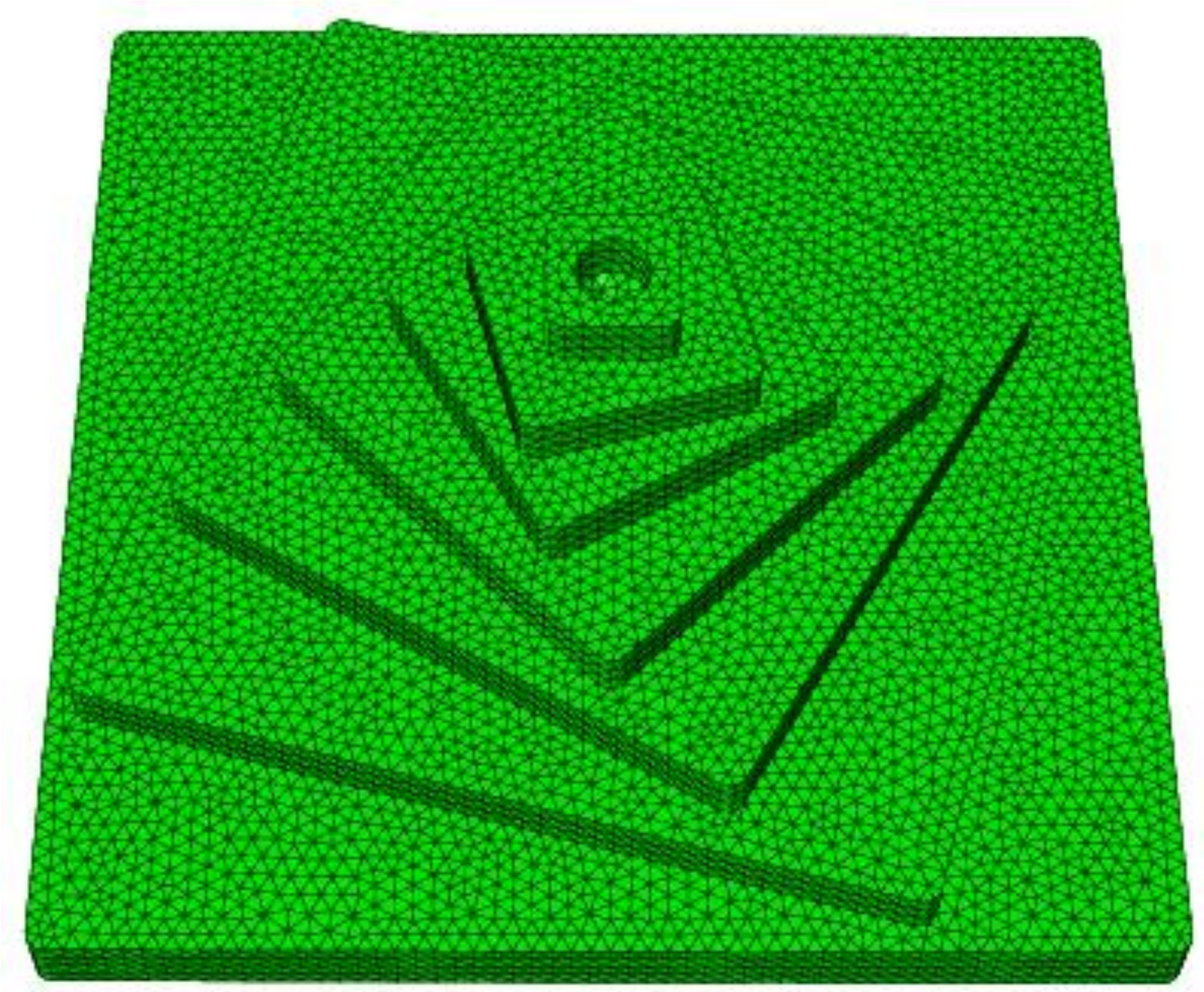
“Cylinders” standard



Overall dimensions approximately 300 mm by 300 mm by 110 mm

Approx. 250,000 nodes

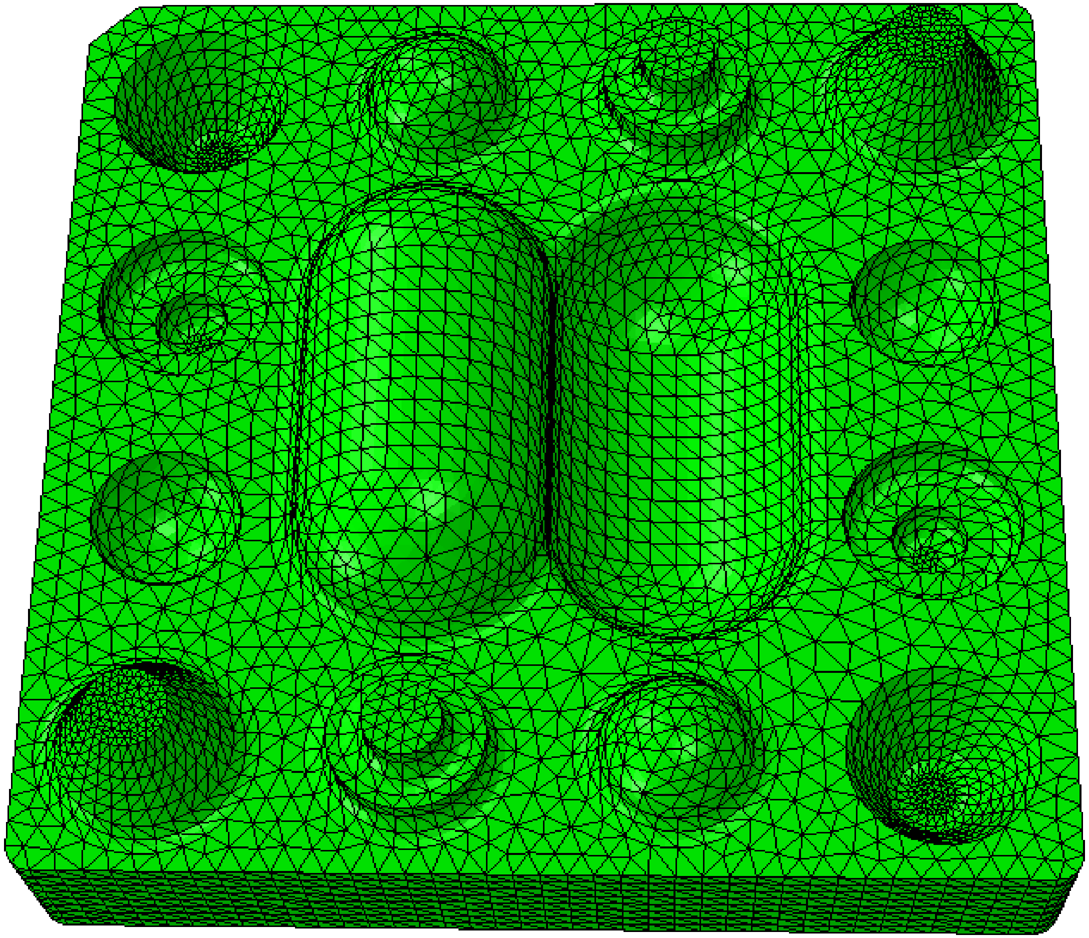
"Squares" standard



Overall dimensions approx 300 mm by 300 mm by 110 mm

Approx 275,000 nodes

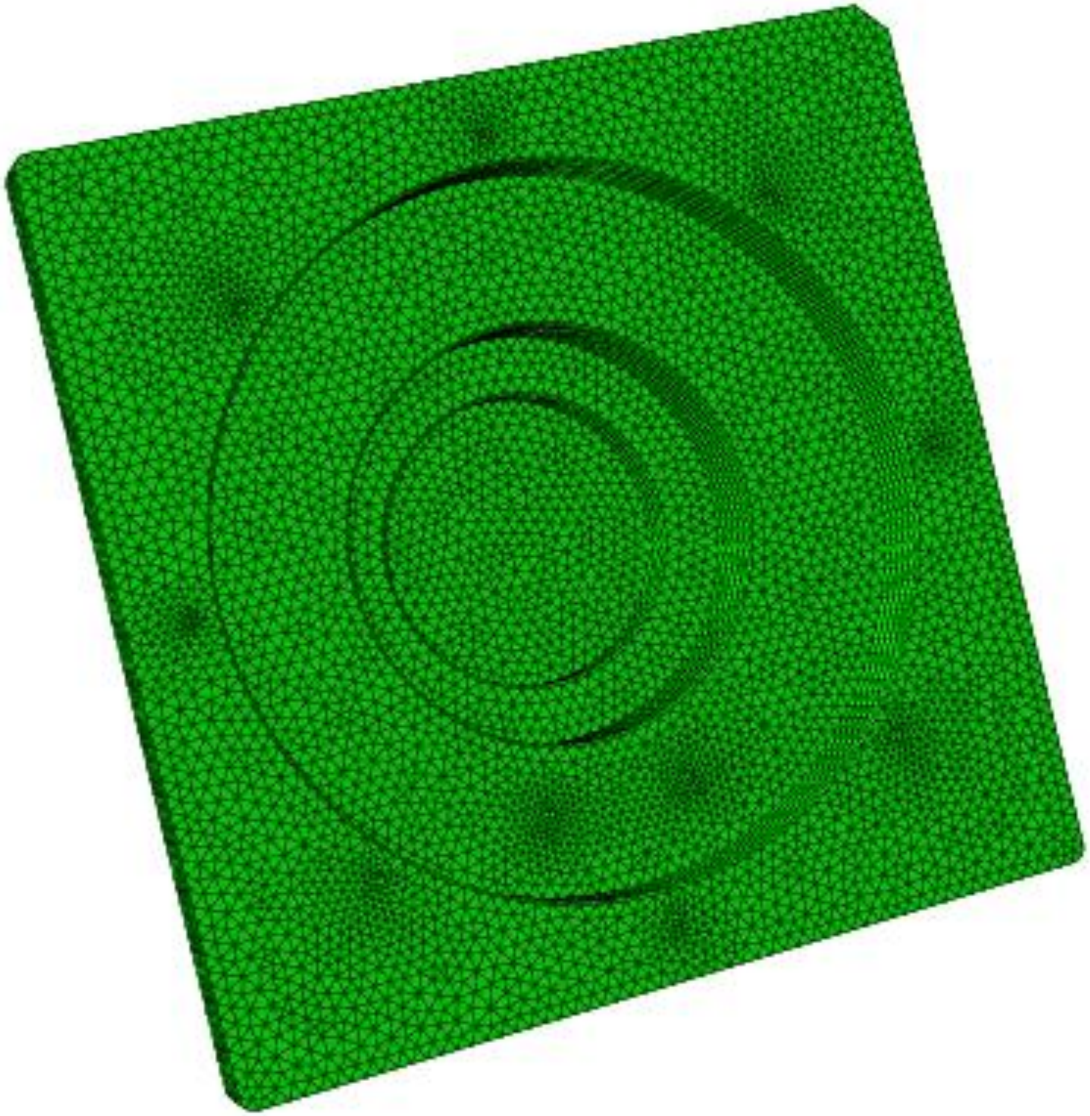
"Prismatic" standard



Overall dimensions approx 200 mm by 200 mm by 65 mm

Approx 225,000 nodes

Hollow underside



Hollow underside reduces mass of standard: makes it easier to work with

Material properties

- Standards taken to be made from Invar36 or aluminium

	Invar36	Aluminium
Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	10.5	237
Specific heat capacity ($J\ kg^{-1}\ K^{-1}$)	515	897
Density ($kg\ m^{-3}$)	8055	2700
Young's modulus (GPa)	148	70
Poisson's ratio	0.3	0.35
Thermal expansion coefficient (K^{-1})	1.3×10^{-6}	23.1×10^{-6}

Part 1: Thermal diffusion and displacement modelling: Boundary & initial conditions

- Simulate case where the standard is placed on to a surface that is hotter or colder than ambient temperature
- Initially the standard is at 20° C
- Standard sits on a fixed surface that is at 10° C or 30° C
  - Lower surface of standard is the same temperature as surface it is in contact with
  - No heat exchange between air trapped by the standard and the standard itself
  - Lower surface of standard cannot move vertically
- Outer surface of the standard loses heat by convection

Time to equilibrate

- Time taken for the model of each standard to reach thermal equilibrium

Standard	Invar36	Aluminium
Hollow prismatic	2,900 s (≈50 minutes)	180 s (3 minutes)
Hollow cylinders	10,500 s (≈3 hours)	710 s (≈12 minutes)
Hollow squares	7,700 s (≈2 hours)	520 s (≈9 minutes)

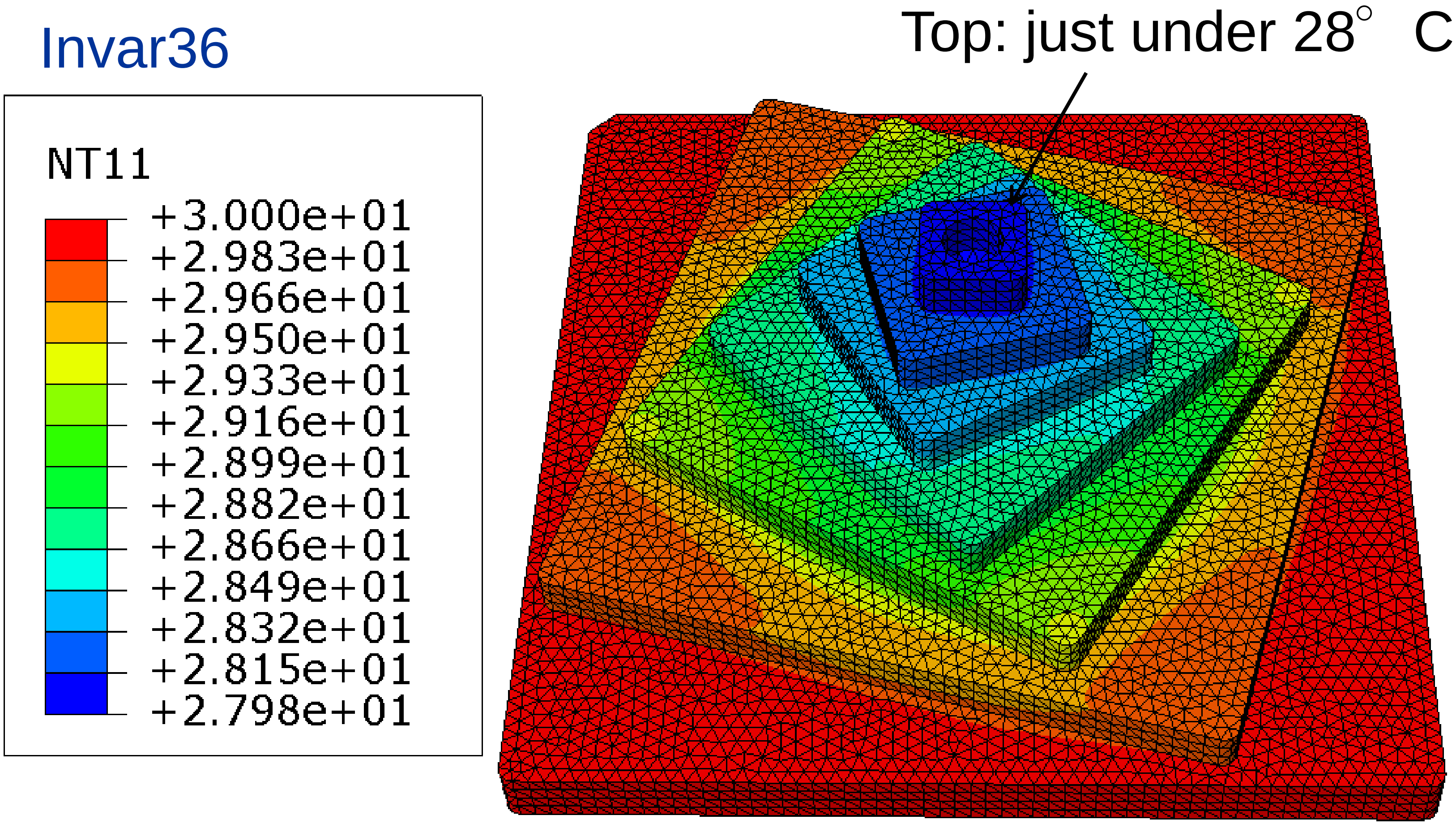
Time to equilibrate

- Time taken for the model of each standard to reach thermal equilibrium

Standard	Invar36	Aluminium	Comparison
Hollow prismatic	2,900 s (≈50 minutes)	180 s (3 minutes)	16.1
Hollow cylinders	10,500 s (≈3 hours)	710 s (≈12 minutes)	14.8
Hollow squares	7,700 s (≈2 hours)	520 s (≈9 minutes)	14.5

Temperature distribution

- Invar36



Temperature distribution

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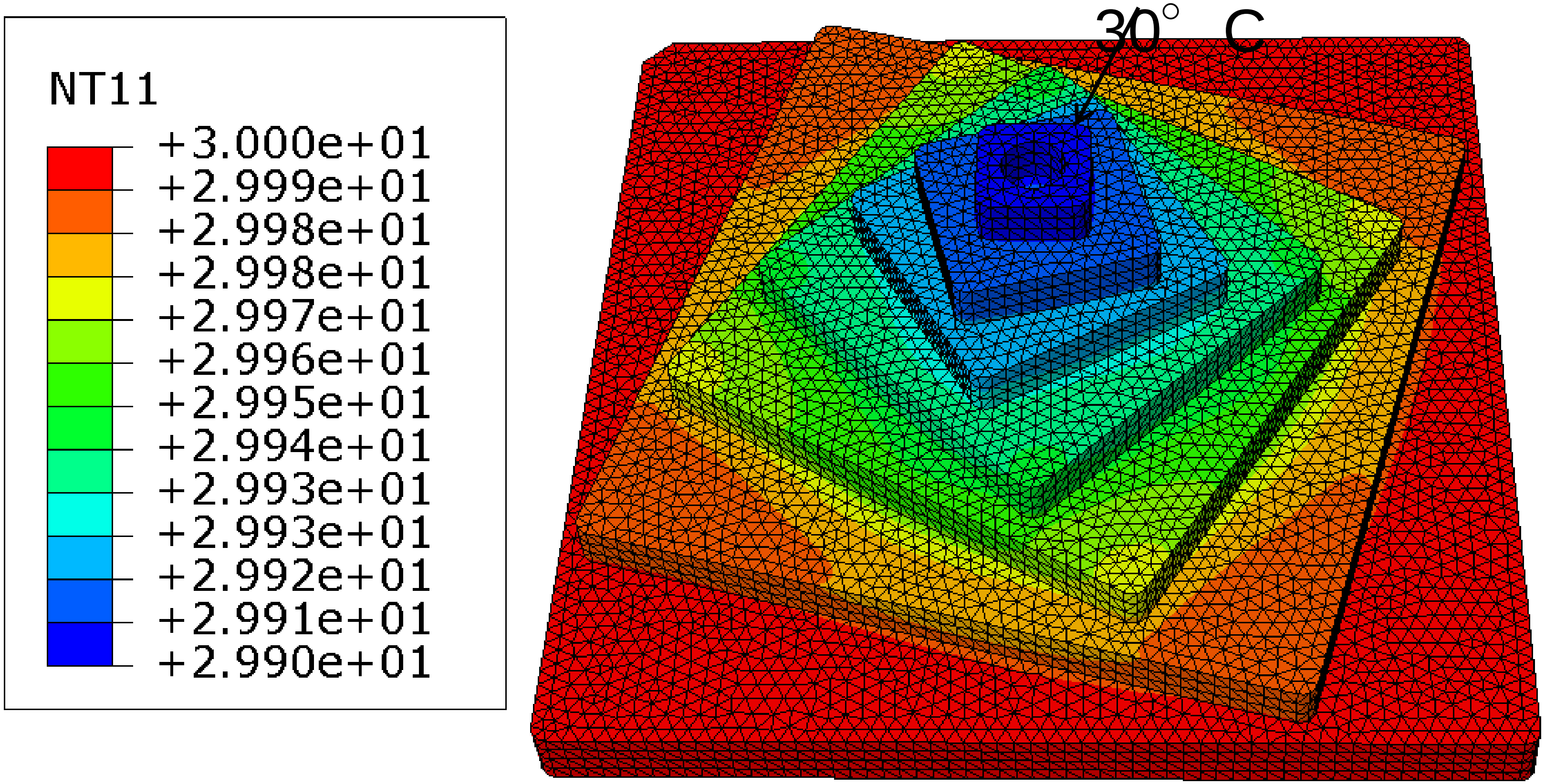
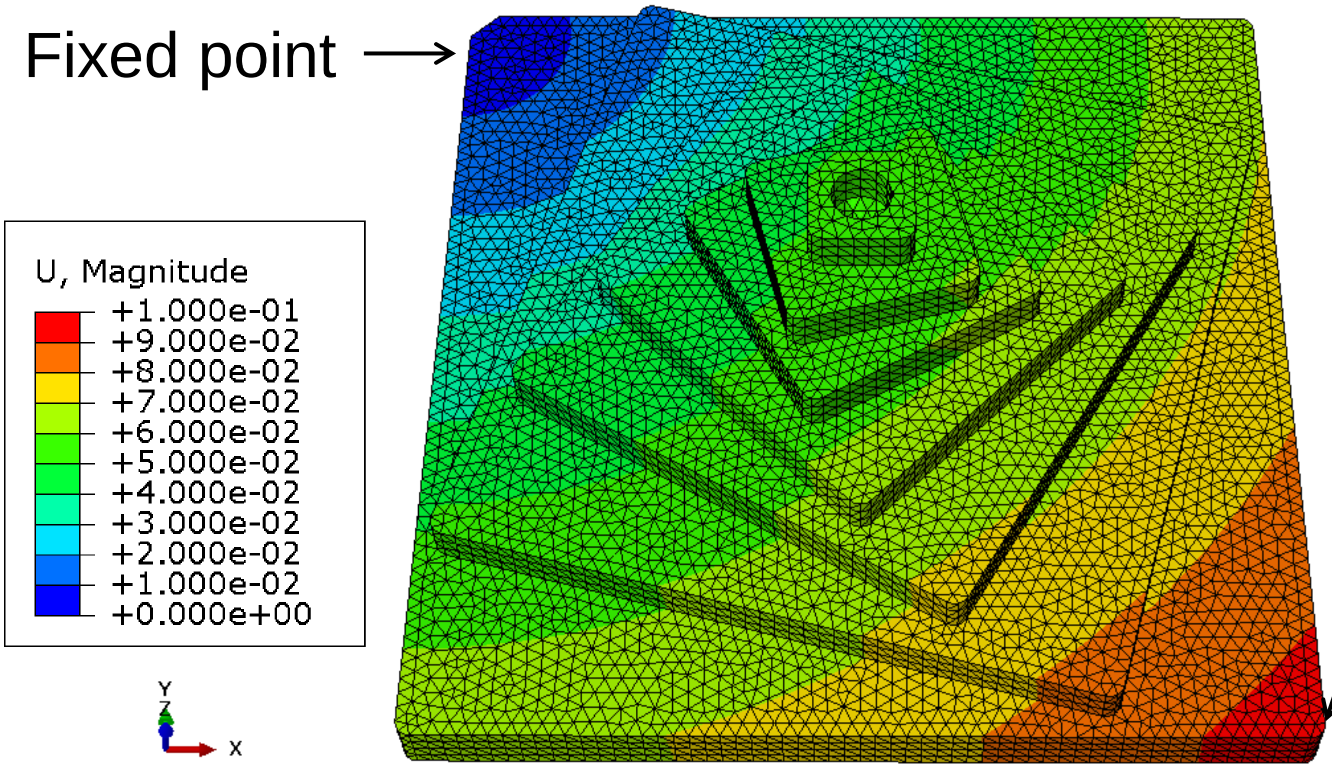
- Aluminium



Typical deformation

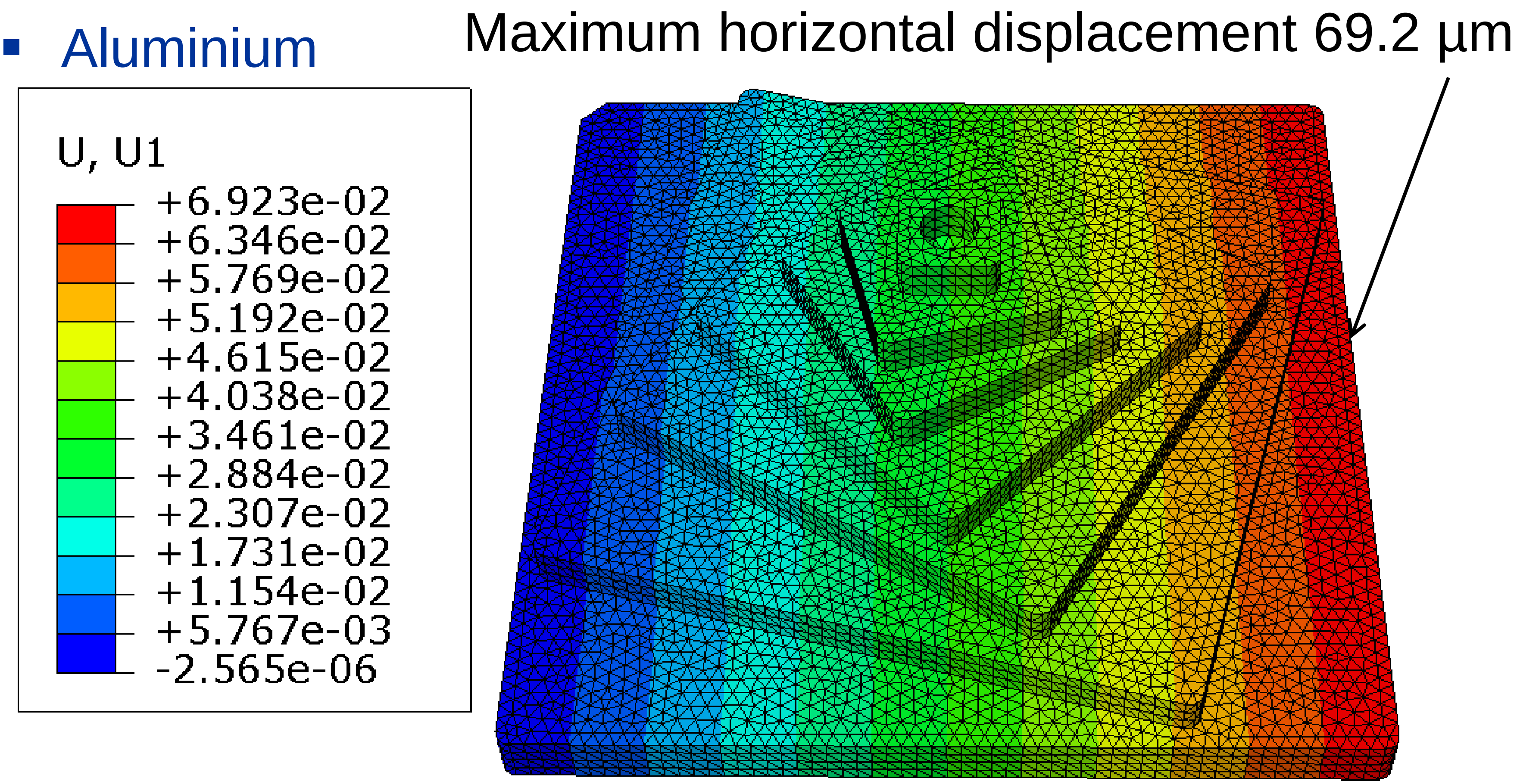
Fixed point



Maximum displacement 96 µm

Horizontal deformation

- Aluminium



Horizontal displacement

- Maximum predicted horizontal expansion of the standards when the base temperature is increased by 10° C, µm

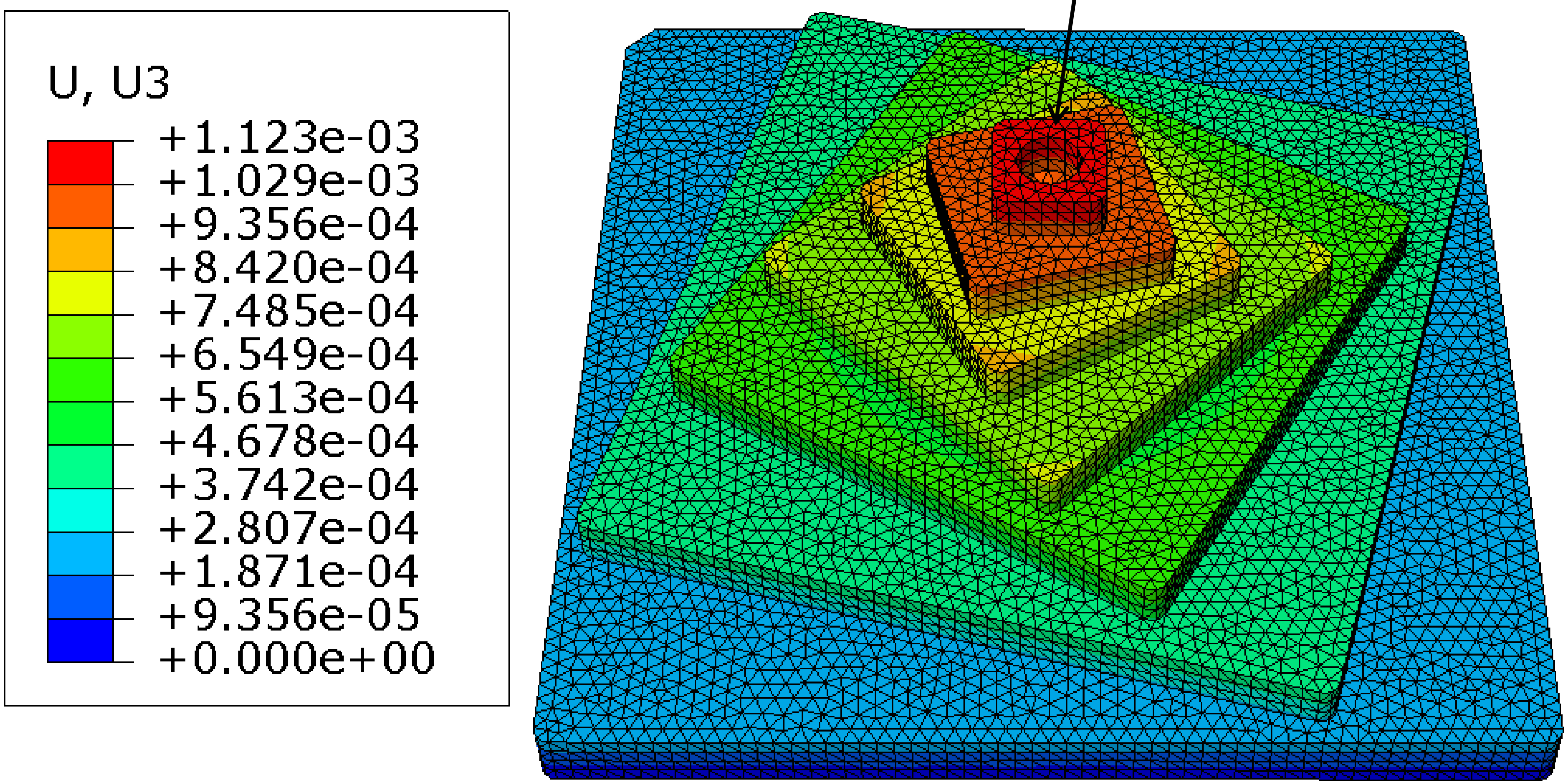
Standard	Invar36	Aluminium
Hollow prismatic	2.57	46.2
Hollow cylinders	3.77	69.2
Hollow squares	3.81	69.2

- The aluminium standard is predicted to expand horizontally about 18 times more than the Invar36

Vertical displacement

Maximum displacement 1.12 µm

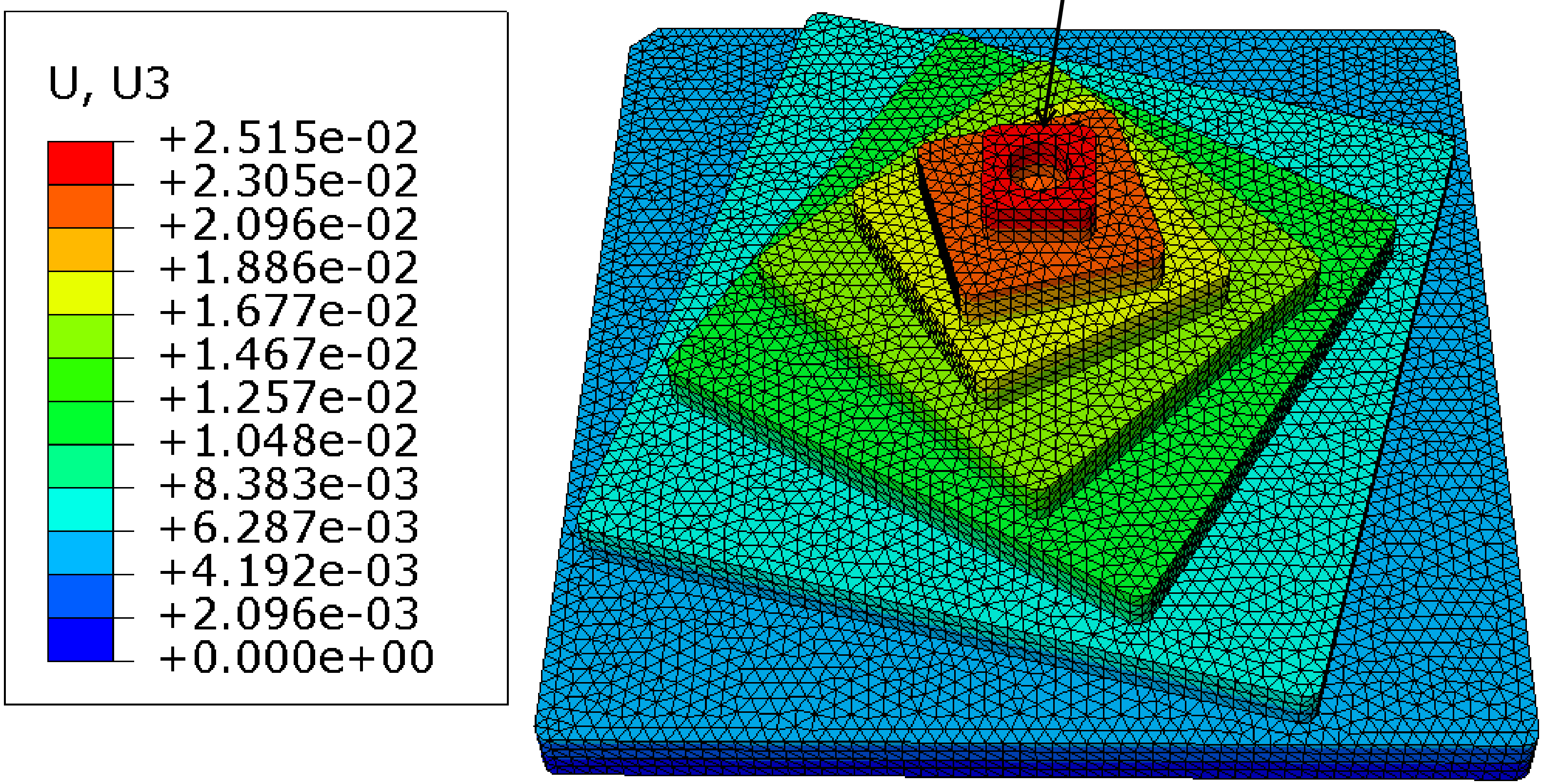
- Invar36



Vertical displacement

Maximum displacement 25.1 µm

- Aluminium



Vertical displacement

- Maximum predicted vertical expansion of the standards when the base temperature is increased by 10° C, µm

Standard	Invar36	Aluminium
Hollow prismatic	0.82	15.0
Hollow cylinders	1.01	25.0
Hollow squares	1.12	25.1

- The aluminium standard is predicted to expand vertically between 18 and 25 times more than the Invar36

Standard stability

The modelling predicts that:

- The aluminium standards reach thermal equilibrium faster than the Invar36 standards – the Invar36 takes about 15 or 16 times longer time to equilibrate
- The Invar36 standards have better dimensional stability under temperature change than the standards made from aluminium - the aluminium standard is predicted to expand about 18 times more than the Invar36

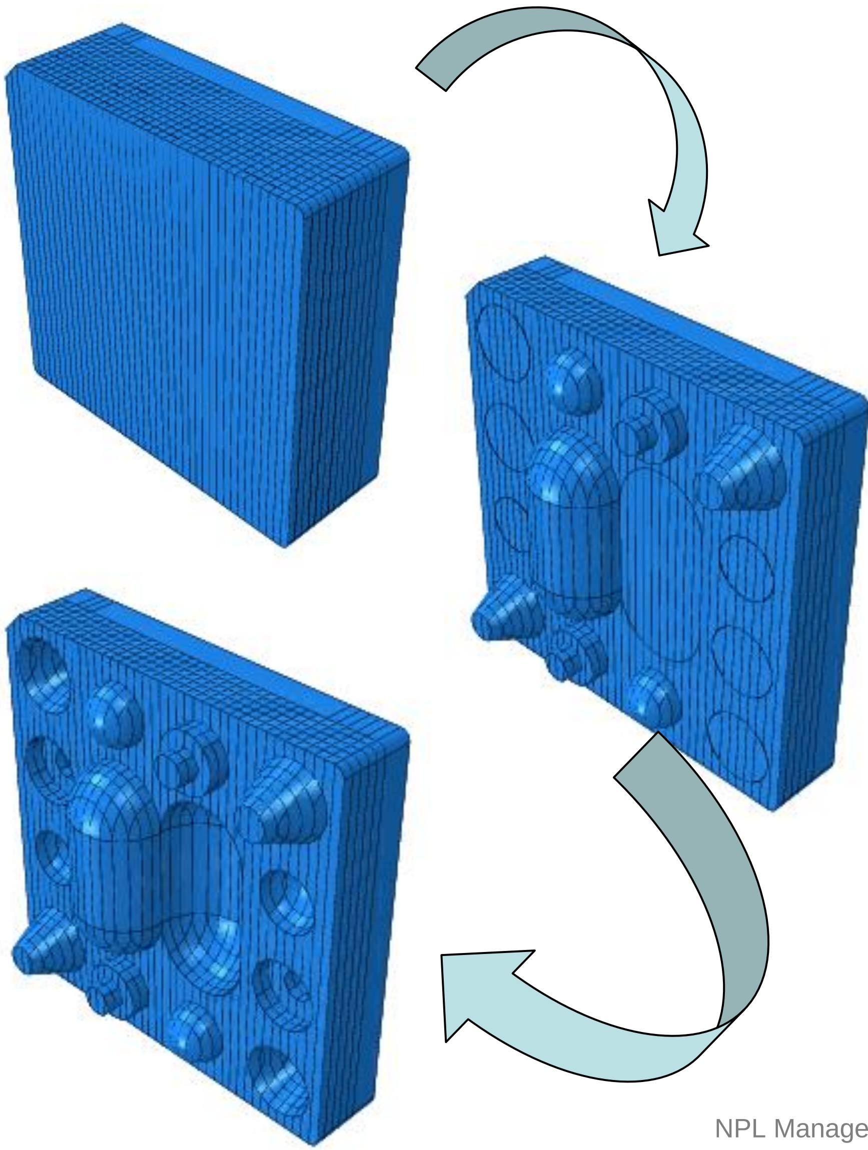
Part 2: The milling model

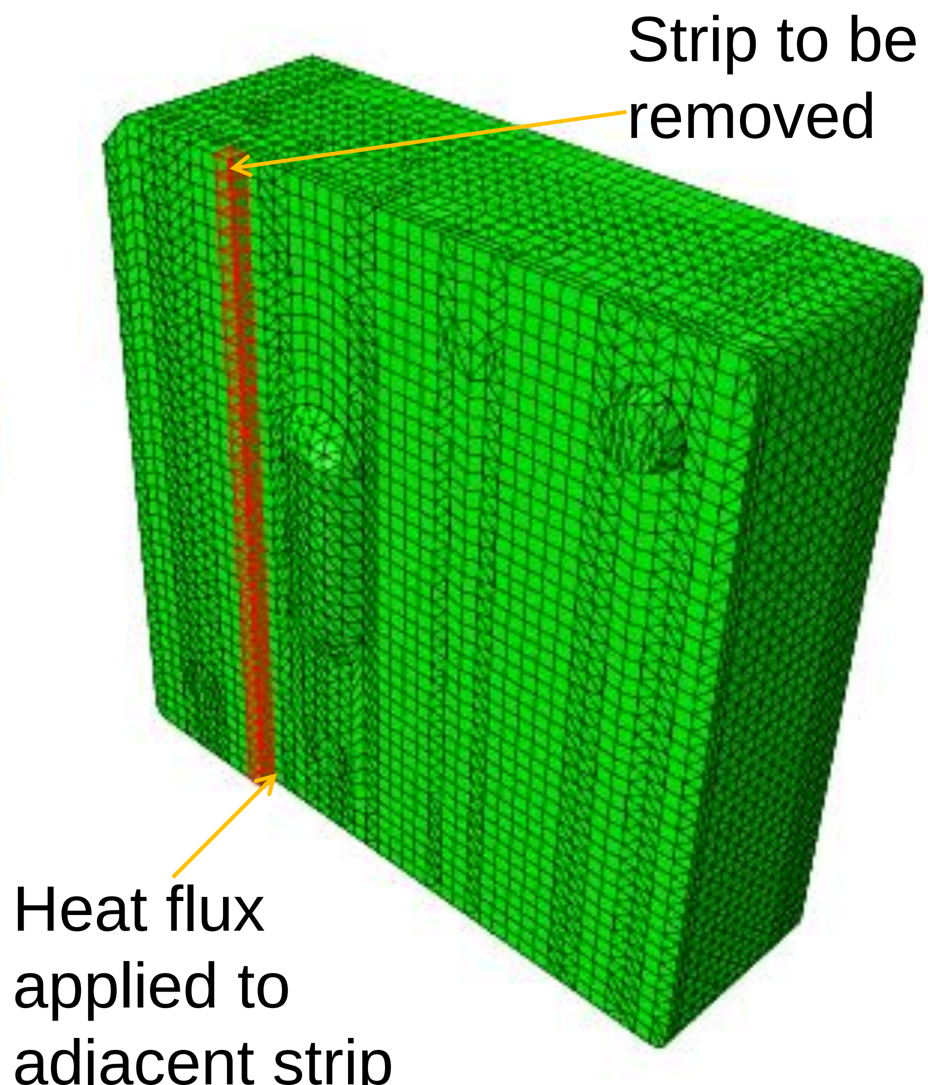
- Work in progress: not complete
- Predicts temperature distribution due to localised heating
- Gives an indication of distortion levels
- Does not predict shape that will be produced when block deforms due to local heating
  - Potential next stage in work: much more complicated (see later)

Manufacturing & modelling

- Standards are created by milling strips of decreasing size from a solid block
  - Model removes a series of strips 5 mm wide by 5 mm deep: this is the initial milling strip size
- Material removal creates localised heating, so a fluid wash is used to cool the standard during milling
  - Model assumes that the combination of heating & fluid create a 2.5 °C temperature rise on newly-exposed surfaces, imposed via fixed heat flux
  - Older surfaces lose heat by convection

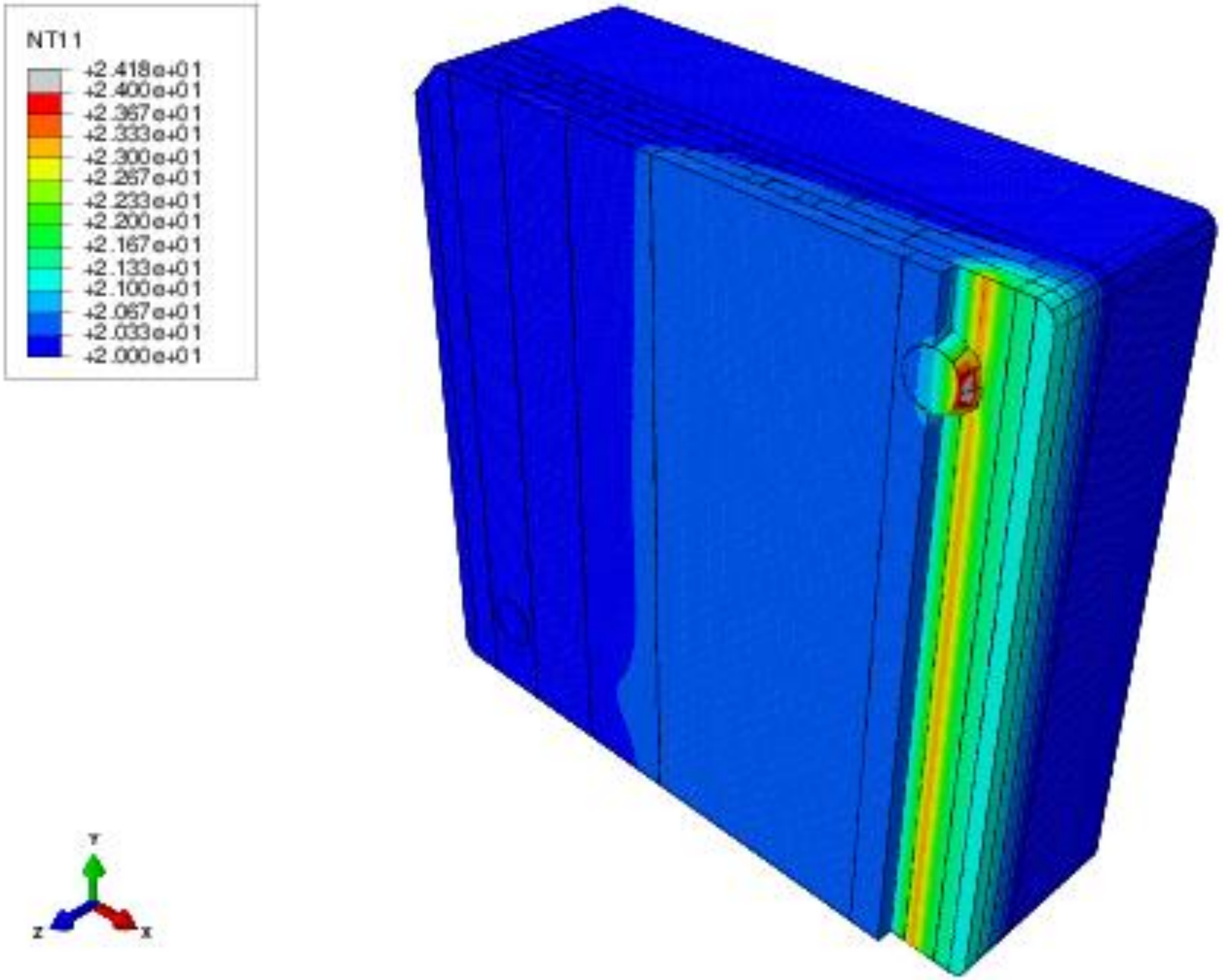
Illustrative sketch





Milling Invar36

Temperature distribution after removing the first 45 strips



Region at a temperature above ambient does not go very far into the material.

Maximum temperature is just over 24 degrees.

Milling Aluminium

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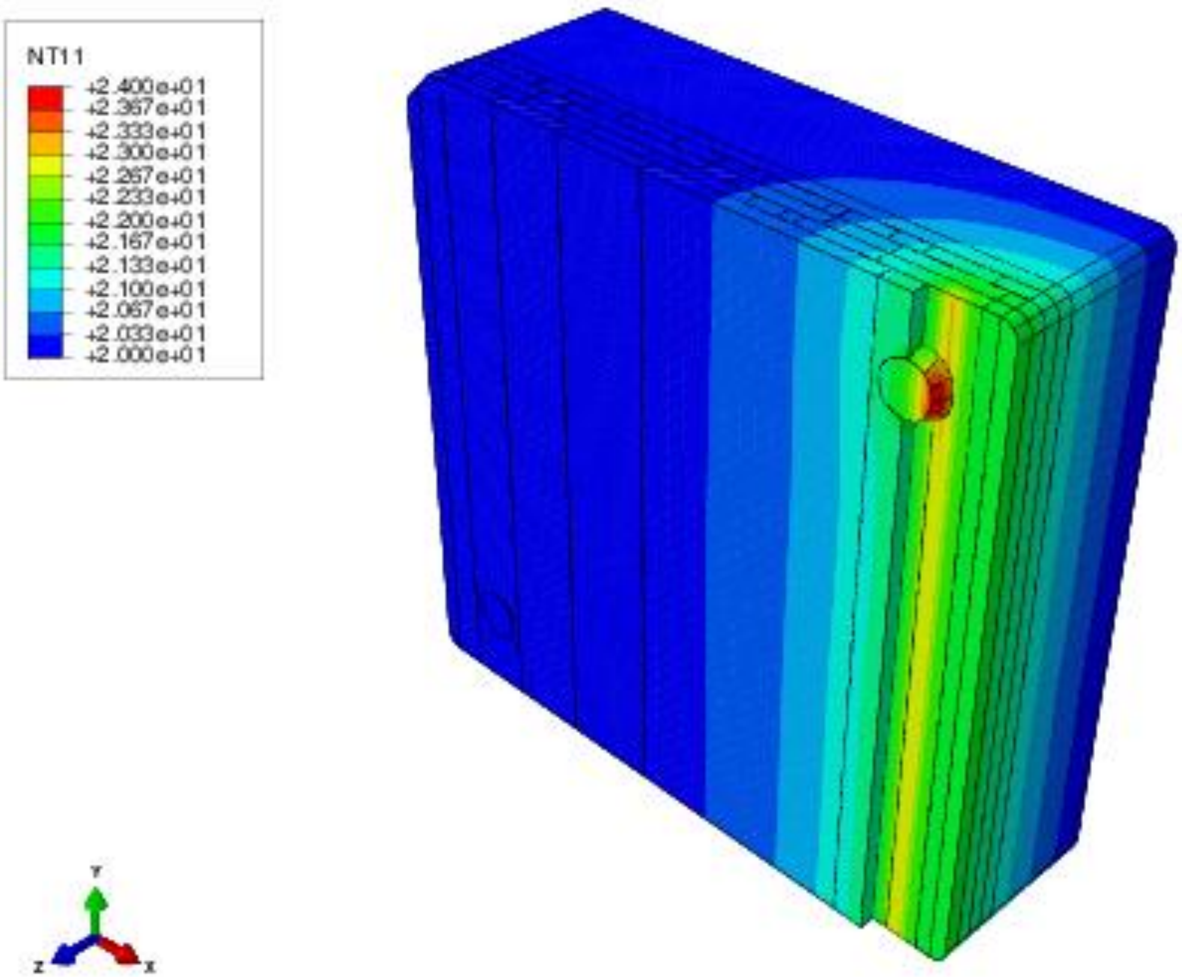
Temperature distribution after removing the first 45 strips



Region at a temperature above ambient goes much further into the material.

Maximum temperature is just under 24 degrees.

Invar36 vs Aluminium

- Heat diffuses into the aluminium more quickly than it does into the Invar36.
- Main block being milled reaches higher temperatures.
- Higher temperatures plus higher coefficient of thermal expansion = more distortion = larger errors

	Invar36	Aluminium
Thermal expansion coefficient	1.3×10^{-6}	23.1×10^{-6}

Next stage

- Next stage would be to consider the effects of deformation on the milling process
  - Simulate deformation during single strip removal
  - Use the deformation to generate an updated geometry from which the next strip will be removed
  - Remove the next strip from the deformed shape
  - End up with prediction of milled shape
- Could be automated, but will be challenging and computationally expensive.

Conclusions

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- Aluminium standards equilibrate much sooner than Invar36 standards
- Invar36 standards expand or contract very little compared to the aluminium standards
  - Choice of materials is important
- Milling model suggests that the energy put into the material diffuses more quickly in aluminium than in Invar36
- Increased speed of diffusion combined with increased thermal expansion coefficient means that aluminium will experience much larger errors during milling
- Improved milling model is possible but challenging