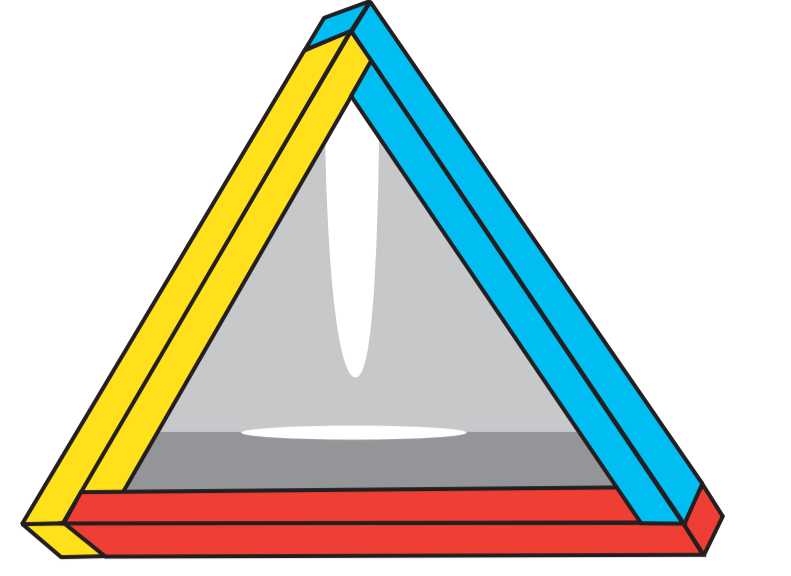




Detection of localised superelastic deformation in shape memory alloys during indentation

A J Muir Wood^a, J-H You^b, S Sanjabi^c & T W Clyne^a



a: Department of Materials Science and Metallurgy, Pembroke Street, Cambridge CB2 3QZ, UK

b: Max-Planck-Institut für Plasmaphysik, Boltzmannstraße 2, D-85748 Garching, Germany

c: Department of Materials Science and Engineering, Sharif University of Technology, P.O. Box 11365-9466, Tehran, Iran

a: www.msm.cam.ac.uk/mmc/ **b:** www.ipp.mpg.de/eng/for/bereiche/material/ **c:** www.sharif.ir

Indentation of shape memory materials

Shape memory materials exhibit a martensitic transformation accompanied by thermal hysteresis (see Figure 1 - temperatures refer to the nickel-titanium alloy studied). Such materials can exhibit useful thermomechanical characteristics, including the shape memory effect and superelasticity. This work concerns identification of superelasticity by indentation.

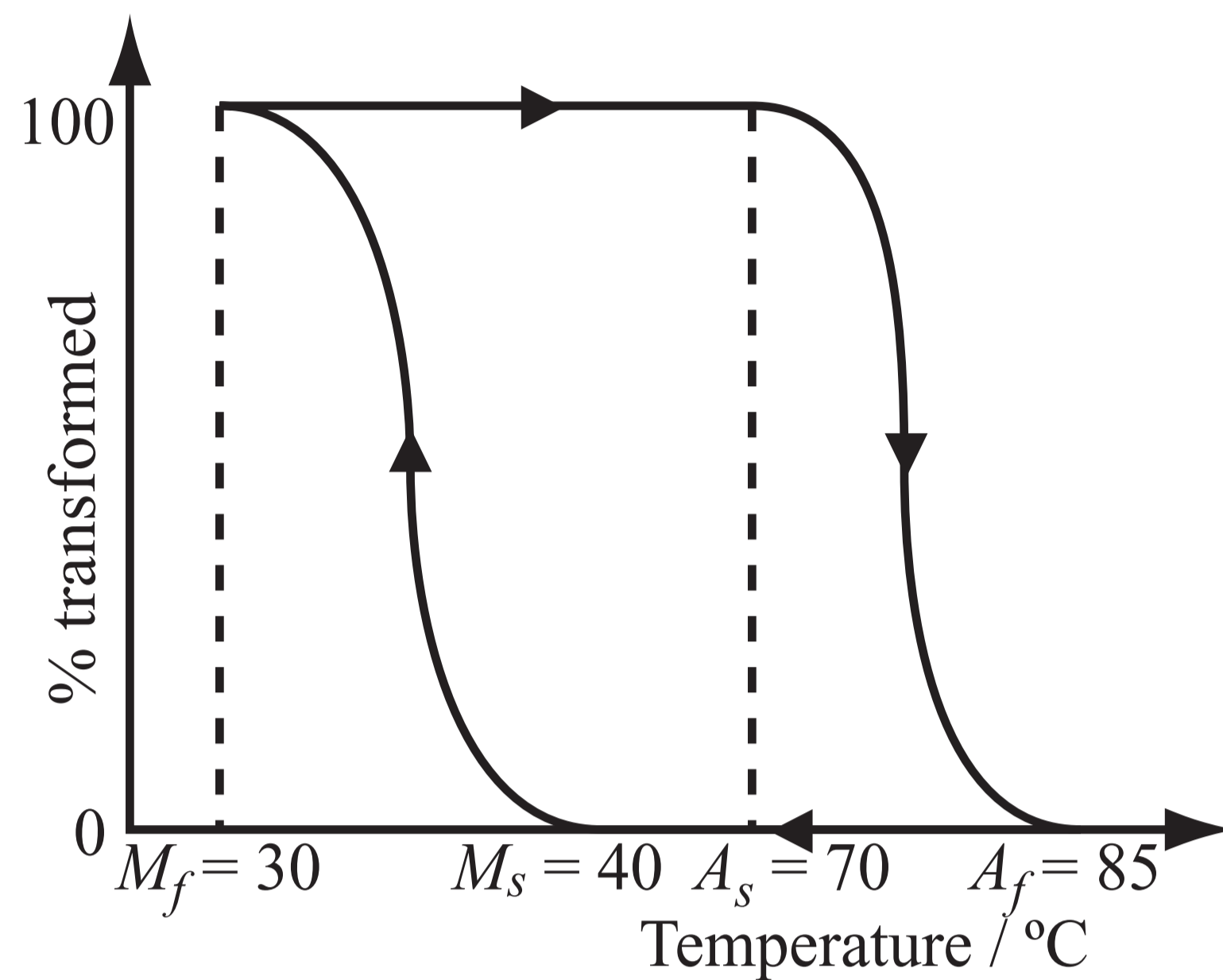


Figure 1: Martensitic hysteresis.

Indentation was performed with both spherical and Berkovich tips. A hot stage allowed high temperature indentation (see Figure 2).

Indentation of a nickel-titanium alloy with a Berkovich tip revealed little difference in the shape of the load displacement plot for the two states (see Figure 3a). Repeating with a spherical tip produced a marked difference (see Figure 3b). This is attributed to the lower peak strain levels present below the spherical tip.

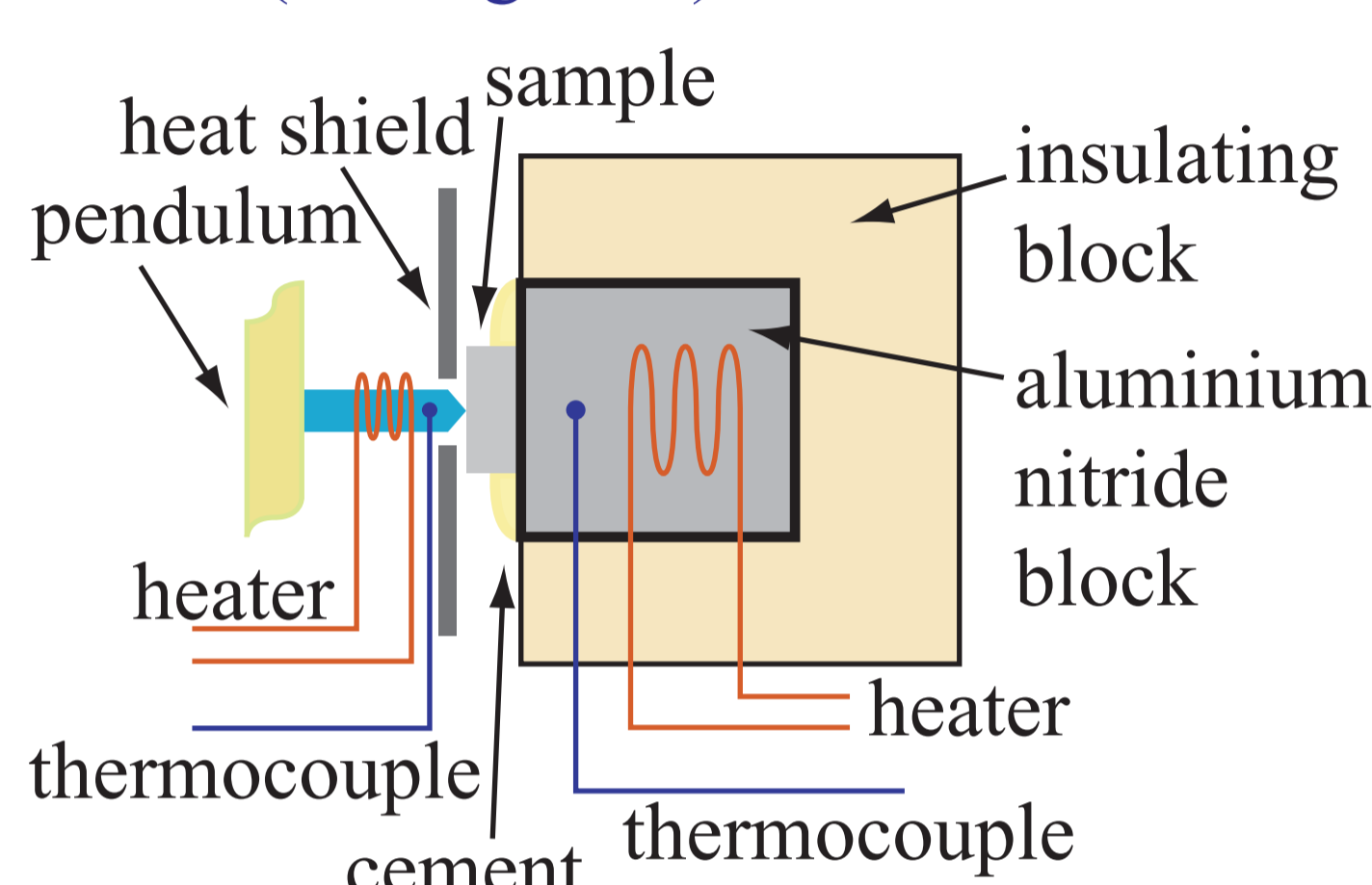


Figure 2: Schematic of the hot stage.

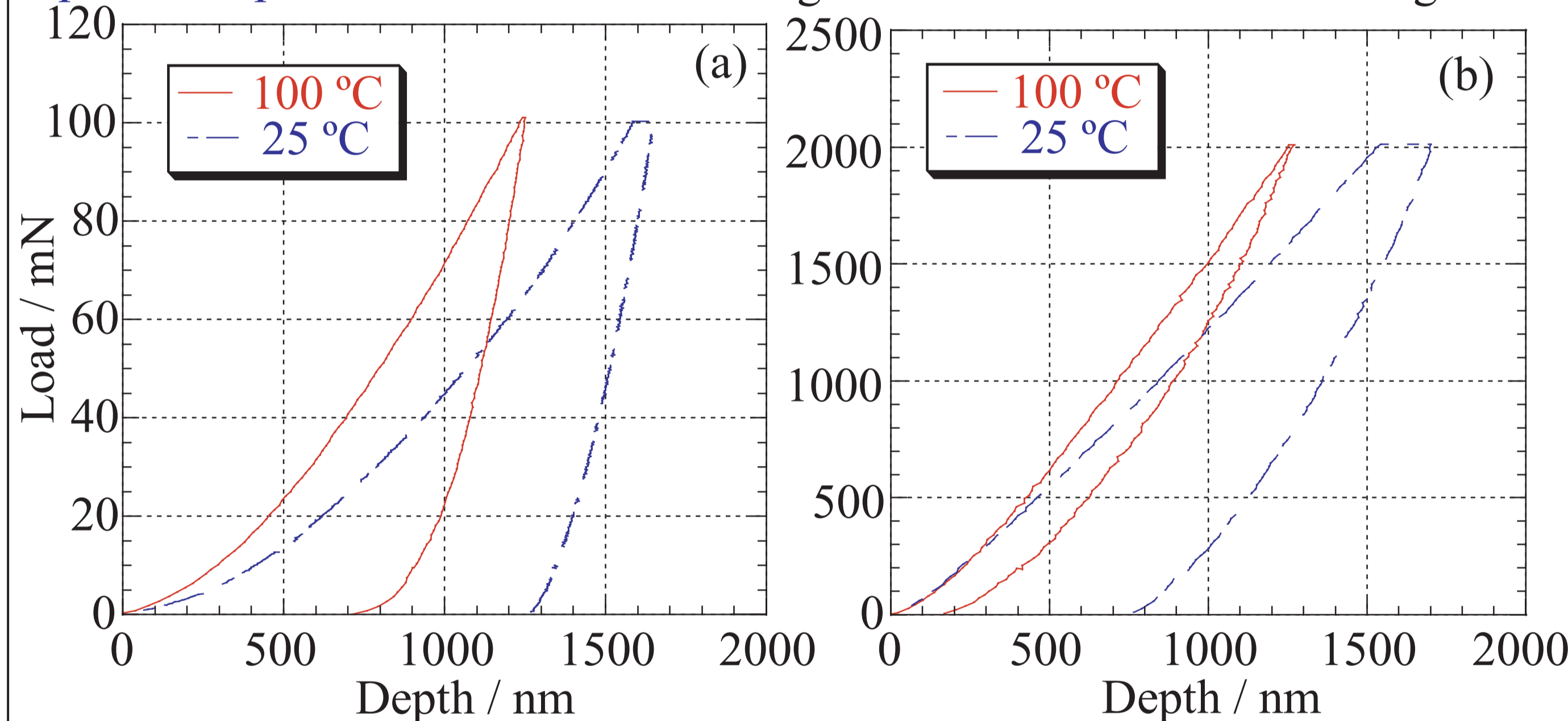


Figure 3: Indentation with a (a) Berkovich and (b) spherical ($r = 650 \mu\text{m}$) tip. On repeating this experiment with a small spherical tip, the difference was not so marked but still apparent (see Figure 4a). This is clarified by considering the remnant depth variation with temperature (see Figure 4b): at temperatures below A_f recovery of the indent is limited, while at temperatures above A_f the recovery, aided by superelasticity, is substantial. If temperature is increased further, recovery reverts to that observed below A_f as the superelastic effect is overcome by standard slip processes.

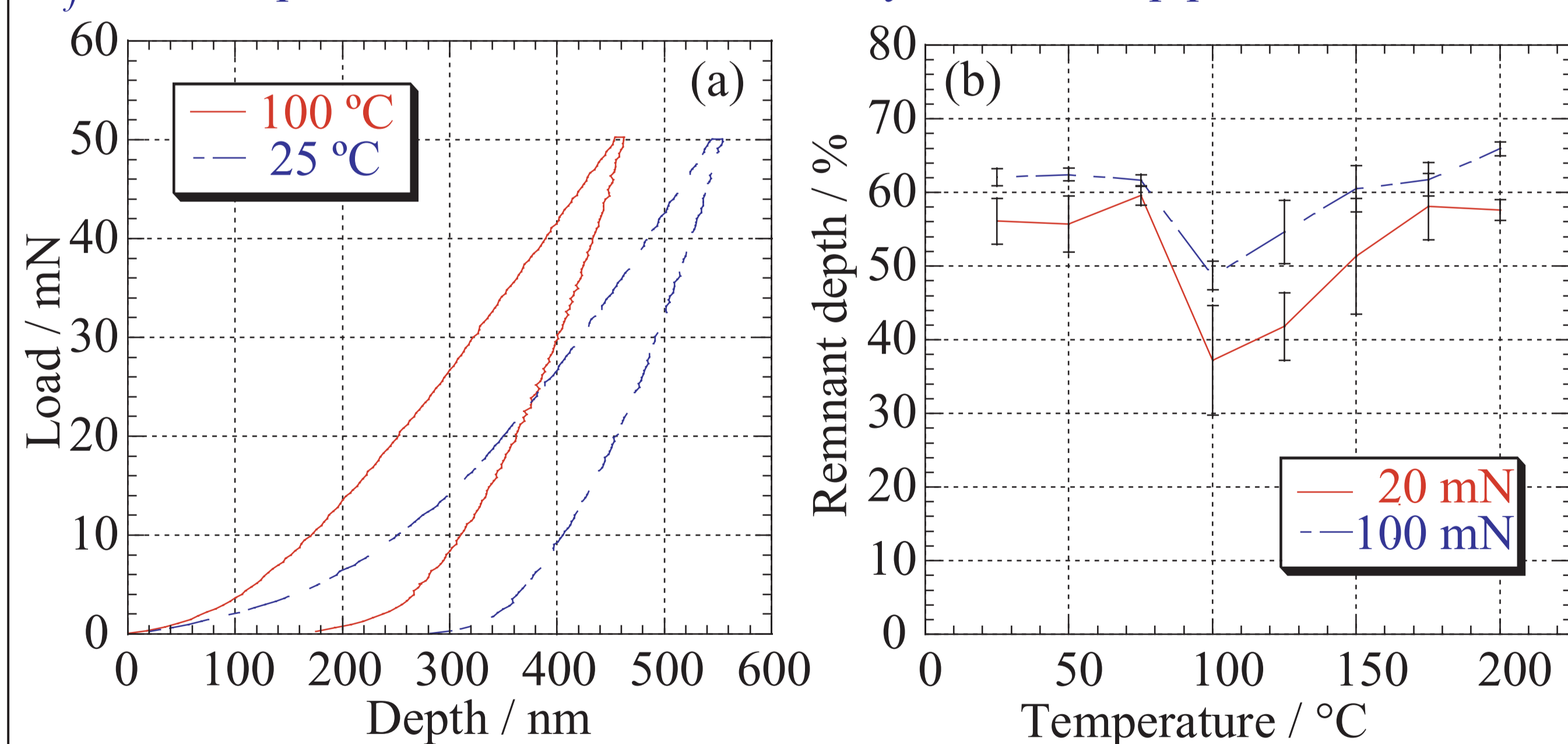


Figure 4: Spherical indentation demonstrating superelasticity ($r = 10 \mu\text{m}$); (a) indentation traces and (b) remnant depth versus temperature ($A_f \sim 80 \text{ °C}$).

Modelling

Modelling of the indentation process was undertaken using ABAQUS, with a special user superelastic subroutine, which showed better agreement in tension than in compression (see Figure 5). The results for this model are shown in Figure 6, with a higher peak strain clearly visible under a conical tip (see Figure 6b) than under an indenting sphere (see Figure 6a) for the martensitic phase. The maximum peak strain under the cone was 200 %.

The superelastic user subroutine limited modelling to the spherical indentation of the parent phase. Agreement with experiment was not good, with much higher recovery seen in the model (see Figure 6c) than in experiment. This is attributed to the limitations of the user subroutine: it seems likely that this fails to take both tensile-compressive asymmetry and the complex yield surface of shape memory alloys into account.

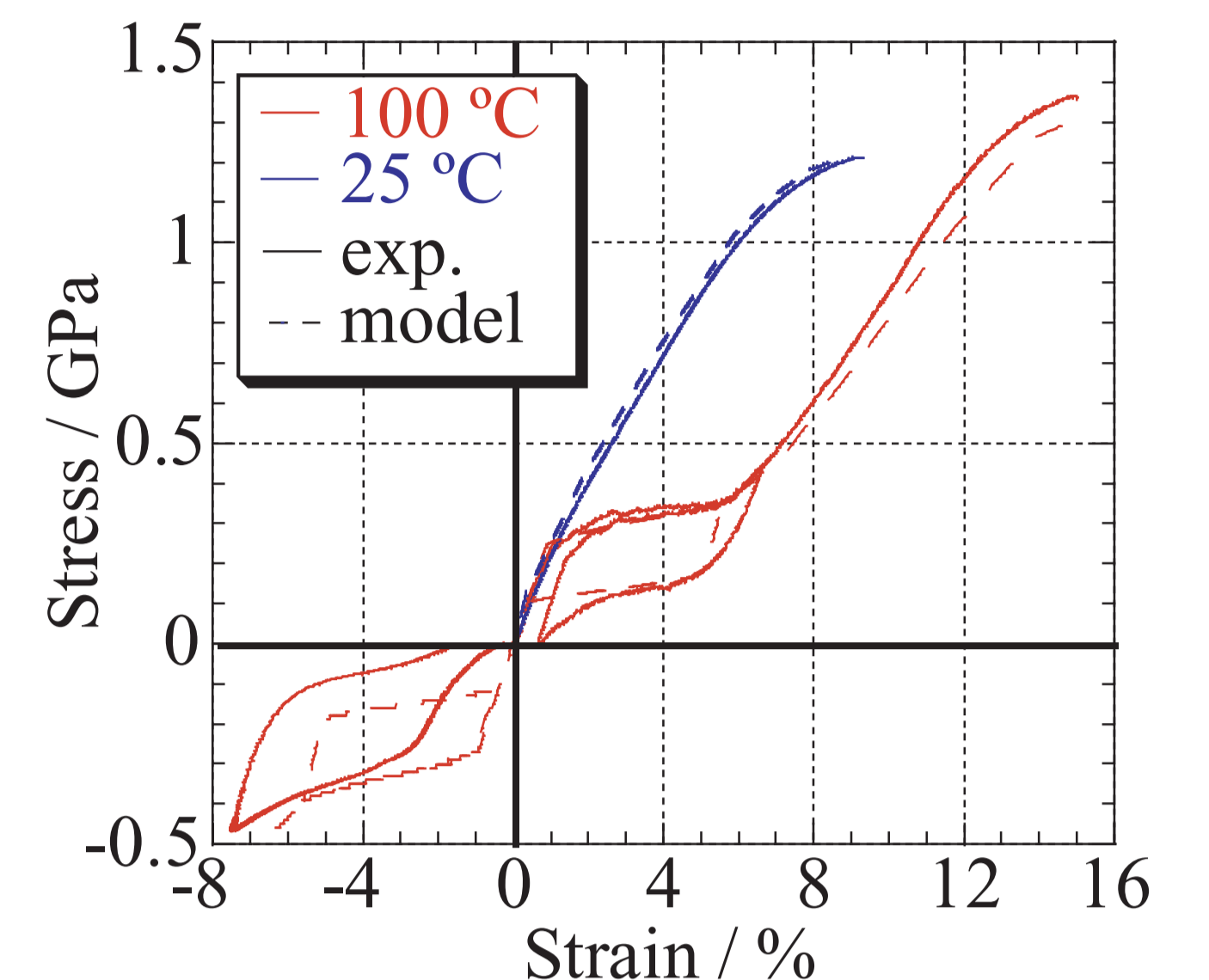


Figure 5: Experimental & modelling stress strain data for both phases.

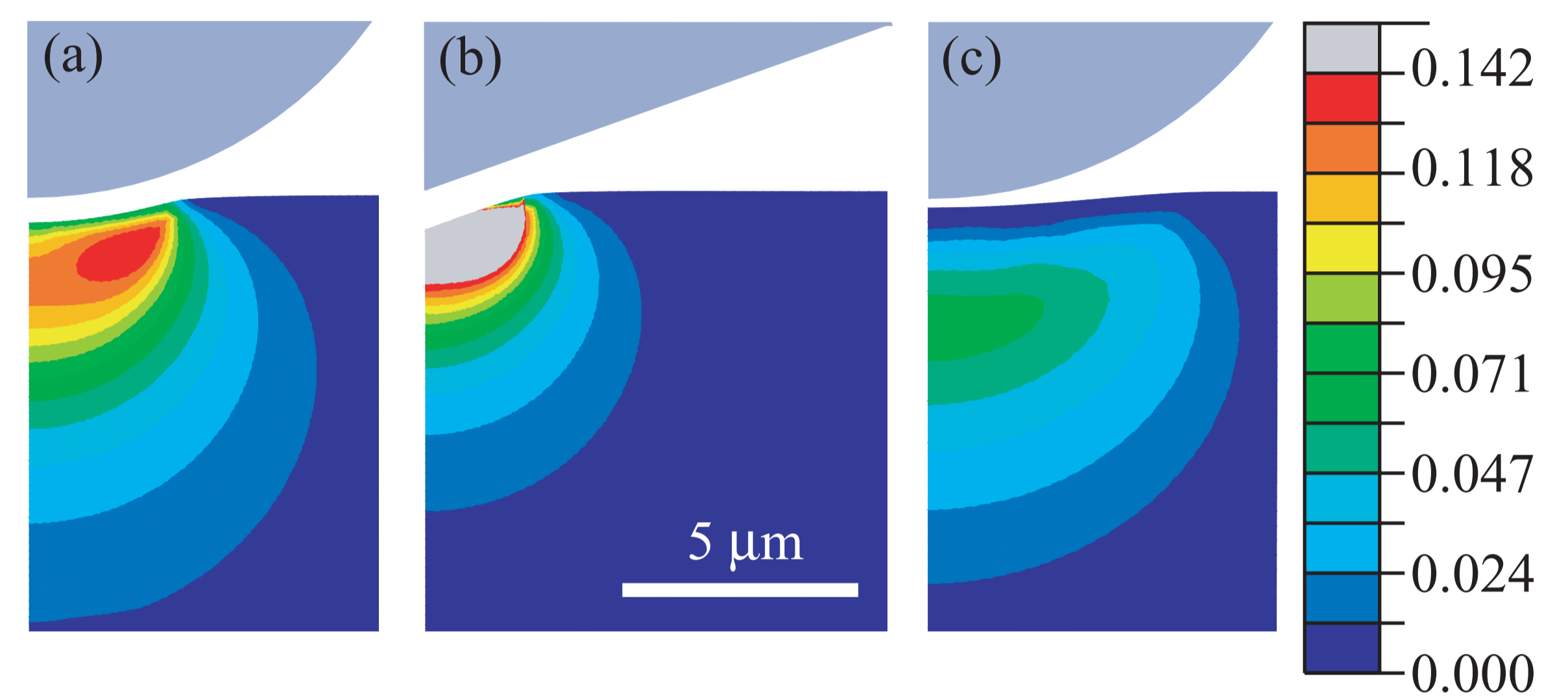


Figure 6: Equivalent plastic strain after indentation to $1 \mu\text{m}$ of martensite with (a) a sphere & (b) a cone and (c) of the parent phase with a sphere.

Thin films

Similar behaviour to that seen for the bulk alloys was seen for both binary and ternary thin films based on nickel-titanium (see Figure 7). A clear transition from martensite to parent phase was seen on indenting at temperatures increasing through their A_f temperatures. This effect was observable for hafnium contents of less than 20 at% and copper contents of less than 10 at%, suggesting that these are the concentration limits for superelasticity in these ternary alloys.

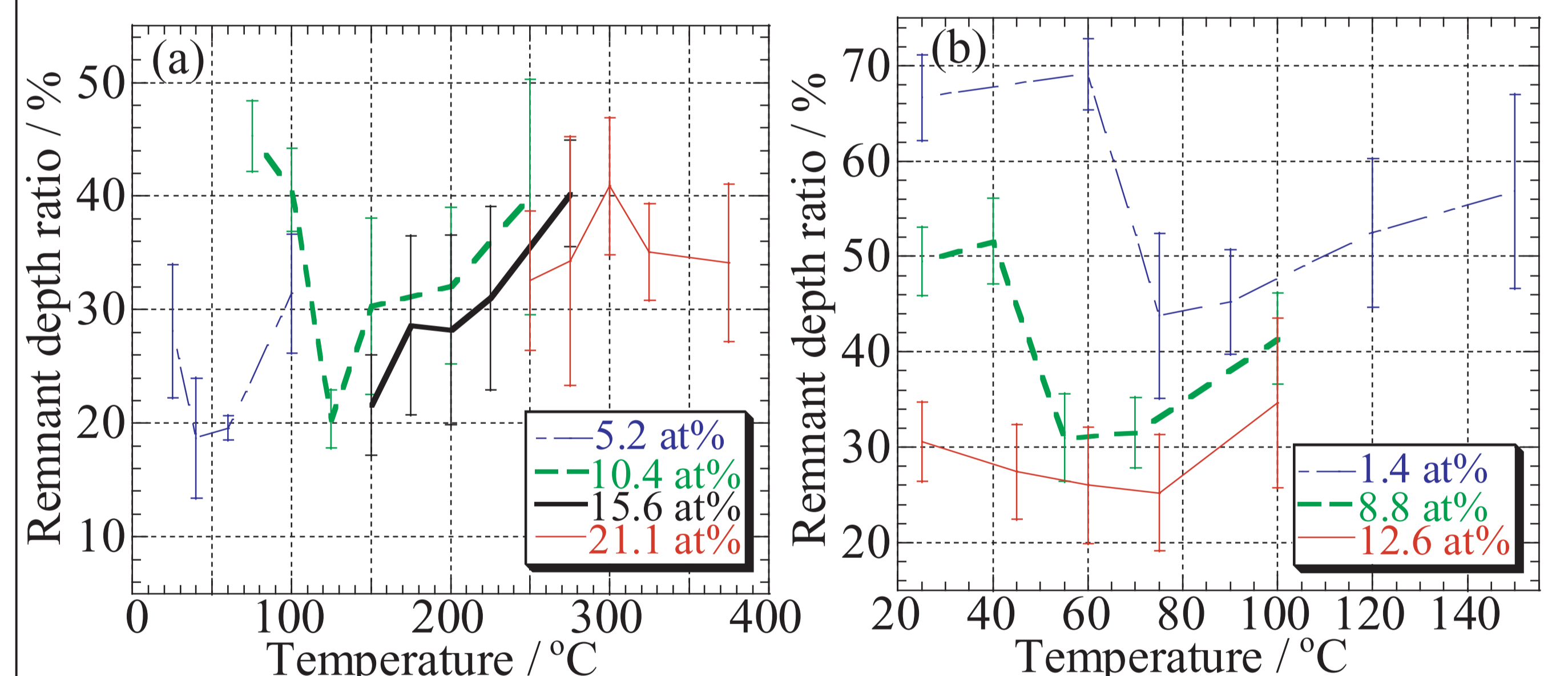


Figure 7: Remnant depth versus temperature for ternary nickel-titanium alloys containing varying concentrations of (a) hafnium and (b) copper.

Conclusions

- Superelastic behaviour cannot be detected using a Berkovich (sharp) tip
- When a spherical tip is used, it is possible to distinguish between superelastic and non-superelastic behaviour
- On indenting through a range of temperatures, the temperature A_f is identified by a sharp drop in the remnant depth ratio
- Modelling of the process supports the argument that this effect is the result of higher peak strains below a sharp tip, than those below a spherical tip
- The limit of superelasticity in thin film nickel-titanium-copper is shown to be 10 at%
- The limit of superelasticity in thin film nickel-titanium-hafnium is shown to be 20 at%

Acknowledgments

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