In-situ Analysis of the Microstrains During Tensile Deformation of an AlSi-MMC at Room Temperature and Elevated Temperature

A. PYZALLA[a,*], A. JACQUES[b], J.-P. FEIEREISEN[b], T. BUSLAPS[c], T. D'ALMEIDA[c] and K.-D. LISS[c]

[a]*Hahn-Meitner-Institut Berlin, Glienicker Strasse 100, D-14109 Berlin, Germany;* [b]*L.P.M. (UMR CNRS 7556), Ecole des Mines de Nancy, Parc de Saurupt, F-54042, Nancy, France;* [c]*European Synchrotron Radiation Facility (ESRF), BP 220, F-36043 Grenoble, France*

First results on the investigation of the tensile load stress–elastic strain response of an AlSi-metal matrix composites are presented. Measurements were performed at room temperature and *in-situ* at elevated temperature using white high-energy synchrotron radiation. The experiments show the evolution of the lattice plane dependent microstrains in the aluminium matrix and the silicon particles.

INTRODUCTION

Metal matrix composites (MMCs) are manufactured in order to combine the beneficial properties of their constituents. In aerospace and automotive

---

*Corresponding author. A. Pyzalla: TU Berlin, Institute for Materials Science and Technology, Sakr BH18, Ernst-Realer-Platz1, D-10587 Berlin, Germany

applications often MMCs with an aluminium matrix are employed. In manufacturing the aluminium alloy composites, hot extrusion processes are widely used. In those cases where the advantageous strength to weight ratio of advanced aluminium alloys has to be combined with the increasing demands on strength and wear resistance, interest focuses on extruded composites containing hard particles [1,2]. As reinforcement, silicon particles have the advantages of a low density and a low thermal expansion coefficient thus decreasing the overall expansion coefficient of the composite. For AlSi-composites with a silicon content as high as 25% a manufacturing route has been developed where a billet consisting of sintered powder is hot extruded [3,4]. During the hot extrusion, due to the differences in the mechanical properties of the matrix and the reinforcement, different loading states and thus microstresses are present in the aluminium matrix and the silicon particles, which affect the formability of the material. In order to determine the elastic strain and the load sharing between the aluminium matrix and the silicon particles at elevated temperature, *in-situ* tensile tests of AlSi-samples in a furnace with a loading device were performed using white beam synchrotron radiation [5,6]. The high photon flux at the sample position enables a recording of a diffraction spectrum with sufficient signal to background ratio within a few hundred seconds. Whereas *in-situ* stress analysis can be done in composites at ambient temperature using neutrons [7,8], at high temperature severe stress relaxation effects occur. Thus, at high temperatures the use of synchrotron radiation with its high flux and thus a short acquisition time is unavoidable.

EXPERIMENTAL DETAILS

Material

The microstructure of the aluminium matrix composite AlSi25Cu4Mg1 in the as-manufactured condition, after extrusion at 450°C [9], shows an homogeneous distribution of about 27 ± 1 vol% fine silicon particles in the aluminium matrix (Fig. 1). The diameter of the particles varies between 5 and 15 μm, approximately. The grain size of the aluminium matrix is ≈ 4 μm.

Experiment Set-up

The experiments were performed at the High Energy Beamline ID 15A of the European Synchrotron radiation facility (ESRF) in Grenoble, France. For the
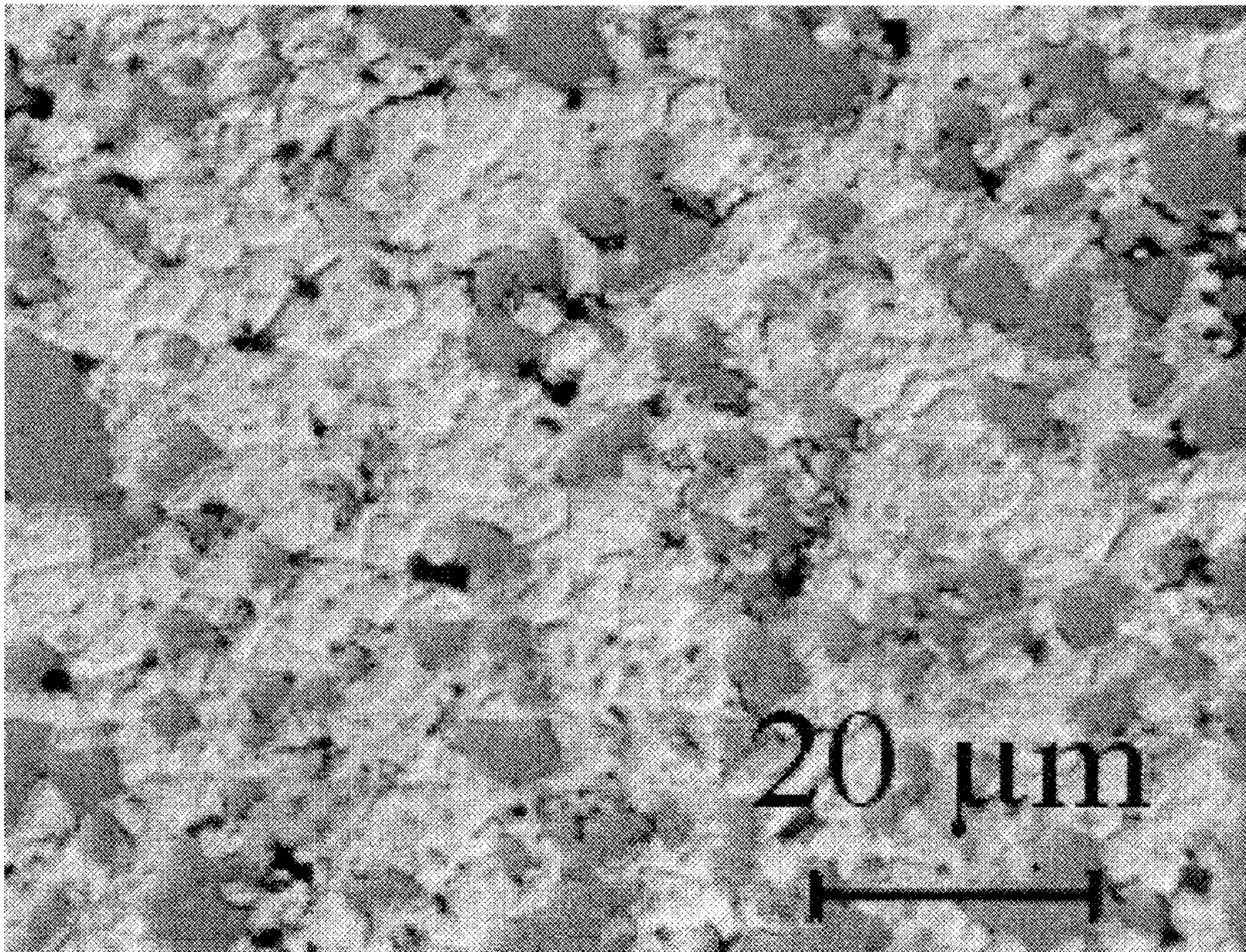
FIGURE 1   Microstructure of AlSi25Cu4Mg1.

experiments an energy-dispersive arrangement using the white beam was chosen. This set-up is described in detail in Ref. [5].

For the experiments a diffraction angle of $2\theta = 10°$ was chosen. In front of the sample a slit with variable horizontal and vertical gap as well as two slits with $60\,\mu$m horizontal gap and $10\,$mm vertical gap were inserted. In the diffracted beam two further slits with gaps of the same size $60\,\mu$m $\times 10\,$mm were placed. The first of these slits was directly attached to the surface of the furnace. The gauge volume was determined to be $70\,\mu$m wide and $1200\,\mu$m long, approximately. The gauge volume was centred in the sample using maximum integrated intensity values of translation scans. In order to increase the number of scattering grains the sample was oscillated $\pm 1°$ in Ω during the measurements. An energy-dispersive Ge-detector was calibrated in an energy range of $25-250\,$keV using the characteristic lines of a ^{133}Ba source.

Furnace With Integrated Tensile Test Device

The furnace allowing *in-situ* tensile tests (Fig. 2) up to $5\,$kN at elevated temperatures up to $1200°$ was developed at L.P.M. (Ecole des Mines Nancy).

The samples used have $4.4\,$mm in diameter, their overall length is $45\,$mm, the active length amounts to $25\,$mm. The sample is heated-up by two pairs of graphite resistors. The combined tensile test-heating device was set-up on the sample stage. The sample was installed horizontally, so that the longitudinal axis of the sample pointed in the direction of the scattering vector that is nearly
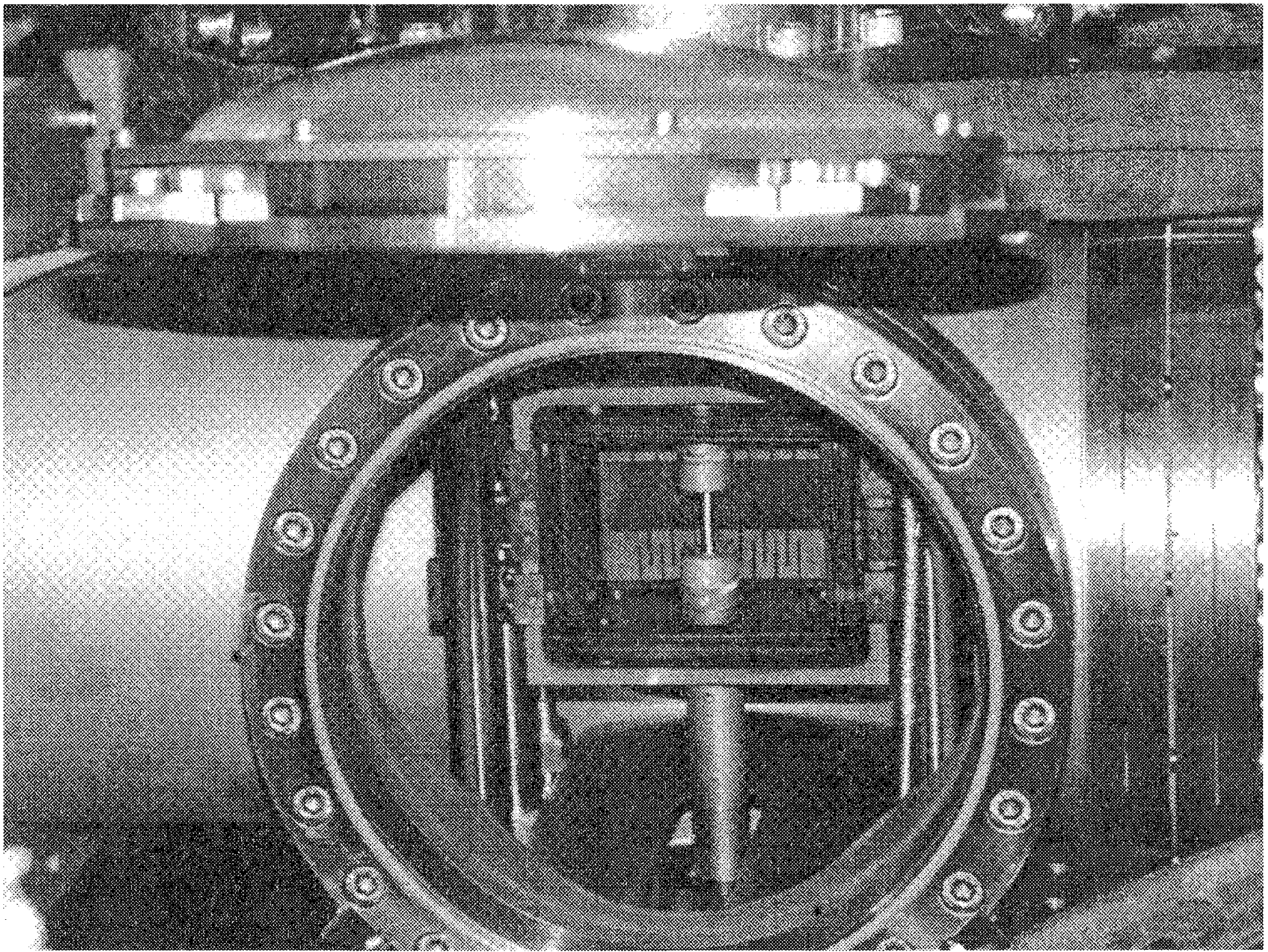
FIGURE 2   Furnace with integrated tensile test device.

perpendicular to the incoming beam. The samples were heated-up in vacuum. Their temperature during the tensile deformation at 250°C varied by approximately ±20 K.

Spectra were taken from the unloaded samples and after defined loading steps up to a maximum load stress of 150 MPa.

Data Evaluation

For all spectra a constant acquisition time of 300 s was used. From the energy dispersive spectra the line position, the integrated intensity and the full width at half maximum of the different reflections was obtained by fitting the reflection profile using a Gaussian distribution. The energy value E^{hkl} representing the line position corresponds to the lattice spacing d^{hkl} including the lattice strain.

The lattice spacing d^{hkl} can be calculated from the respective energy value according to Bragg's law

$$d^{hkl} = \frac{hc}{2\sin\theta}\frac{1}{E^{hkl}} = \text{constant} \quad \frac{1}{E^{hkl}} \tag{1}$$

with hkl denoting Miller's indices, θ is the Bragg angle, h is Planck's constant and c is the velocity of light.

The strain ε_i^{hkl} of the lattice plane hkl in the direction i of the sample can be determined using

$$\varepsilon_i^{hkl} = \frac{d_i^{hkl} - d_0^{hkl}}{d_0^{hkl}} = \frac{E_0^{hkl}}{E_i^{hkl}} - 1 \qquad (2)$$

For the determination of the strain-free lattice distance d_0^{hkl} of the silicon particles, powder was chemically extracted from the samples. A spectrum of the silicon powder was recorded at ambient and at elevated temperature.

RESULTS

A typical high energy synchrotron radiation spectrum of AlSi25Cu4Mg1 is shown in Fig. 3. Obviously in the energy range between 30 and 100 keV a number of reflections of the silicon particles and the aluminium matrix is accessible. The ratio between the intensity of the reflections and the background obtained justifies the short acquisition time of 300 s chosen for each spectrum.

Tensile Deformation At Ambient Temperature

The elastic strain–load stress-curve obtained for the silicon particles (Fig. 4) shows initially compressive residual strains which result from the cooling of the
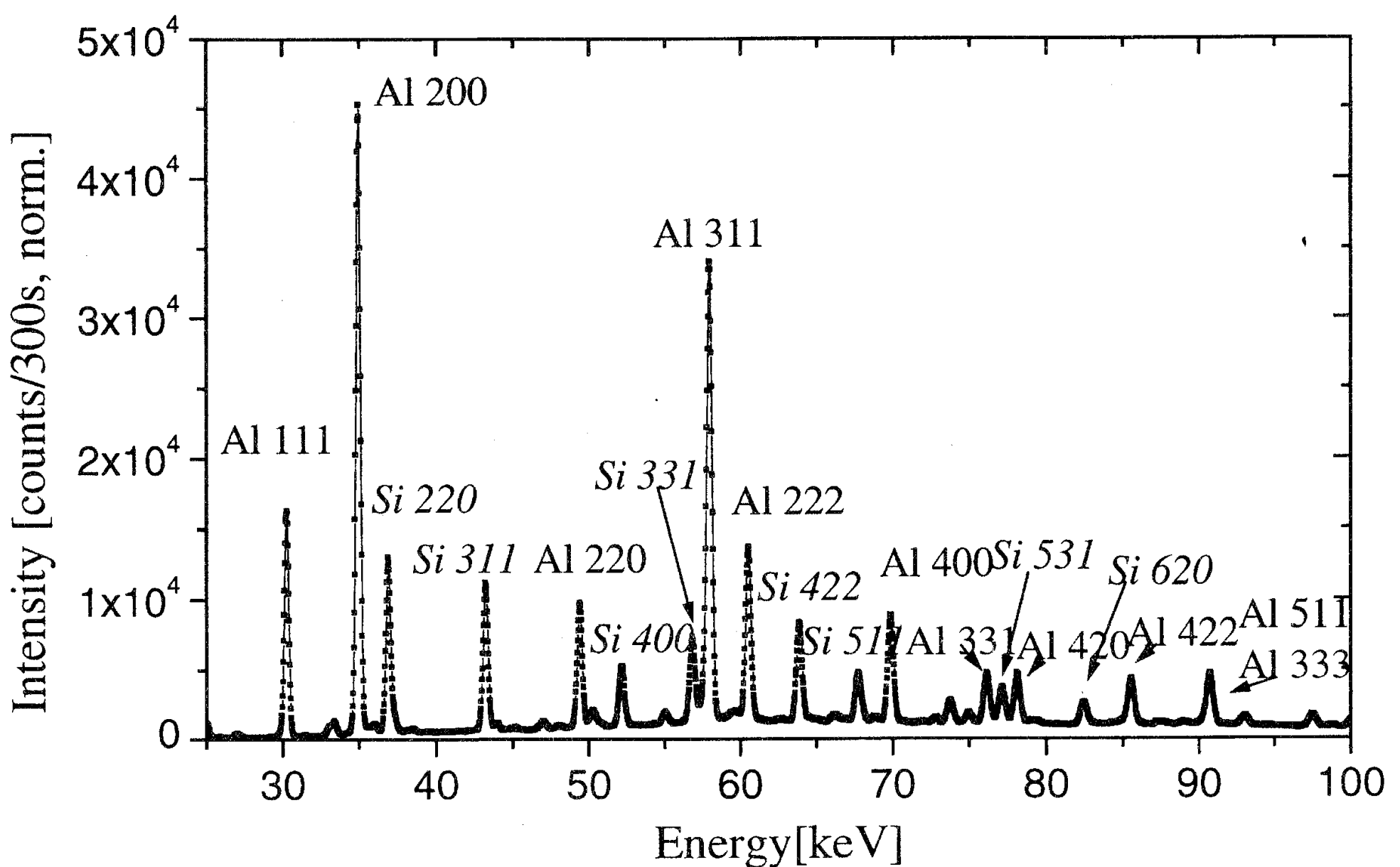

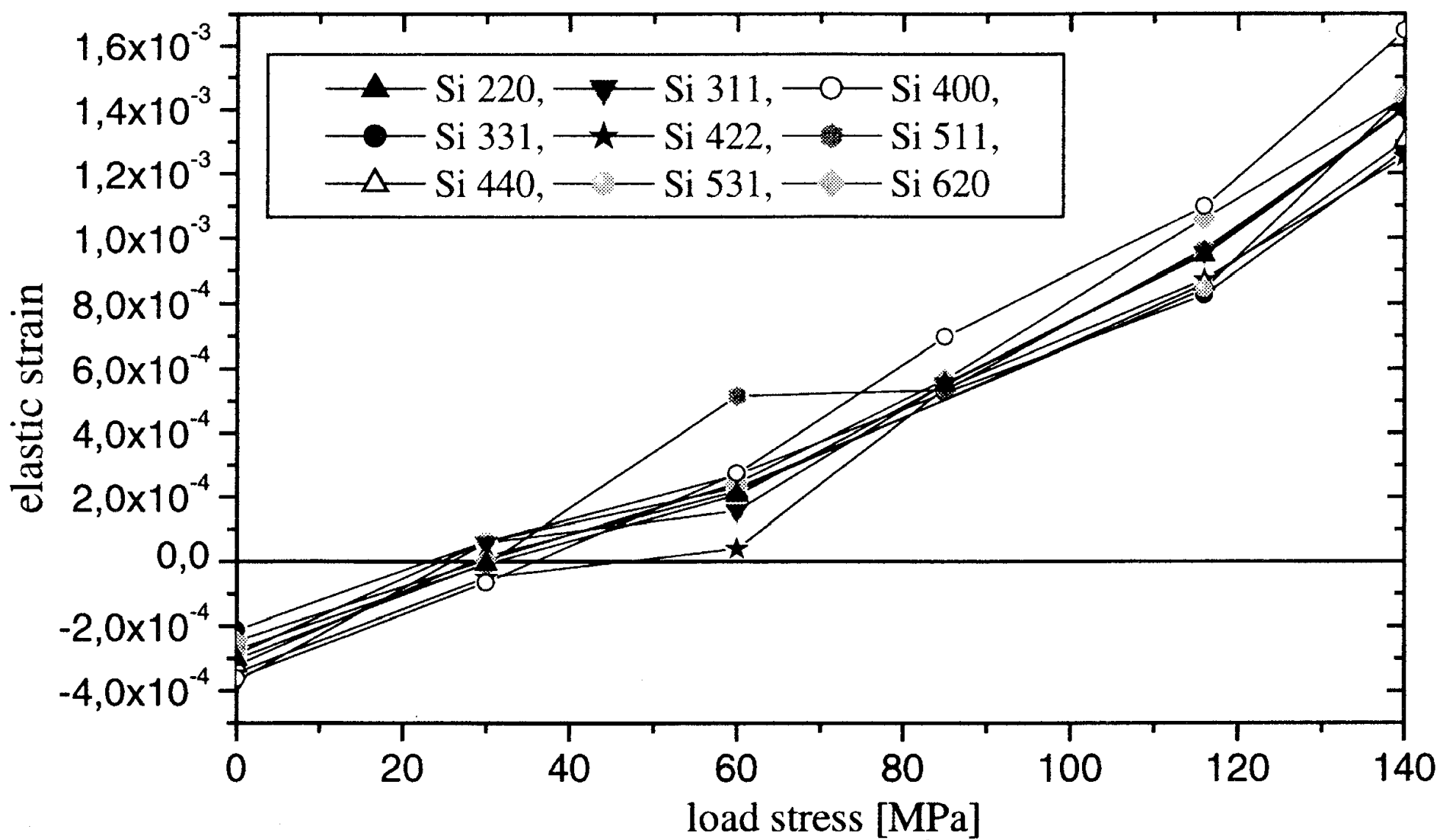FIGURE 3   Typical spectrum of AlSi25Cu4 Mg1, acquisition time 300 s.

FIGURE 4 Elastic strain of the Si-particles in dependence on the load stress, temperature RT, error margin $\pm 1 \times 10^{-4}$.

AlSi-alloy after the extrusion processes and the differences in the thermal expansion of the silicon particles and the aluminium matrix. During the tensile loading the elastic strain in the silicon particles changes to tensile values and increases steadily. This indicates that part of the load stress during the deformation is taken up by the silicon particles. The lattice plane dependence of the strains of the silicon particles compares well with the lattice plane dependence of the diffraction elastic constants of silicon.

In the initial state the aluminium matrix contains tensile residual strains balancing the compressive residual strains in the silicon particles (Fig. 5). With increasing tensile load the tensile strains in the aluminium matrix increase. This increase, within the limits of experimental accuracy, is steeper up to approximately 30–60 MPa, than for higher load stresses. The change in the slope of the curve indicates that plastic deformation in the matrix is initialised at low load stresses and might be attributed to strain inhomogeneities at the interface between the silicon particles and the aluminium matrix. For higher load strains a comparison between the elastic strain of the individual lattice planes reveals differences, which might be attributed to the onset of texture formation. This in future will be studied in further detail.

Tensile Deformation At 250°C

The lattice distances of the silicon powder and the silicon particles in the composite reveal that at 250°C, before loading, the silicon particles and thus also the matrix are strain-free within the limits of experimental accuracy.
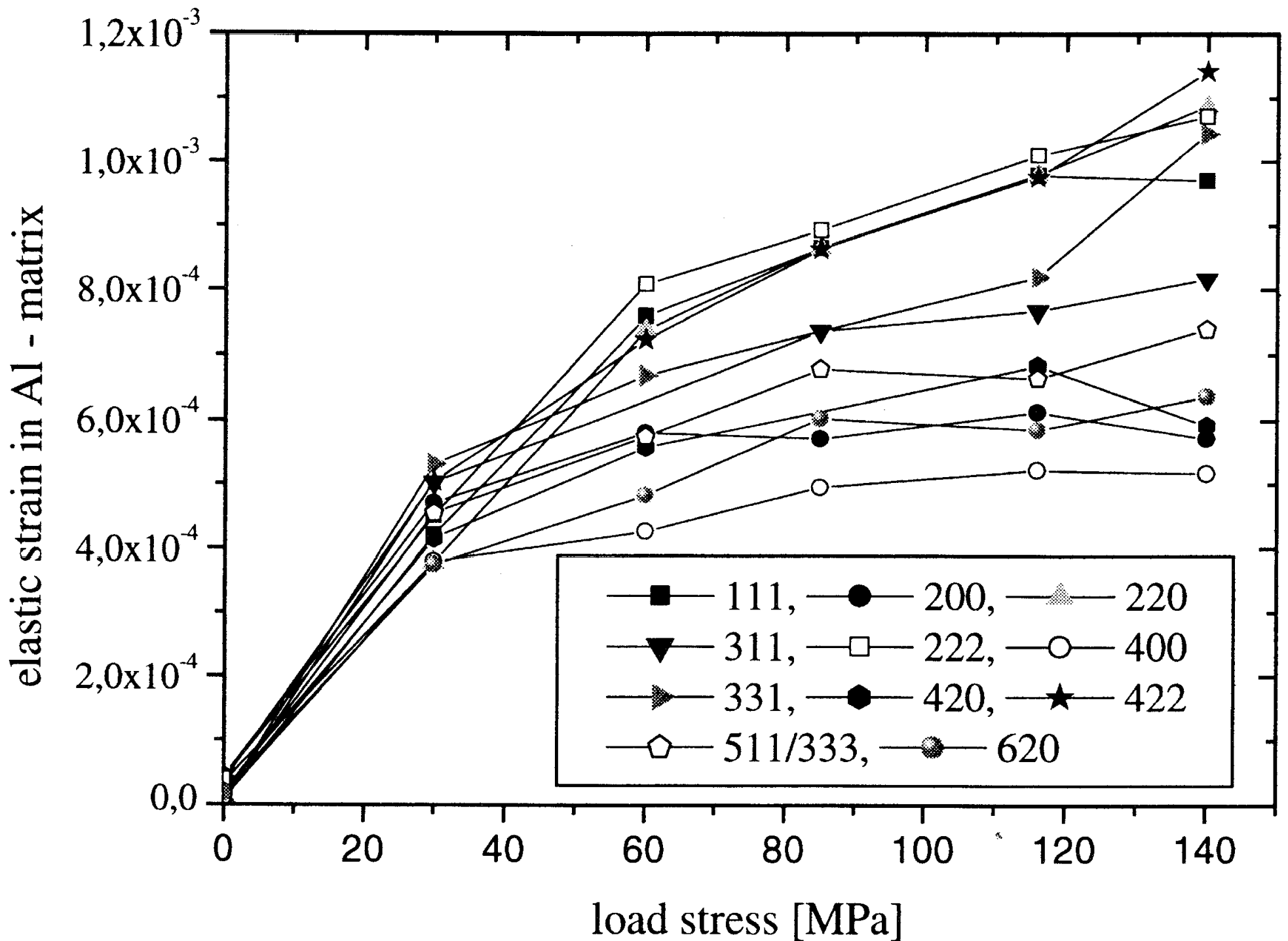
FIGURE 5   Elastic strain of the Al-matrix in dependence on the load stress, temperature: RT, error margin $\pm 1 \times 10^{-4}$.

The load stress–elastic strain curve of the aluminium matrix is shown in Fig. 6. A comparison of this to the curve obtained at room temperature (Fig. 5) reveals higher strains of the aluminium matrix at equivalent load stresses, which is due to the lower elastic modulus at elevated temperature. Differences of strain values for
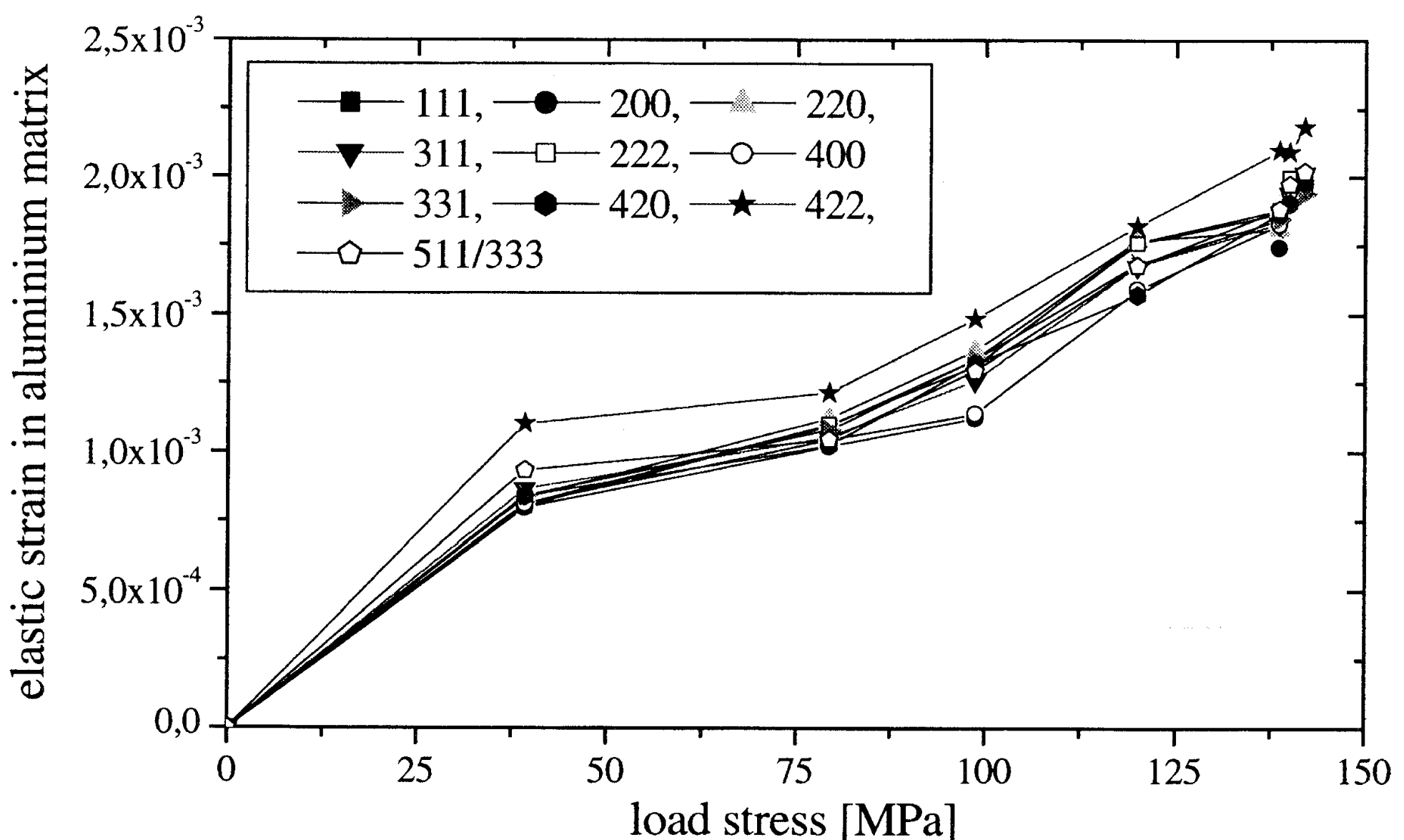

FIGURE 6   Elastic strain of the Al-matrix in dependence on the load stress, temperature: 250°C, error margin $\pm 1 \times 10^{-4}$.

the individual lattice planes show the same tendencies as the experiments at room temperature.

CONCLUSIONS AND OUTLOOK

Tensile deformation of an AlSi-alloy was carried out at ambient and at elevated temperature using white high energy synchrotron radiation. First results of the experiments show the development of the lattice strains in the aluminium matrix and the silicon particles with increasing tensile load stress.

The lattice strain–load stress curves will be compared to macroscopic stress–strain curves in order to determine the onset of full plastic deformation of the aluminium matrix. Further work will concentrate on the investigation of the temperature dependent behaviour of the matrix and the particles, especially the load transfer between the phases and on the development of the microstrains in the aluminium matrix during high temperature deformation as well as on studying stress relaxation effects at high temperatures.

Acknowledgements

References

[1] Das, S. (1997), *J. Mater. Sci.* **16**, 1757–1760.
[2] Hummert, K. and Ringhand, D. (1995), *wt-Produktion und Management* **85**, 291–296.
[3] Müller, K.B. and Winsemann, U. (1999), *Aluminium* **75**, 314–320, Part 1.
[4] Müller, K.B. and Winsemann, U. (1999), *Aluminium* **75**, 531–536, Part 2.
[5] Reimers, W., Pyzalla, A., Broda, M., Brusch, G., Dantz, D., Liss, K.-D., Schmackers, T. and Tschentscher, T. (1999), *J. Mater. Sci. Lett.* **19**, 581–583.
[6] Pyzalla, A. and Reimers, W. (2000), *Mater. Sci. Forum* **347–349**, 34–39.
[7] Seol, K. and Krawitz, A.D. (1990), *Mater. Sci. Engng* **A127**, 1–5.
[8] Korsunsky, A., Daymond, M.R. and Wells, K.E. (2000), *Mater. Sci. Forum* **347–349**, 492–497.
[9] Pyzalla, A., Wegener, J., Müller, K.B. and Liss, K.-D. (2000), *Mater. Sci. Forum* **331–337**, 781–786.