Inhomogeneous Shrinkage of Polymer Materials in Selective Laser Sintering

J. Shen, J. Steinberger, J. Göpfert, R. Gerner, F. Daiber, K. Manetsberger, S. Ferstl

DaimlerChrysler Research Center, Ulm, Germany

Abstract

It is well known that the laser beam of an SLS machine can be controlled almost exactly. The inaccuracy of the mechanical movements of the machines is also much lower than the actual errors of the SLS parts. How can we explain this discrepancy?
One answer is the temperature inhomogeneity in the build field and in the part bed. In this article the effect of temperature dependent volume relaxation of pre-sintered polymer parts on the inaccuracy of the SLS process will be discussed. The investigation shows that it depends on the temperature, pressure and time.
Measurements of the temperature distribution in an SLS part bed were carried out. By determining coordinate-dependent scaling factors, an empirical method to compensate this non-linear shrinkage is presented in this article.

Introduction

Direct manufacturing of functional or series parts using rapid prototyping technologies is one of the main goals of the RP activities at the DaimlerChrysler Research Center. The challenge is not only to manufacture these parts faster and cheaper but much more accurate. RP parts should show the properties of a end-product or at least close to those. Especially, aerospace applications with their accuracy standards represent high challenges for the RP techniques. Big thin walled investment casting patterns will be required with a high-accuracy. In most cases the current SLS technique of polymer materials cannot fabricate parts accurate enough for these applications. As a result, SLS patterns have to be finished manually, which yields to high labour cost and long process lead time in addition to quality problems.

Inhomogeneous temperature distributions in the surface of the powder bed and in the part bed are the main reason of the SLS inaccuracy [1]. In the cooling stage (post-sinter process), a laser sintered nylon part shrinks non-linearly in the powder bed. This z-dependent inhomogeneous shrinkage was firstly observed by the DaimlerChrysler RP Workshop in Sindelfingen [2]. It could not be compensated by a linear scaling of the data model, which is provided by DTM Sinterstations. The dimensions in the downside were always smaller than in the upper side.

In this study the inhomogeneous z-shrinkage of different polymers will be investigated and their mechanisms will be discussed. An empirical compensation method of the shrinkage will be presented.

The Investigation Methodology

In order to measure the shrinkage inhomogeneity, a special sample geometry was designed. It is a hollow, cylindrical square rod providing equidistant holes as measuring marks. Twelve samples were arranged in the part bed in a manner as shown in figure 1. In this way, the shrinkage factors depending on the coordinates in all three directions could be determined. The distances between the holes were measured using a coordinate measuring machine. The scaling factors could be calculated as the ratio of the measured value to the set value.

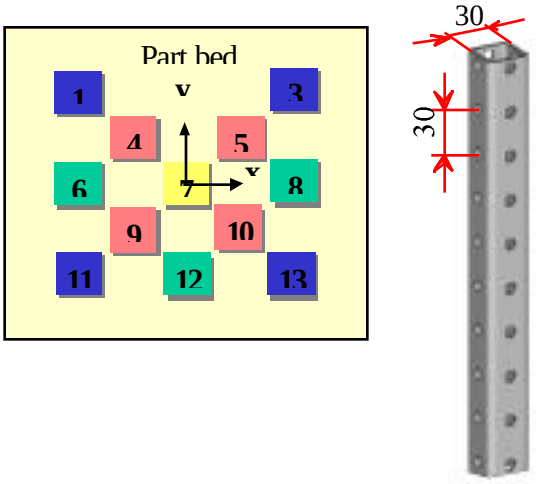

Figure 1: Samples for the measurements of z-shrinkage [1,3].

In order to investigate the temperature dependency of the non-linear shrinkage and finally to compensate this shrinkage completely, isothermal volume changes of pre-sintered powder parts of polymer materials were investigated. A dilatometer was used to measure the relative variation of the linear contraction at different heating/aging conditions. The samples were cylindrical rods with a diameter of 7 mm and a height of 5 mm. They were prepared partly in a furnace (PS) and partly using SLS (PMMA copolymer). Using this apparatus, load on the samples could be varied during the measurements to emulate the pressure on the sintered parts in the part bed during SLS process. The lowest load on the sample was found at 2,2 g. The estimated, maximum pressure in the Sinterstation 2500 is about 28 g/cm^2 [4].

Phenomenological Description of the z-Shrinkage

Inhomogeneous distributed shrinkage values in z-direction during laser sintering are observed in both investigated materials: amorphous PMMA copolymer and semi-crystalline PA12 (figure 2). Shrinkage is stronger in the downside than in the upper side, as expected. The z-dependence of the shrinkage was not linear. Furthermore, the absolute shrinkage values decline with increasing distance from the center of the part bed and showed a concentric distribution. Comparing the values of the two materials one sees that the shrinkage of PA12 is more than twice as high than that of PMMA copolymer.

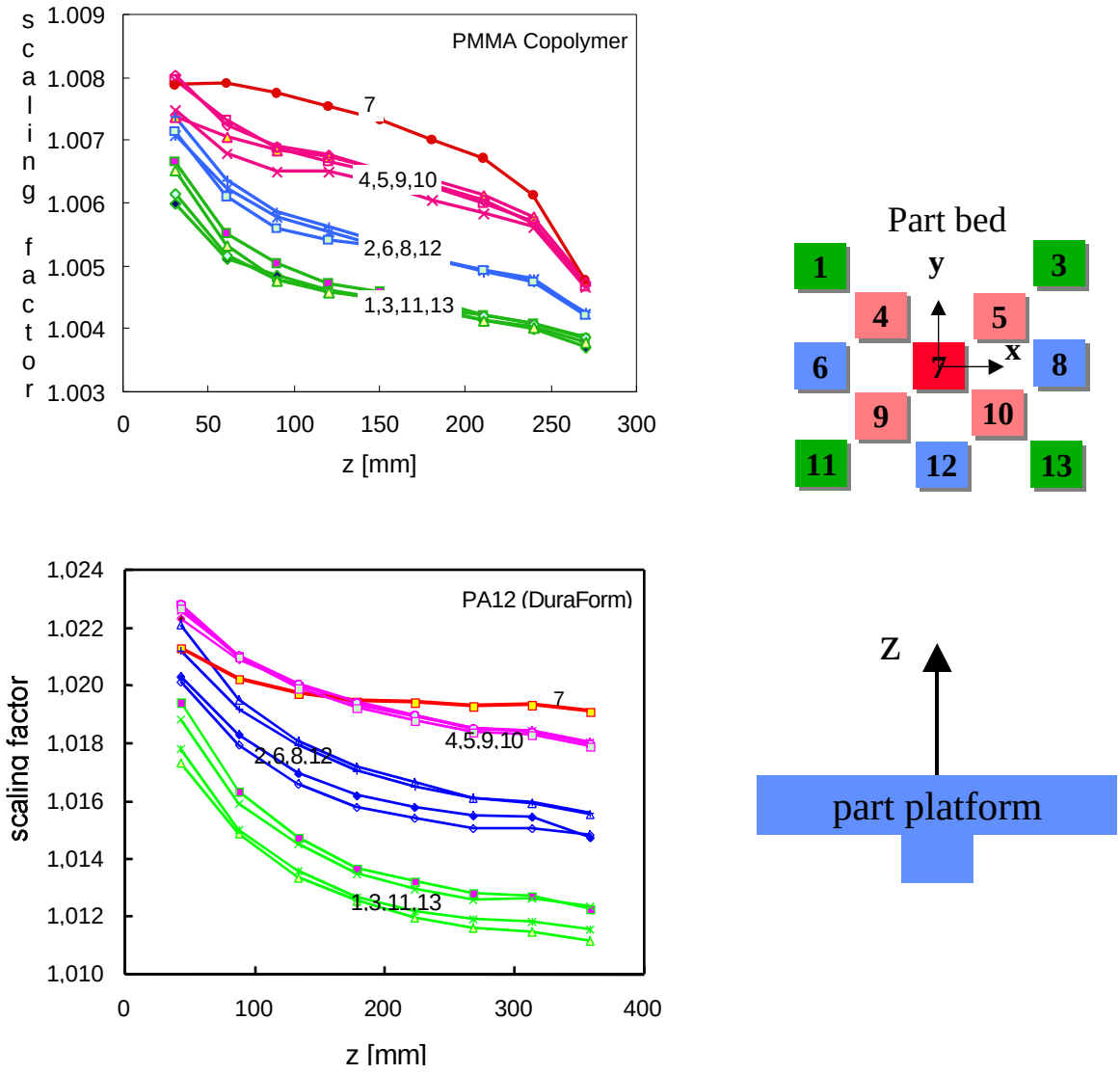

Figure 2: Measured scaling factors, which are necessary to compensate shrinkage for a semi-crystalline PA12 and amorphous PMMA copolymer [1,3].

Mechanisms of the Inhomogeneous Shrinkage

The concentric distribution of the scaling factors in the x-y-plane (figure 2) leads to the assumption that the shrinkage depends on the temperature gradient in the x-y-plain. Usually a laser sintered segment cools down in the part bed during the SLS process. The heat of the powder bed including laser sintered segments dissipates through the walls and the bottom of the SLS part bed. The resulting isotherms are 3-dimensional surfaces. Figure 3 shows a cross section of the isotherms. A sample in the center of the part bed remains, therefore, longer under higher temperatures than a sample near the jacket of the part bed. The next question is, how the volume of a sintered part changes depending on temperature and time?

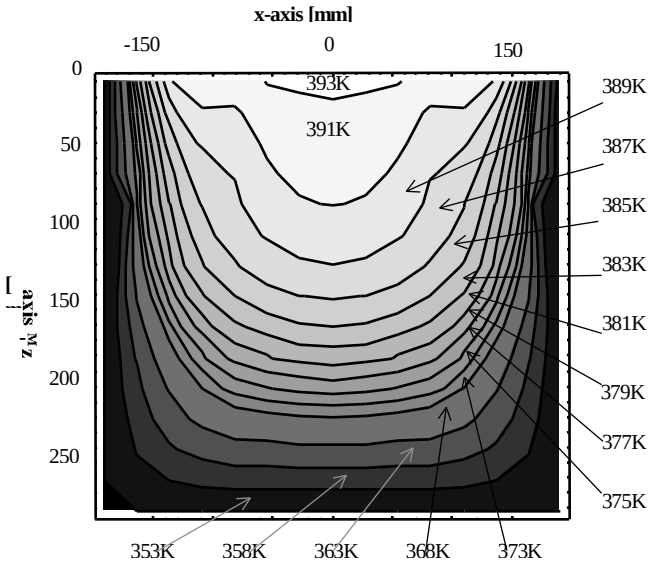

Figure 3: Measured temperature distribution (x-z-cross section) in the part bed during laser sintering of a PMMA copolymer powder [1,4].

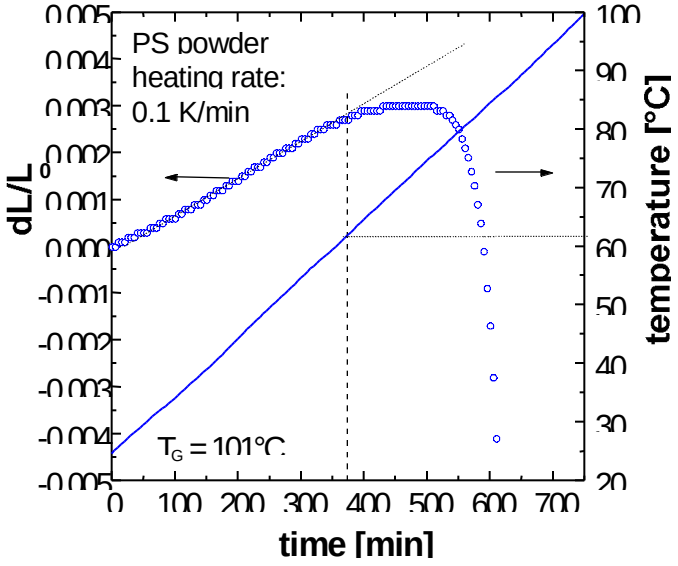

Figure 4: Linear length variation of a sintered PS powder sample at heating.

In order to answer this question, sintered powder samples were measured using a dilatometer. Due to the small heating rate at 0.1 K/min it is supposed that the sample has the same temperature development as the temperature curve in figure 4. Below 62°C the sample shows a linear thermal expansion with the coefficient of 0.76 10^{-4} K^{-1}. This is a little bit higher than the reference value of a pure PS [5]. In the temperature range between 62°C and the glass transition temperature (101°C), the sintered powder sample shrinks and leaves finally the linear curve. This

behavior was not observed at a solid PS material under comparable conditions. It is a special phenomenon of pre-sintered powder samples.

In a pre-sintered powder sample there are a lot of vacancies and vacancy clusters. At an elevated temperature below but near the T_G the main chains of the polymer are still fixed. But their branch chains are already activated thermally. It means, a slow movement of the branch chains is enabled [5]. A small motion of the sintering necks or in the contact zones between the particles could cause a relatively big dimensional change if the particles of concern drop into a vacancy cluster. Consequently, the shrinkage value depends on the thermal activation (aging temperature) as shown in figure 5. Above the glass transition temperature of T_G = 101°C the thermal motion is much stronger. The volume change takes place in a much shorter time, as shown in figure 6.

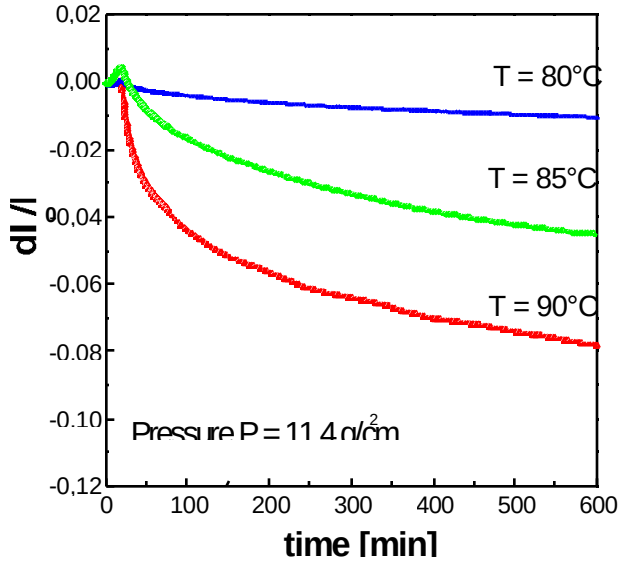

Figure 5: Isothermal shrinkage of pre-sintered PS powder samples at various aging temperatures (T_G = 101°C).

In addition to the temperature changes in the powder bed the pressure on a sintered segment varies with the height. Similar to liquid in a bottle, the static pressure due to powder weight beyond the sintered segment increases with the height of the segment within the part bed. The maximum value, as mentioned above, is 28 g/cm^2. In real process one has to consider the friction between powder and parts which also varies with the part bed temperature and geometry of the part. This will be considered in our future studies.

To measure this effect, different loads in the dilatometer were tested. The minimum pressure was realized at 5.7 g/cm^2. The measurements were carried out using a PMMA copolymer. The aging temperature was 110°C. Figure 7 shows the resulting isothermal shrinkage of the sintered parts at three pressures from 5,7 to 26 g/cm^2. As the pressure increases, a higher shrinkage is observed.

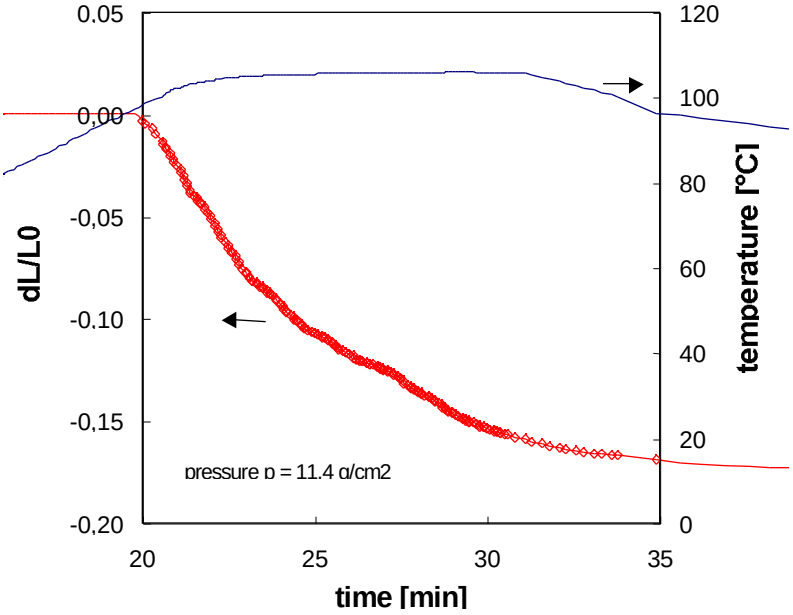

Figure 6: Isothermal shrinkage of pre-sintered PS powder samples at a temperature T = 105°C.

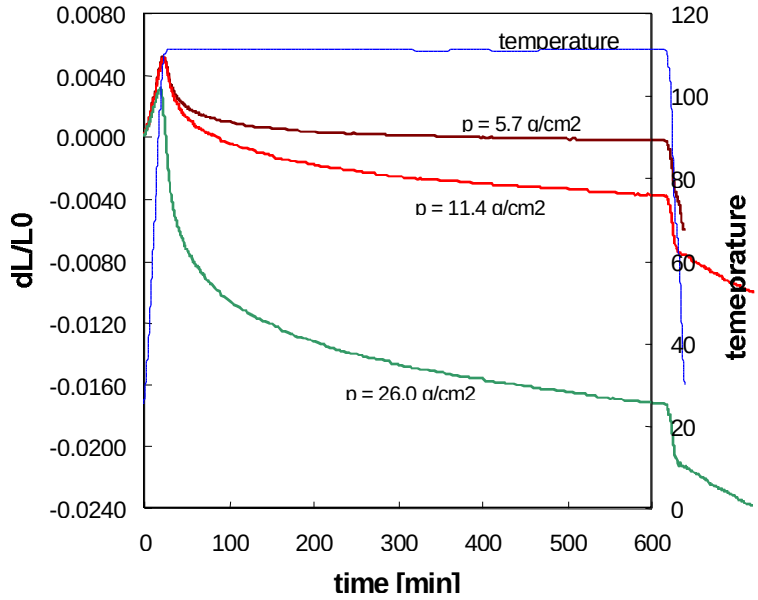

Figure 7: Isothermal shrinkage of pre-sintered PMMA powder samples at T = 110°C and various pressures.

Normally, in the current laser sintering machines the slice thickness is kept constantly. This means the part platform sinks each time with a constant value. In the course of the time the powder bed and the sintered segments in the part bed shrink continuously. The integrated shrinkage value in the time until the next powder layer was deposited leads to an increased thickness of the actual deposited new powder layer. This effect reduces the scaling factor towards high z-coordinates in figure 2 additionally.

Empirical Compensation of Non-Linear z-Shrinkage

In order to compensate the inhomogeneous z-shrinkages, a numerical fit function was found to describe the measured scaling factors. The functions have a bell-shaped profile and show a relatively good agreement with the measurements. The samples described above were firstly scaled using the fit function. Then they were built by laser sintering and measured once again. Figure 8 shows the results of the z-compensation. The new scaling factors are in comparison to the initial inhomogeneous shrinkage shown in figure 2 (DuraForm) much homogeneous and their values are nearly 1.0.

This function applied to a real part with a complex geometry may lead to different results. One reason is the changed temperature distribution due to the laser energy that is irradiated into the part. The second reason is that segments of a real part cannot shrink freely. It is similar to the case when the rods are bond together. Their shrinkage values are then mutually dependent. The influence of the temperature change can be neglected if the energy input of the laser beam is kept small, for example in the case of thin-walled parts (low part volumes). Figure 9 gives a comparison of the dimensional errors of a thin walled part in z-direction. The colored area marks the tolerance range. Using the compensation function an in z-direction more accurate part was built.

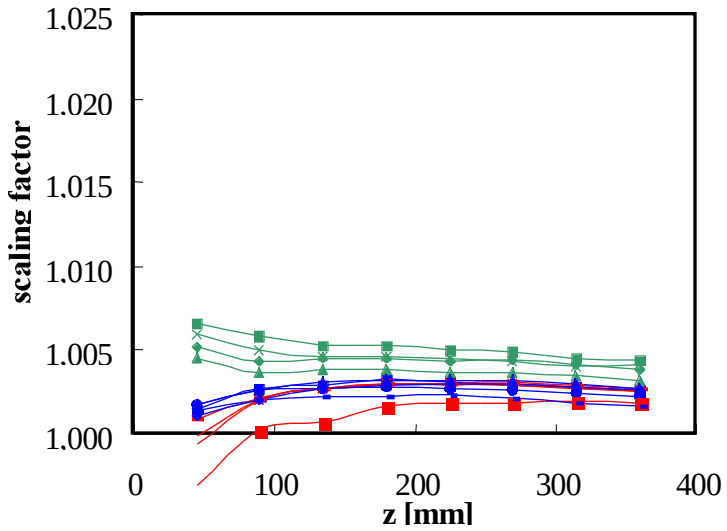

Figure 8: The scaling factors of the sample rods after the empirical compensation of the non-linear z-shrinkage of nylon (PA12 DuraForm) [1].

Summary and Future Work

During the selective laser sintering process of polymer materials, an inhomogeneous shrinkage was observed. This depends on the temperature distribution and build rate. These shrinkages are caused by time-dependent volume changes of pre-sintered porous parts which occurs even at a

temperature 30 K lower than the T_G. Additionally, the pressure caused by the powder weights influences the dynamic of the shrinkage.

The non-linear z-shrinkage can be compensated empirically if the temperature distribution in the part bed does not deviate a lot from that during the build of the sample rods. A general compensation is only possible if the laser sintering process is simulated.

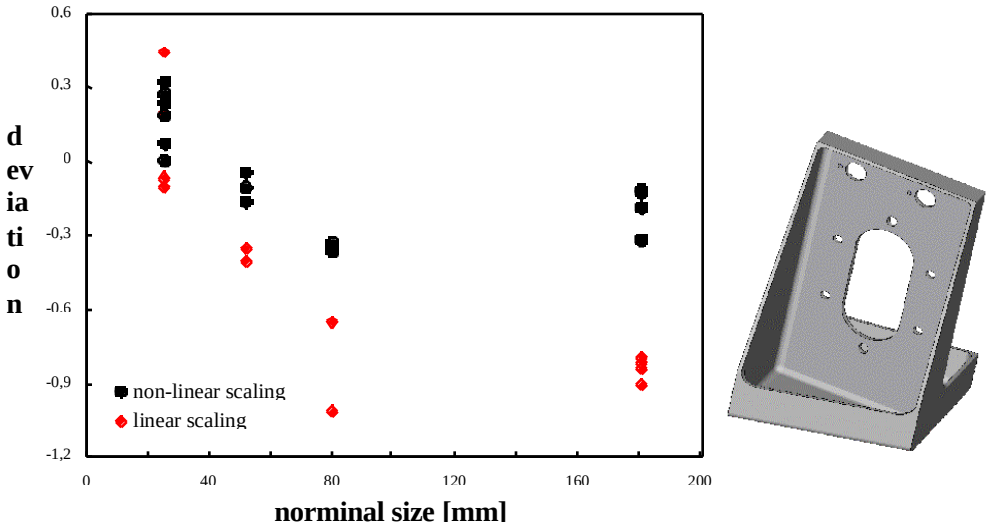

Figure 9: Reduction of z-errors of a thin walled part by applying the scaling function [1].

References

1. Steinberger, J.: Optimierung des Selektiven-Laser-Sinterns zur Herstellung von Feingussteilen fuer die Luftfahrtindustrie, PhD-Thesis, Technical University of Munich, to be published in 2000.
2. Ernst, E.: Untersuchung der Einflussfaktoren auf das Schwindungsverhalten von Polyamid-Sinterbauteilen, Diploma-Thesis, University of Stuttgart, 1997
3. Gerner, R.: Herstellung genauer Kunststoffmodelle mittels SLS fuer die luftfahrttaugliche Feingussprozesskette, Fachhochschule Ulm, 2000.
4. Göpfert, J.: Untersuchungen der physikalischen Ursacheneffekte der inhomogenen z-Schwindungen beim selektiven Lasersinterprozess, Diploma-Thesis, Fachhochschule Ulm, 1999.
5. Greiner, R.: Zum Ausdehnungs- und Volumenrelaxationsverhalten eines amorphen Polymers, PhD-Thesis, University of Erlangen, 1987.

Acknowledgements

The authors thankfully acknowledge the support of the Institute of Dynamic Material Testing (Ulm) and its members for dilatometer measurements, especially that of Professor Pechhold, Dr. Gross and Dr. Eckert.