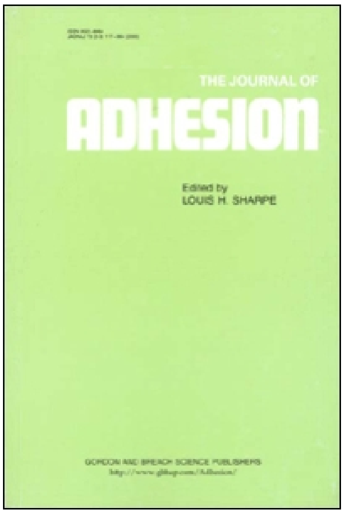

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Creep Resistance of Pressure Sensitive Mounting Tapes*

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The first part of the paper deals with an approach towards a systematic testing procedure to evaluate the creep behavior of single lap shear specimens bonded with PSA mounting tapes under the influence of temperature and humidity. The study includes commercial tapes as well as self-formulated pressure sensitive adhesives based on styrene block copolymers. The second part of the paper relates the obtained data, consisting of the time-dependent sample deformation and time-to-failure, to the observed failure modes. The results show that the creep behavior of a pressure sensitive adhesive is not only dependent on the environmental conditions but also on the substrate material and its surface composition. The results for the self-formulated adhesives reveal the possibility of enhancing creep resistance of PSA's by adding fillers to the formulation. The paper closes with a modification of the Burgers model that is suitable for describing the creep/creep recovery behavior of tested lap shear specimens. The effect of nonlinear behavior in cyclic loading experiments is described and a thesis for the relation of nonlinear creep behavior to damaging processes in the adhesive bond is presented.

Keywords: Pressure sensitive adhesives; PSA; creep; Burgers model; humidity; adhesion; adhesive joints

INTRODUCTION

PSA tapes have become an attractive bonding method. They are easier to use than mechanical fasteners or liquid adhesives and can be made of non-polluting and non-toxic raw materials, and thus should

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be considered an alternative to conventional adhesive systems which must meet increasingly stringent governmental regulations. In addition, previous investigations have shown that pressure sensitive adhesives are often much more durable than two-component adhesives [1,2]. Yet the lack of reliable data about the long-term creep behavior of PSA bonded joints under environmental conditions hinders their use in structural applications. Like all polymers, pressure sensitive adhesives have mechanical behavior that is highly time and temperature dependent. High performance pressure sensitive formulations for bonding applications not only need excellent shear stability, but also tack and viscoelastic flow properties. These characteristics are difficult to combine into a single homogeneous material. The pressure sensitive adhesive must get into contact with the surface to be bonded and, even more important, stay in contact even under constant mechanical stress and environmental influences [3]. To make things even worse, for typical mounting applications a certain minimum thickness of the mounting tape including facestock and adhesive is needed to provide sufficient gap filling properties, depending on the surface roughness or difference in the shape of the parts to be attached. This minimum thickness is about 0.3 mm and typical values of mounting tapes are 0.6 mm–1.1 mm.

EXPERIMENTAL

Three basic techniques are commonly used to investigate the creep behavior of joints bonded with pressure sensitive adhesives. The first method measures the relaxation of the polymer. A defined deformation is applied to the sample and the decrease in force needed to keep this constant deformation is recorded. The second technique most closely resembles the actual use of the adhesive. Under an applied constant stress to the adhesive bond, the deformation of the sample over time and the time to failure are registered. Although the time to failure is a very important characteristic for practical applications, its investigation is often a walk on the razor's edge. When choosing a slight to low load, the sample will last forever, whereas a load too high will cause sudden failure. This illustrates a fundamental problem in studying creep behavior; that is, to find this often small range of stress that leads to strain rates and, thus, deformations which can be sometimes tolerable or fatal depending on the application. The third method has shown to be a good starting point for our investigations and involves constant strain rates. Single lap shear specimens are tested with crosshead speeds ranging from 100 mm/min to 1 mm/h in a standard testing machine. By looking at the change in lap shear strength with strain rate and interpreting the stress-strain curves, the approximate loads for lap shear specimens under constant load can be estimated. The main advantage of this procedure is that it saves a lot of time.

RESULTS AND DISCUSSION

Experiments with Constant Strain Rates

We chose 3M's 4945 Acrylic Foam Tape for our first tests because it is widely accepted as one of the best mounting tapes. Results are presented in the following diagram, obtained with single lap shear samples of approximately one square inch (6.5 cm^2) bonding area at room temperature at different crosshead speeds. The mounting tape specimens were placed on the test surface and rolled twice with a 4 1/2 pound (2 kg) roller according to PSTC-7. After removing the release liner, the second metal strip was placed on the sample to form a single lap shear specimen and again was rolled twice. The prepared specimens were then tested after a dwell time of two weeks at room temperature and approximately 30% humidity. The failure of the single lap shear specimens in Figure 1 started with a delamination between adhesive and substrate material, and then proceeded as a partly cohesive and partly adhesive separation. The diagram reveals that both the maximum lap shear strength and the ratio of high strain rate values to low strain rate values depend on the substrate materials [4]. These results were verified for different PSA's and extended to other materials, and thus demonstrate that the substrate must be taken into consideration when the long term behavior of pressure sensitive adhesives is important to the application.

One way to increase the shear resistance of pressure sensitive formulations without changing the adhesive's properties is to add fillers, such as solid or hollow glass beads, to the adhesive mixture. The effect

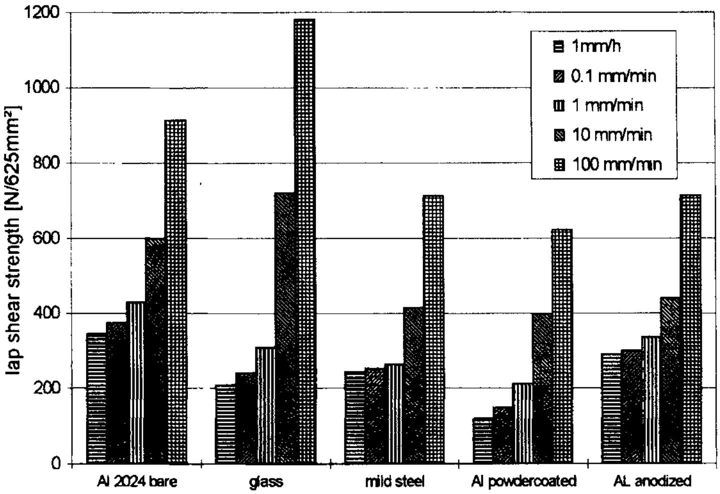


FIGURE 1 Influence of substrate material and strain rate on lap shear strength. Single lap shear joints, 3M VHB 4945, 25mm × 25mm, 20°C.

of 20 vol. percent solid glass beads of 110 μm–180 μm diameter on a formulation consisting of 100 parts by wt (pbw) Cariflex 1107 (SIS block copolymer), 120 pbw Resin, 10 pbw plasticizing oil, and 4 pbw Irganox® (anti-oxidant) was evaluated. At high shear rate values, the lap shear strength of the unfilled formulation is better than that of the filled one. At appoximately 2.5 mm/min., however, the two curves cross and the increase in long-term shear stability by the addition of glass beads becomes obvious.

Further improvements were obtained by coating the tape containing glass beads with a thin layer of the same adhesive formulation but with a slightly higher oil content. The tack and peel values just after bonding are better than those of the uncoated material, and the overall shear properties stay unaffected, possibly because of diffusion of the oil from the surface into the bulk in order to distribute itself evenly in the adhesive. From the experiments at constant strain rates, we obtain not only information about the velocity-dependent lap shear strength, but also data on the relationship between the elongation of the specimen and the strain rate. An increasing strain at the point of failure with slower strain rates indicates a failure of the bulk material, while a decrease of strain with slower strain rates is often associated with interfacial delamination between the adhesive and the substrate.

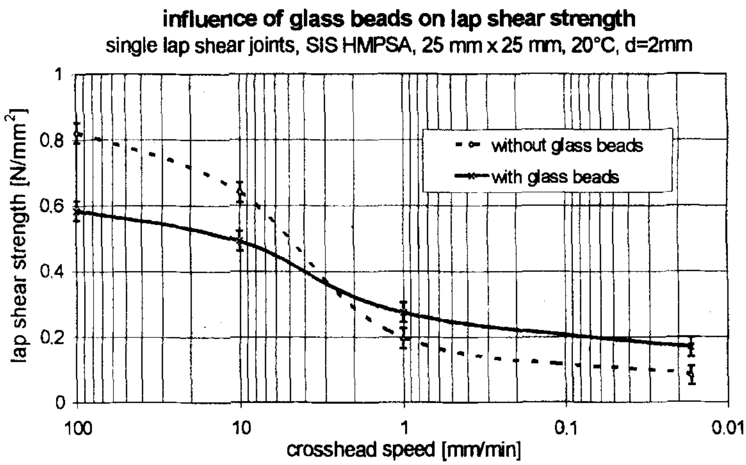


FIGURE 2 Influence of glass beads on lap shear strength, single lap shear joints, SIS-Hotmelt model PSA No. 1, Al 2024 bare, 25mm × 25mm, 20°C, $d_k = 2$ mm.

Long-term Creep Behavior

An extrapolation of the elongation at the point of failure and lap shear strength under constant strain rate data allows a rough prediction of the stress necessary for a similar specimen to fail after 100 h under constant load. Further extrapolation can then be carried out in a similar manner. The results of the static load experiment with the same adhesive formulation are shown in Figure 3.

The set of curves shown in Figure 4 was obtained with a high performance acrylic tape in the static load experiment. Data were collected every six minutes in these experiments to reduce the number of data points to be recorded.

Figure 5 shows that, at elevated temperatures, the times to failure for these loads are drastically reduced. In addition, at 20°C the strain at the point of failure increases with lower loads, while the set of curves at 60°C shows the opposite trend.

The observed differences are explained by the failure modes. At 20°C the separation is caused by a crack running through the core of the tape, leaving a wedge of mounting tape on each part of the specimen. At 60°C the separation takes place at the interface between the core, consisting of an acrylate polymer reinforced with hollow glass beads, and the tacky acrylate adhesive [5]. Further tests, as presented

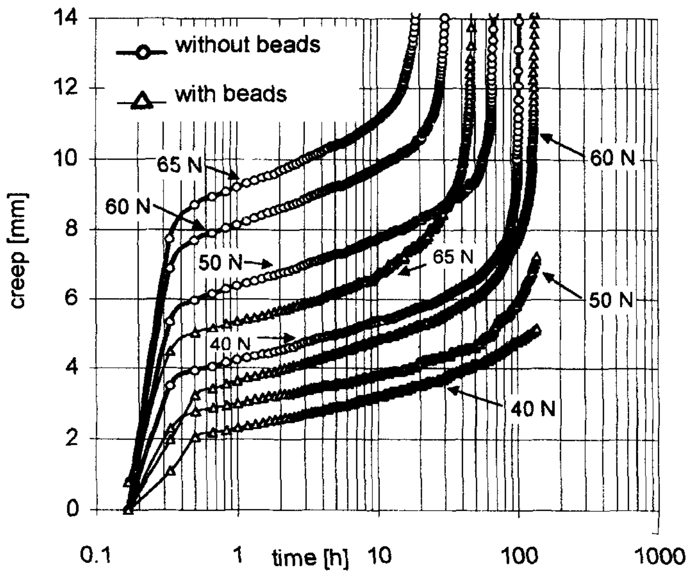


FIGURE 3 Influence of glass beads on creep, single lap shear joints, SIS-Hotmelt model PSA No. 1, Al 2024 bare, 25mm × 25mm, 20°C, $d_k = 2$ mm.

in Figure 6, show that high humidity can further affect this separation. This illustrates that a core material which is not strongly enough attached to the adhesive layers can cause new problems by adding two more interfaces, namely, those between the adhesive and the core material, which can possibly separate. An ideal pressure sensitive mounting tape should have a gradual change in its properties from the tacky surface to the shear resistant backing layer to avoid failure in areas where high deformations take place.

Further Analysis of the Creep Behavior

The Burgers model [6, 7] is a universal model suitable for describing the linear viscoelastic deformation of adhesives under mechanical stress. The model consists of four single elements which are connected as shown in Figure 7. In our work, this model is used to describe the overall elongation of the lap shear specimens. The transformation of tensile units to shear units is possible but was not carried out. This makes reference to the model easier and does not affect the conclusions.

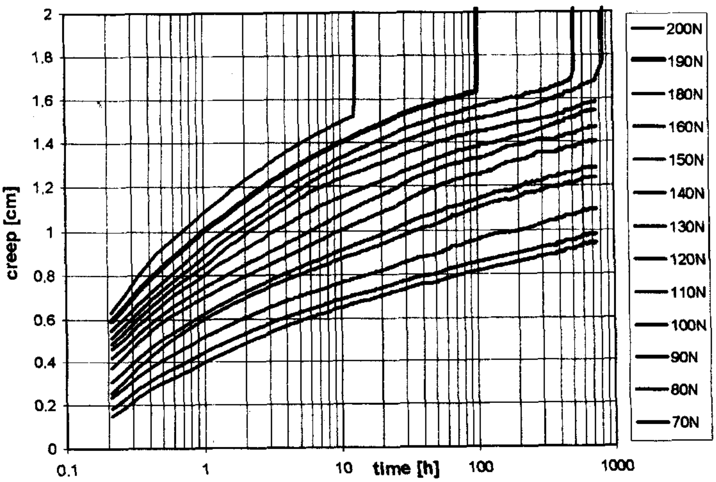


FIGURE 4 Creep behavior of 3M VHB 4945, Al 2024 bare, 25mm × 25mm, 20°C, humidity $\varphi = 30\%$.

From a set of recorded creep data, the values of the spring constant, C_0, and the dashpot viscosity, D_0, can easily be determined. The elastic component, C_0, causes an instant elongation after the loading of the creep specimen with a static load, and the dashpot viscosity, D_0, is

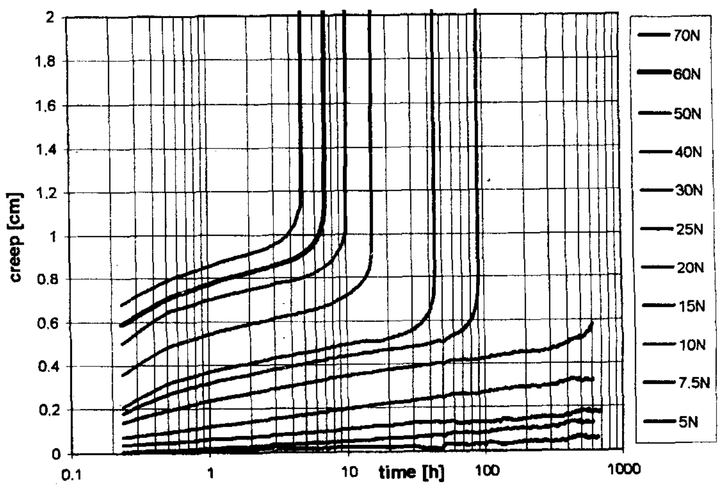


FIGURE 5 Creep behavior of 3M VHB 4945, Al 2024 bare, 25mm × 25mm, 60°C, humidity $\varphi = 30\%$.

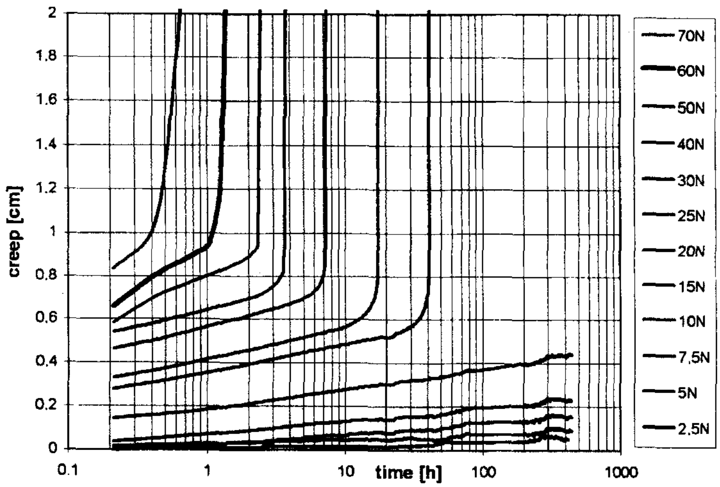
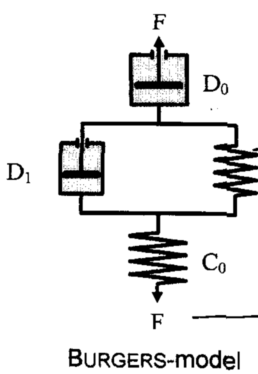


FIGURE 6 Creep behavior of 3M VHB 4945, Al 2024 bare, 25mm × 25mm, 60°C, humidity $\varphi = 80\%$.

responsible for the constant creep velocity in the steady region of the creep curve (Fig. 8).

Values independent of the geometry of the specimen can be obtained by replacing F with $\tau(\tau = F \cdot A^{-1})$ and dx by $\tan\gamma(\tan\gamma = dx \cdot d_k^{-1})$ where A is the size of the bonded area and d_k is the thickness of the adhesive layer. The estimation of the remaining unknown values, C_1 and D_1, in



$$dx_{(D_0)} = F \cdot D_0^{-1} \cdot dt \quad (1)$$

$$dx_{(C_1)} = dx_{(D_1)} \quad (2)$$

$$dx_{(C_1)} \text{ (if } t = 0) = 0 \quad (3)$$

$$F_{(C_1)} = dx \cdot C_1 \quad (4)$$

$$F_{(D_1)} = F - F_{(C_1)} \quad (5)$$

$$dx_{(D_1)} = F_{(D_1)} \cdot C_1^{-1} \cdot dt \quad (6)$$

$$dx_{(C_1)} \text{ (if } t \to \infty) = F \cdot C_1^{-1} \quad (7)$$

$$dx_{(C_0)} = F \cdot C_0^{-1} \quad (8)$$

FIGURE 7 Burgers model and corresponding recursive relations.

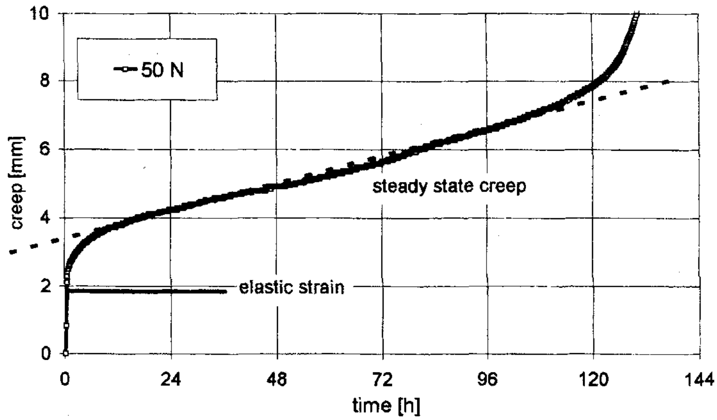


FIGURE 8 Creep under static load, SIS-Hotmelt model PSA No. 2, single lap shear specimen, Al 2024 bare, 25mm × 25mm, $d_k = 2$mm, 20°C.

the parallel connection shown in Figure 7 can be done by curve fitting the creep curves obtained in cyclic loading experiments.

In the cyclic loading experiment, loads are applied to lap shear specimens for 24 hours and then removed for a 24-hour recovery period and so on. The time dependent deformation measured in this test is shown in Figure 9. The curve generated by connecting the points of residual strain at the end of the recovery periods represents the increase in plastic deformation of the specimen due to the element D_0 in the Burgers model (Fig. 7).

The slope of this curve is almost linear until failure of the specimen, whereas the curve described by the total strain after the loading periods has a progressively increasing slope.

The graph shows that the recursive relations of the Burgers model follow the actual measurements only in the case of low stress levels or in the early stages of the creep experiment. Since the model contains only linear components, the calculated curves of the unrecoverable strain and total strain are always parallel. The conformity of the calculated and measured creep values could be improved by adding a time-dependent, non-linear factor to the elastic element C_1 in the Burgers model (Equation (2) in Fig. 7). The corresponding equation for the modified model is:

$$F_{(C_1)} = dx \cdot (C_1 - kt \cdot t)^{-1} \tag{9}$$

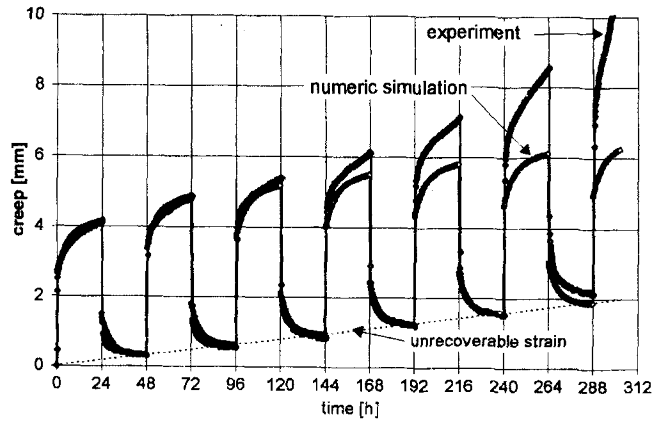


FIGURE 9 Creep under cyclic loading, numeric simulation according to the Burgers model and measurement, SIS-Hotmelt model PSA No. 2, single lap shear specimen, Al 2024 bare, 25 mm × 25 mm, $d_k = 2$ mm, 20°C.

The term $-kt \cdot t$ in Equation (9) is limited to values greater than C_1. In our experiments, the sample failed before $C_1 - kt \cdot t$ reached zero. This simple modification of the Burgers model provides a much better description of the creep/creep recovery behavior of the investigated lap shear specimens, as shown in Figure 10.

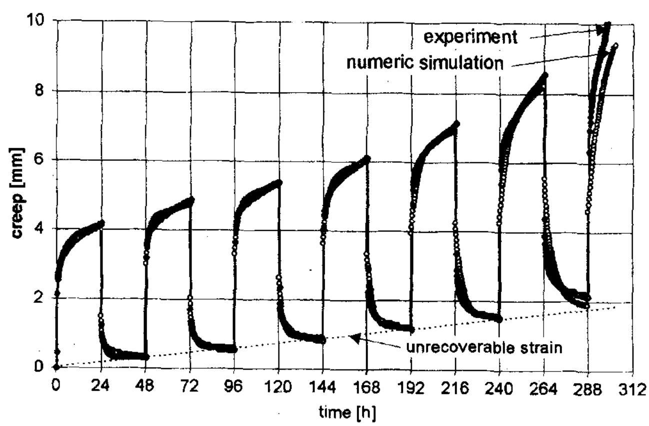


FIGURE 10 Creep under cyclic loading, numeric simulation according to the modified Burgers model and measurement, SIS-Hotmelt model PSA No. 2, single lap shear specimen, 25mm × 25mm, $d = 2$mm, 20°C.

CONCLUSIONS

Creep curves reveal how the constant loads supported by PSA's are affected by environmental conditions such as temperature and humidity. There are many applications for pressure sensitive adhesives, however, where practically no static load occurs and the cycle time of periodic stress is rather short. Nevertheless, it has to be assured that the adhesive joint will not fail under load for the life of the bond. The nonlinear creep behavior represented by the k_t factor causes a weakening of the spring element C_1 in the modified Burgers model, and could be interpreted as a result of bond-breaking processes taking place during the experiment. If the size of the k_t factor was related to the time to failure of the creep specimen, the processes leading to creep rupture could be detected early in the creep experiment, long before failure of the sample. Further work has to be carried out to support this thesis.

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