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Beating noise, vibrations and impacts with polyurethane pads

Applications in railway constructions & industry and the materials chemistry behind

Elastomers are defined by their reversible deformation behaviour: Consider a specimen underlying an external force. Once this force vanishes, its initial geometry will be restored. In the case of ideal-elastic materials this happens nearly instantly, while so-called viscoelastic materials need some time to restore the initial geometry. Depending on the application, engineers make use of one or the other class of elastomers. For example, almost ideal-elastic materials are the best choice to isolate vibrations in, e. g., building industry and railway engineering. In contrast, viscoelastic elastomers allow damping of impacts as well as damping of the amplitude of vibrations. For such applications, Getzner Werkstoffe offers a material series named Sylodamp. This article describes the basic physical and chemical principles that make it possible to develop materials with pre-defined damping characteristics.

By M. Heim, M. Seidl-Nigsch, H. Loy

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1 Introduction: Impacts and resonance in the case of periodic forces

Getzner Werkstoffe develops and produces foamed materials made from polyurethane. These materials are used to reduce structure-borne noise and to protect components. They are used in the railway, construction and industry sectors. Depending on the individual application they may be highly elastic or plastic. An example for the use of a pronounced viscoelastic and, thus, dampening rail pad to reduce the vibration of rails and sleepers and, therefore, noise emanating from the railway superstructure is illustrated in figure 1.

When employed in technical systems such as rail superstructures, building foundations and machine bearings, Getzner's elastic materials act primarily as springs, isolating vibrations and thus protecting buildings from structure-borne noise. Generally speaking, structure-borne noise is generated by dynamic-periodic forces or impact loads. Elastic bearings either decouple the source of the noise from the environment – as in the case of railway tracks – or they separate a vibrating environment from the object to be protected, such as a building.

At their simplest, systems like these are described as single mass oscillators with a mass m (fig. 2). In reality, the spring element is not an ideal-elastic material. The physical equivalent model therefore more closely resembles that of a spring and a damper connected in parallel. The stiffness of this spring-damper combination under dynamic loading depends on the frequency f. The dynamic modulus of elasticity E_{dyn} (f) of the material is a measure of this stiffness and determines – in conjunction with other variables – the natural frequency f_0 of the single mass oscillator:

$$f_0 = \frac{1}{2\pi} \cdot \sqrt{\frac{E_{dyn} \cdot A}{d \cdot m}} \quad (1)$$

where A represents the bearing area and d the bearing thickness. In addition to the stiffness of the material (E_{dyn}), the design of the bearing (full-surface, strip or discrete; A,d) and the mass also affect the natural frequency. When designing a bearing, the engineer must coordinate the various parameters to produce the desired natural frequency – bearing in mind that there are usually constraints on the parameter values that can be employed. For example, the bearing thickness is limited and the mass is fixed in advance.

The natural frequency of a spring-mounted system is its central parameter, as it is this that determines the effectiveness of the sound control measures, since the (always incomplete) decoupling of the element vibrating at a frequency f depends on the ratio f/f_0. The transfer coefficient L quantifies this relationship:

$$L = 20 \cdot \log \left[\sqrt{\frac{1+\eta^2 \cdot (f/f_0)^2}{(1-(f/f_0)^2)^2+\eta^2 \cdot (f/f_0)^2}} \right] \tag{2}$$

where η is referred to as the mechanical loss factor.

Bearings are designed such that $f/f_0>\sqrt{2}$, as only then will decoupling – even if incomplete – of the dynamic forces actually take place (negative value of L, fig. 3). The larger f/f_0 or the smaller f_0 is, then the smaller L will be, and the better the bearing isolates the vibrating element. The ideal material for vibration protection therefore exhibits as small a dynamic modulus of elasticity E_{dyn} as possible (equation 1). This is why minimising the modulus of elasticity, and hence the transfer coefficient L, is often the objective when developing new materials. (In general, however, application-specific requirements – for example with regard to long-term stability – transform minimising into optimising.)

On the other hand, there are some applications that require the bearing material to fulfil specific requirements in terms of vibration amplification ($f/f_0<\sqrt{2}$). In situations where, for example, a machine that requires a relatively long period of time to start up or reach its operating frequency f is to be decoupled, the material will have to reduce the resonance phenomenon at $f/f_0 = 1$ (fig. 3).

The transfer function maximum in the case of ideal-elastic materials is very high; in the physical equivalent model it corresponds to the spring element (cf. fig. 2). By contrast, in the case of so-called viscoelastic materials a component of the deformation is delayed, which results in damping of the vibrations; this corresponds to a parallel connection of the spring and damper (fig. 2). The extent of the damping is an expression of the mechanical loss factor η: the larger the loss factor, the smaller the highest (positive) value of the transfer function (fig. 3).

If a material is intended to dampen load peaks in the event of impact loading and, thus, requirements exceed the restriction of resonance phenomena that occur in the case of periodic forces, then its loss factor will have to be very high. With Sylodamp, Getzner Werkstoffe has developed the ideal material for such applications. This paper explains both the physical and chemical relationships that underlie the design of Sylodamp – and it describes applications that are already using the material. Finally, we take a look into the near future and discuss the potential of highly damping polyurethane elastomers for products that are intended to protect against railway noise (fig. 1).

2 Theory of viscoelastic materials

2.1 Loading, deformation and time

Mechanical deformation is reversible with elastic materials. Test bodies or components made of ideal-elastic material return to their original geometry immediately once the load is removed; those made from a viscoelastic material do so as well, but require a finite period of time – the (recovery) deformation is delayed following a change in load (fig. 4).

This delay is the macroscopic consequence of damping movements at an atomic level (parallel-connected damper in the physical equivalent model shown in figure 2). A viscous deformation component is also present if the deformation is not completely reversible. This corresponds to a series-connected

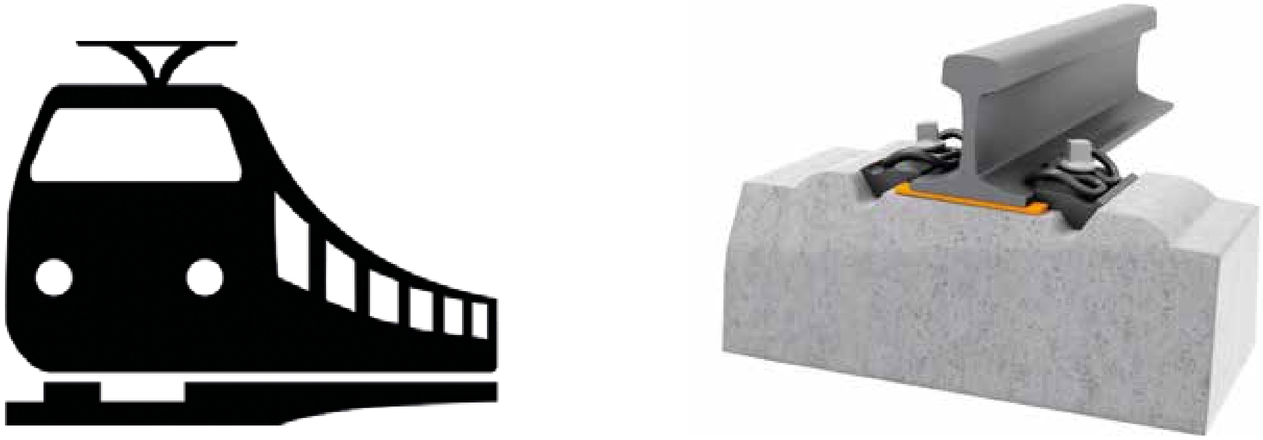


Fig. 1: Left: The railway superstructure emits noise due to vibrating rails and sleepers. Right: Dampening rail pads (orange) placed between rails and sleepers reduce the amplitude of vibrations and, thus, reduce noise.

damper in the equivalent model. Creeping is a special type of viscous deformation. It takes place slowly and hence requires an extended period of loading. It resembles the flow of a polymer melt.

Both damping components of the total deformation (viscoelastic and viscous) correlate with the rearrangement of sections of the polymer chains, with the migration of side chains through the surrounding polymer matrix and other – potentially irreversible – movements [1b]. The material heats up as the result of microscopic frictional effects (energy is dissipated) so that only one – more or less large – part of the work performed by the external force is stored as potential energy.

By contrast, the ideal-elastic component of the total deformation (spring in figure 2) correlates to the change in interatomic distances and the distortion in the valence bond angles [1b]. The respective movements are associated with hardly any heat loss as the change in the spatial coordinates of the atoms involved is small.

2.2 Mechanical loss factor and dynamic modulus of elasticity

In the event of periodic-dynamic loading, the shift between the deformation and load curves – quantified using the angle δ (fig. 4) – is a suitable measure for characterising the damping of the material. The so-called phase shift δ is a consequence of the time difference Δt between the changes in deformation and load. Therefore, δ is large if the viscoelastic (and/or viscous) component of the deformation is large, too. It is worth using the tangent of the phase shift, as this represents both the relationship of dissipative to potential energy as well as the relationship between the loss modulus and the storage modulus. At the same time, we are already familiar with this variable from the introduction, as it is the mechanical loss factor η:

$$\eta(T,f) = \tan\delta\ (T,f) = \frac{E_D(T,f)}{2\cdot\pi\cdot E_{pot}(T,f)} = \frac{E_D(T,f)}{\pi\cdot\sigma_0(T,f)\cdot\varepsilon_0(T,f)} = \frac{E''(T,f)}{E'(T,f)} \quad (3)$$

where T is the temperature, f the frequency, δ the phase shift, E_D the dissipative energy (thermal energy), E_{pot} the potential energy, σ_0 the tension, ε_0 the deformation, E'' the loss modulus and E' the storage modulus.

The term loss factor indicates that the energy that is converted into heat is related to the recoverable deformation energy (which is the stored potential energy). It needs to be made clear at this point that the parameters used to describe the damping of vibration-prone systems or components (damping constant, damping coefficient, Lehr's damping ratio, logarithmic decrement, etc.) have to be distinguished from the variables used to characterise damping materials.

Fig. 2: Physical equivalent model for vibration-prone mechanical systems. In the case of periodic loading with the frequency-dependent force F(f), the spring-damper combination exhibits a dynamic stiffness that corresponds to the dynamic modulus of elasticity E_{dyn} of the material being used.

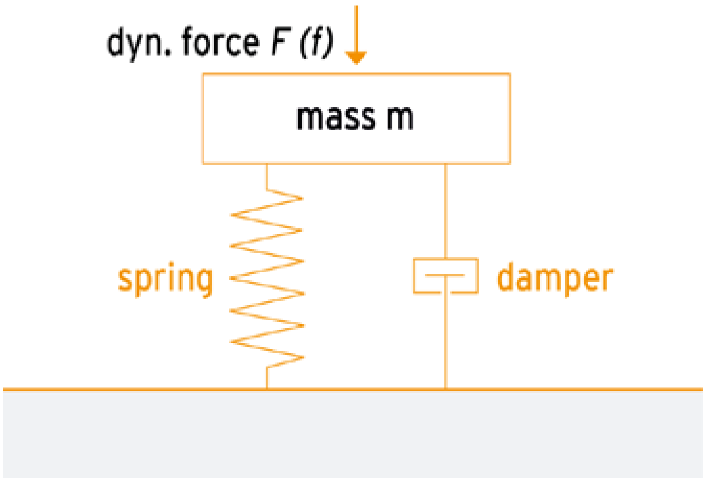
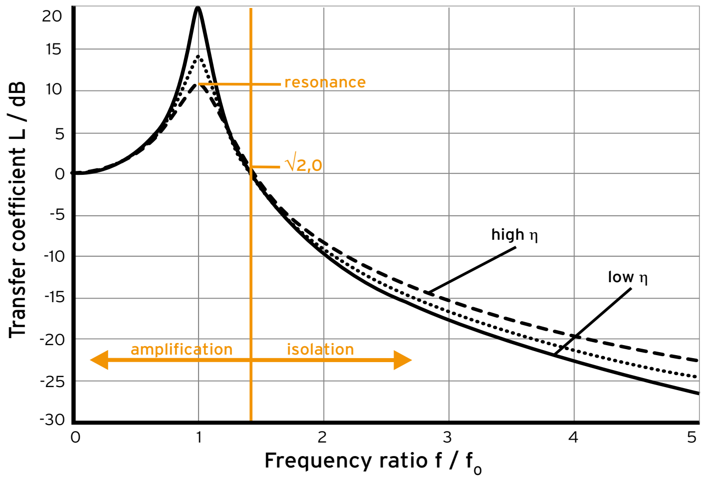


Fig. 3: Transfer coefficient L as a function of the relationship between the frequency f of the dynamic force and the natural frequency f_0. The mechanical loss factor η determines the actual shape of the curve.



The quantitative relationship between the deformation and load curves (fig. 4) denotes the stiffness of the material – in the case of the relative deformation and tension this is the dynamic modulus of elasticity E_{dyn} (a complex variable):

$$E_{dyn}(T,f) = E'(T,f) + i \cdot E''(T,f) = E'(T,f) \cdot |1 + i \cdot \eta(T,f)| \quad (4)$$

where the correlation $E''=\eta \cdot E'$ has been used.

E_{dyn} (in conjunction with other variables) determines the natural frequency f of the single mass oscillator (equation 1). The absolute value is expressed as:

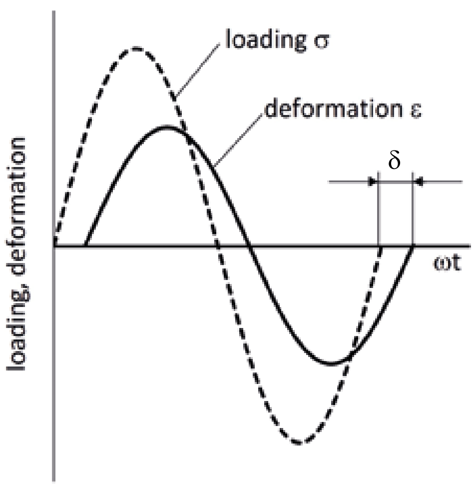
$$|E_{dyn}(T,f)| = \sqrt{[E'(T,f)]^2 + [E''(T,f)]^2} = \frac{\sigma_A(T,f)}{\varepsilon_A(T,f)} \quad (5)$$

where σ_A is the tension amplitude and ε_A the deformation amplitude (fig. 4).

Both the dynamic modulus of elasticity and the loss factor of an elastomer depend on the temperature and frequency. Furthermore, they are also a function of the pre-load and the tension amplitude (force-controlled measurement). The temperature dependency of the specified variables is at the heart of the development of an elastomer, as it is very pronounced due to various physical-chemical states: the curves E'(T) and E_{dyn} (T) show a step and the curve η(T) has a maximum (fig. 5). The properties of the material in the energy elastic range differ markedly from those in the entropy elastic range. For example, the modulus of elasticity of the two states can diverge by a factor of between ten and one thousand [1d].

In the energy elastic range – in other words at a low temperature – the mobility of the polymer chains is so limited that they cannot follow periodic-dynamic loading with the frequency f. The deformation associated with the loading therefore only correlates with the change in the interatomic distances and the distortion of valence angles, which explains why the deformation is small and the modulus of elasticity high. The material is also hard and brittle. The deformation work is stored as potential energy, resulting in a very high ideal-elastic component of deformation and a very small loss factor. When the loading decreases, the interatomic potential – in other words the interaction energy between the atoms – causes the microscopic forces that are responsible for the observable macroscopic recovery. This is why this state is known as the energy elastic state.

Fig. 4: Relationship between sinusoidal, dynamic loading σ and the deformation ε as response signal in the case of a viscoelastic material according to [1a]. ωt is the phase angle, ω the angular frequency given by $2\pi \cdot f$ and δ the so-called phase shift.



By contrast, in the entropy elastic range – that is, at a high temperature – the mobility of the polymer chains is very high. The rotation and rearrangement of chain segments and any existing side chains take place on a time scale that is short relative to the frequency f of the periodic-dynamic loading. The deformation curve of the material is therefore only shifted slightly compared with the load curve (fig. 4). For this reason, the mechanical loss factor in this temperature range is small. Due to the microscopic movements, the material is soft and the modulus of elasticity is therefore low. In the entropy elastic state, in contrast to the energy elastic state, energy is not the variable that makes the deformations reversible, but entropy: in a load-free state, the polymer chains exist as bundles. This is because, unlike extended chains, they result in less Gibbs energy due to the larger entropy term. Under load, the polymer chains are extended and the deformation energy is stored in the form of less entropy (or more Gibbs energy).

2.3 High-damping elastomers

For technical applications – as well as for general use – elastomers are almost always found in their entropy elastic state. It is in this state that they possess the properties that a spring element, for example, needs in order to provide vibration isola-

Fig. 5: Storage modulus E', loss modulus E'' and mechanical loss factor η of an elastomer with periodic loading (with constant frequency f) as a function of temperature according to [1c]. The stepped section of the storage modulus/the peak of the loss modulus define the glass transition range. The energy elastic range lies on its low temperature side, with the entropy elastic range on its high temperature side. The glass transition temperature T_g describes the position of the glass transition range; here, it is defined as the inflection point in the E' curve.

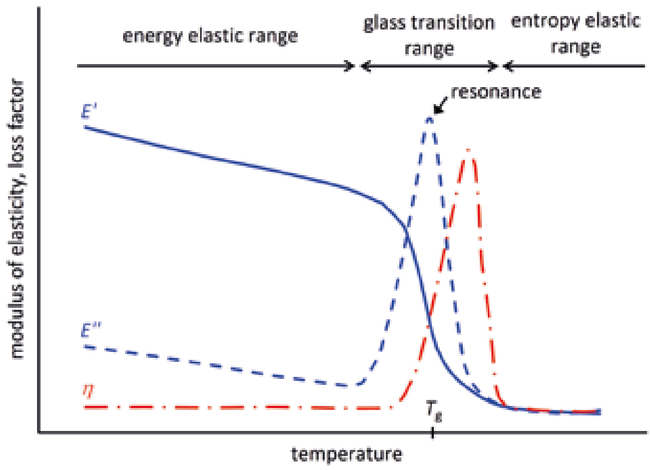


Fig. 6: The Sylodamp series consists of materials with six varying degrees of stiffness.

tion: E_{dyn} and η are small; consequently the transfer coefficient L in the range $f/f_0>\sqrt{2}$ is also small (fig. 3).

High damping elastomers – in other words those that absorb energy – are an exception: at service temperature, they have to exist in a transition state between the energy elastic and entropy elastic states. This is namely where elastomers transform deformation work into heat to absorb a large amount of the introduced energy. The temperature window associated with this transition state is known as the glass transition range, since the at least partially amorphous (glassy) solid softens when heat is applied. Because its chemical structure is based on macromolecules in the case of elastomers, the amorphous solid state is not converted immediately into a liquid state. However, the mobility of the chain segments and side chains is reminiscent of how they move in a polymer melt (which in the case of thermoplastics is in fact achievable through further heating).

In the entropy elastic state, the polymer chains relax quickly relative to the frequency f of the periodic-dynamic loading. In the energy elastic state, by contrast, they relax very slowly. In both cases, their microscopic movements are therefore decoupled from the macroscopic deformation. The consequence of this is that in the transition range between the two states, the movements of the chain segments (and any existing side chains) are not decoupled from the external deformation. The frequency f therefore determines the position of the transition range, while the coupling itself determines the properties of the elastomer in the corresponding temperature window. In much the same way as vibration-prone mechanical systems (fig. 2), the polymer chains move more or less in phase with the periodic loading. In extreme cases, resonance occurs, as with macroscopic systems (fig. 3). This situation usually occurs when the frequency f and the reciprocal of the relaxation time $1/\tau(T)$ are the same. The closer $f \cdot \tau(T)$ is to 1, the greater the coupling and the larger the loss modulus E''(T). The glass transition range therefore marks a peak in the curve E''(T) (fig. 5). Due to the relation $\eta(T)=E''(T)/E'(T)$, the mechanical loss factor also exhibits a peak. While resonance in mechanical systems results in an amplification of the vibration amplitude (fig. 3), it has a damping effect in elastomers (fig. 5).

The free volume theory of glass formation [1e, 2, 3] provides an explanation for the large loss modulus in the transition range: The volume of a test specimen decreases as it cools, causing the free volume between the polymer chains to decrease as well. At the same time, the interactions between the chains increase, since the interatomic distances become smaller. Even though the chain segments and side chains are still able to move, microscopic friction effects convert some of the macroscopic deformation work into heat. The corresponding energy component is lost and is hence no longer available to restore the original geometry of the test specimen, which delays the deformation with respect to the loading (fig. 4).

The peak of the curves E''(T) and η(T) is broad in the case of polymers as they are characterised by a wide range of relaxation times. Every difference in the chemical structure of individ-

Fig. 7: Mechanical loss factor of the six types of Sylodamp as a function of temperature (dynamic-mechanical analysis of a static loading below the upper limit of the static range of use, sinusoidal excitation with a speed level of 100 dB at a reference value of $5 \cdot 10^{-8}$ m/s and a frequency of 10 Hz, shape factor 3).

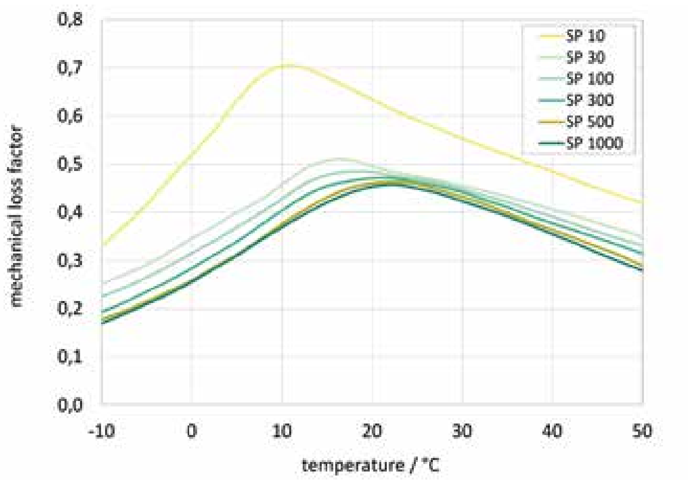


Fig. 8: Dynamic modulus of elasticity of the six types of Sylodamp as a measure of the stiffness of the materials as a function of temperature (dynamic-mechanical analysis of a static loading below the upper limit of the static range of use, sinusoidal excitation with a speed level of 100 dB at a reference value of $5 \cdot 10^{-8}$ m/s and a frequency of 10 Hz, shape factor 3).

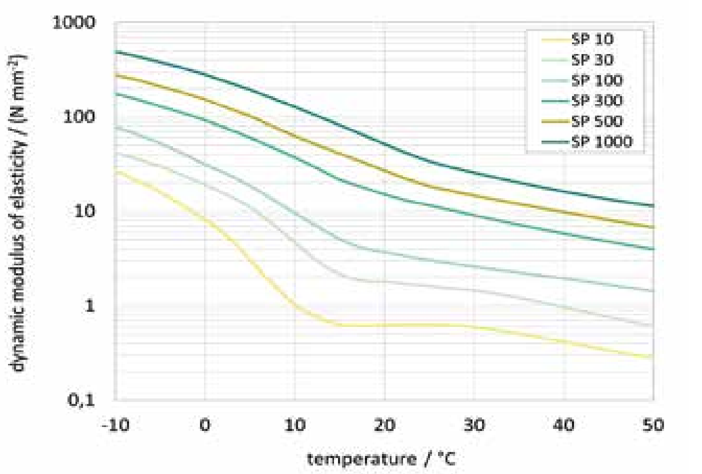


Fig. 9: Bearings of a compressor on parallel-connected cylinders made from Sylodamp and steel springs, respectively.

ual chain segments, in the length of side chains, etc., and every difference in the spatial environment of a segment results in a different relaxation time. The glass transition temperature T_g is a measure for the position of the glass transition range. There are various ways to define T_g, for example, as the temperature at which the curvature of the curve E'(T) changes its sign (inflection point, fig. 5).

2.4 Design of viscoelastic polyurethanes with pronounced damping

At service temperatures, products made of elastomers usually have a mechanical loss factor η of 0,1 to 0,2; their damping effect is therefore moderate. There are some elastomers with $\eta<0,1$ on the market, for example Sylodyn from Getzner Werkstoffe. Damping is very low with these materials. They are therefore used in such cases where they are to fulfil the function of a spring with as little loss as possible. An example is vibration protection, in which the transfer coefficient L in the relevant range ($f/f_0>\sqrt{2}$) should be as small as possible. On the one hand, the smaller η is, the smaller L will be (fig. 3). On the other, L is a function of the natural frequency $f_0 \propto \sqrt{(E_{dyn})}$ of the system. The smaller f_0 (or E_{dyn}) is, the larger the relationship f/f_0 – the x-axis in figure 3 – and the smaller the associated transfer coefficient L. Then again, the lower the loss modulus E'' and the loss factor η, the smaller the dynamic modulus of elasticity E_{dyn} (equation 5). Damping therefore increases the transfer coefficient L (equation 2) directly through η and indirectly through the correlation chain $E''–E_{dyn}–f_0$.

Elastomers with $\eta\geq0,3$ are strongly damping and are used as energy absorbers in impact load situations or to limit the resonance phenomenon in the case of periodic loading (fig. 3). When synthesising suitable polyurethane materials, the developer has to establish a recipe that is able to satisfy a range of different requirements in the best possible way:

a) Extent of the damping
b) Long-term mechanical stability
c) Width of the glass transition range

Regarding a): To achieve a loss factor $\geq$0,3, the specified service temperature has to lie close to the peak of the η(T) curve (fig. 5), in other words, within the glass transition range. The position of the glass transition is, for this reason, a command variable. It depends on four structural features [1f]: interactions between individual chains/chain segments (Van der Waals interactions, hydrogen bonds) and covalent bonds restrict the mobility of the main chains. Physical and chemical crosslinking therefore raises the glass transition temperature T_g. Moreover, T_g will be greater according to the extent to which the ability to rotate around the C–C bonds and the mobility of the chain sections with respect to each other are prevented. For this reason, bulky side groups and ring structures in the main chain increase the temperature of the glass transition range. Different polymers exhibit very different values for T_g, ranging from -70 °C (polyisobutylene) to 145 °C (polycarbonate) [1g].

Regarding b): Raw materials with damping structural features not only increase the viscoelastic component of deformation but also frequently the viscous component of deformation of the material. This has a detrimental effect on the creep as well as on the fatigue behaviour since the viscous deformation is irreversible, which reduces recovery ability. To fulfil the respective requirements of many technical applications, the recipe must therefore achieve the right balance between the conflicting material properties of damping and long-term mechanical stability.

Regarding c): The service temperature – in other words the temperature at which the materials must fulfil their function – is in fact a finitely wide range. In just about every application (installed in devices, inside buildings or outdoors), damping products must therefore demonstrate the required degree of energy absorption within a certain temperature window. As the service temperature has to lie close to the peak of the mechanical loss factor η(T) (see point a)), the peak should be as wide as possible. In this case, η(T) and energy absorption will not depend so heavily on temperature, and damping will be sufficiently high across the entire range of use. The broader the range of relaxation times, the broader the glass transition peak.

Fig. 10: Sylodamp protector to protect the body in the event of impact loading.

From a structural point of view, the material must therefore be heterogeneous, and the individual, local structures should all be present to about the same extent.

The diverse goals with respect to the properties of a new elastomer with high levels of damping and the chemical-physical correlation between these properties constitute a complex situation. Accordingly, the value of both theoretical and practical experience as a resource for companies that are developing their own recipes has to be strongly emphasised.

3 Sylodamp

Sylodamp is a highly damping polyurethane material from Getzner Werkstoffe. The characteristics profile of the material is the result of an optimisation process that takes account of all the requirements placed on a damping elastomer (see above). What it is definitely not is the result of maximising a particular property (damping, for example). Instead, it achieves a balance between a high loss factor ($\eta \geq 0{,}45$) and long-term mechanical stability.

3.1 Properties

Sylodamp is available in six varying degrees of stiffness, each of which is indicated by a particular colour (fig. 6). The varying degrees of stiffness enable an efficient construction for different static loads in the range 0.005 N/mm^2 to 0.5 N/mm^2. Depending on the type used, Sylodamp is able to tolerate load peaks that can be as much as ten to fifty times larger than the upper limit of the static range of use. The compression set is less than 5 % (test conditions: 25 % compression, 23 °C, 72 hours; examination 30 minutes after removal of the load).

In the case of classical elastomers, practically the whole glass transition range lies below room temperature. Thus the mechanical loss factor at room temperature is low: 0,1 to 0,2. By contrast, it is $\geq 0{,}45$ for the types of the Sylodamp series, as in their case the peak of the curve $\eta(T)$ lies close to room temperature, and is therefore in the service temperature range (fig. 7). At the same time, the width of the $\eta(T)$ peak, and hence the glass transition range, are so large that the damping characteristics of the material within the range of use are not too dependent on the temperature.

The rebound resilience of 13 % to 16 % and the (with respect to the weight per unit volume) relatively high dynamic stiffness (fig. 8) reflect the pronounced damping response of Sylodamp.

3.2 Applications

Sylodamp reduces the extent of resonance phenomena in applications with periodic loading (fig. 9). In the event of an impact, it isolates structure-borne noise and causes a fast decay of the vibration's amplitudes. It also protects mechanically stressed components, sensitive electronics and people (fig. 10) from excessive forces – for example when used as a material for the feet of punching machines, as impact protection, etc.

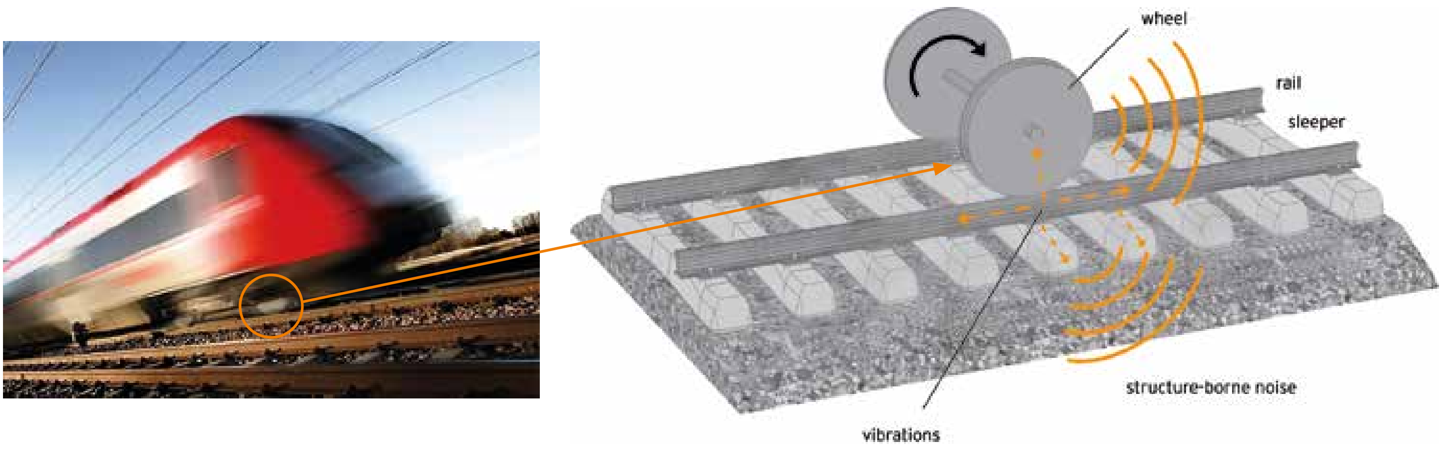
Engineers can optimise the required effect (vibration isolation, vibration damper, reduction in maximum force) by combining the materials with differing spring or damping characteristics in parallel or in series (fig. 9). Carrying out local structure-borne or airborne noise measurements helps optimise the application in question and select the materials in the best possible way.

4 Noise and vibration reduction in railway

The characteristics profile of Sylodamp maintains a balance between the conflicting material properties of damping and long-term mechanical stability. As a result, the material will bring about improvements to products in many ranges of use that do not have extreme specifications.

However, if the requirements with respect to the fatigue behaviour are exceptionally high – as it will be in the railway industry for instance – the formulation of the recipe realised

Fig. 11: Noise caused by railway traffic: the interaction between the wheel and the rail causes the wheels, rails and sleepers to vibrate [5], generating airborne noise.



in Sylodamp will need to be modified. During the optimisation process, the long-term stability factor will receive greater weight, and raw materials that match the target properties of the final product will be used. Railway-specific products made from polyurethane materials with high levels of damping have huge potential, since they extend the service life of the railway superstructure [4] and can also reduce railway noise. The latter is steadily increasing due to the heavier utilisation of railway tracks – as is the noise pollution that affects human's health.

It is the vibration of rails and sleepers that causes the noise emanating from the railway superstructure (fig. 11). High-damping rail pads could reduce these vibrations and hence help reduce noise levels. Rail pads normally act as elastic elements between the rail and the sleeper. They cause the load of the train to be distributed across several sleepers, thus protecting the superstructure and reducing how often it needs maintenance. Conventional rail pads made of elastic materials with small mechanical loss factors fulfil this requirement very well, but have practically no effect on the vibrations from the rails and sleepers and the associated noise emissions. By contrast, viscoelastic, high-damping rail pads (fig. 12) have the potential to lower vibration amplitudes and hence the emitted noise level.

5 Summary

High-damping elastomers are viscoelastic materials. As they deform, they absorb motion energy due to friction between the chain segments in the polymer matrix. Engineers therefore use damping elastomers to reduce load peaks resulting from impacts and to limit resonance phenomena in the case of periodic forces. With Sylodamp, Getzner Werkstoffe has developed a range of materials for such applications. At room temperature, it has a pronounced damping effect: the mechanical loss factor for all six types of Sylodamp is ≥0,45.

To achieve such a high loss factor, the viscoelastic component of deformation has to be very large. Sylodamp is therefore based on chemical structures that cause the material to exist at room or service temperature in the glass transition range, where the polymer chains move more or less in phase with the periodic loading; at the same time, the free volume available for these microscopic movements is low. Both cause microscopic friction so that energy is dissipated.

The characteristics profile of Sylodamp is the outcome of a physical-chemical optimisation process that results in both a high loss factor and a high long-term mechanical stability of the material. It is therefore ideal for a broad range of applications in which people, sensitive electronics or mechanically stressed components have to be protected from excessive forces.

Moreover, high-damping polyurethane elastomers have huge potential as protection against noise. For example, damping rail pads in the railway superstructure can reduce the vibrations of wheels, rails and sleepers, and thus lower noise emissions. To satisfy the rail industry's requirement concerning fatigue behaviour within the development of an innovative damping rail pad, the formulation used for Sylodamp is to be modified to give greater weight to the long-term stability factor.

Fig. 12: Sample of a high-damping rail pad made of viscoelastic polyurethane

6 Literature

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