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Comparative Analysis of Die Materials for Reducing the Rebound-Effect in Electromagnetic Forming Processes

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Abstract. The rebound-effect that frequently occurs during electromagnetic sheet metal forming is one of the main causes of deviations in the shape and dimensional accuracy of flat surfaces. The selection of the die material and its corresponding energy absorption capabilities has a critical impact on this effect. This article analyses materials with different physical properties in terms of their energy absorption behavior under dynamic impact load. A variety of model tests are being conducted to examine a wide range of impact velocities and energies. The experimental setups comprise two variations of a drop tower test, which can be used to determine the percentage of impact energy absorbed at high and low momentum. To achieve higher impact velocities, a third experiment involving an electromagnetically accelerated impact body was conducted for the material that demonstrated the best result in the preceding tests.

Introduction

Electromagnetic forming (EMF) is an impulse-based, high-velocity forming process for electrically conductive materials that uses Lorentz forces for plastic forming. As shown in figure 1, during electromagnetic forming, a tool coil is subjected to a damped sinusoidal current, which generates a magnetic field around the coil and induces an oppositely directed current in the workpiece. The interaction between these currents and magnetic fields creates Lorentz forces that deform the workpiece. Due to the high forming velocity, this process results in significantly higher formability and reduced spring back when forming aluminum sheet alloys compared to conventional processes. However, the high forming velocity means that the workpiece has a correspondingly high level of kinetic energy when it encounters the die. If this kinetic energy is not dissipated sufficiently, the remaining energy can cause the workpiece to bounce back. This is called the rebound-effect [1].

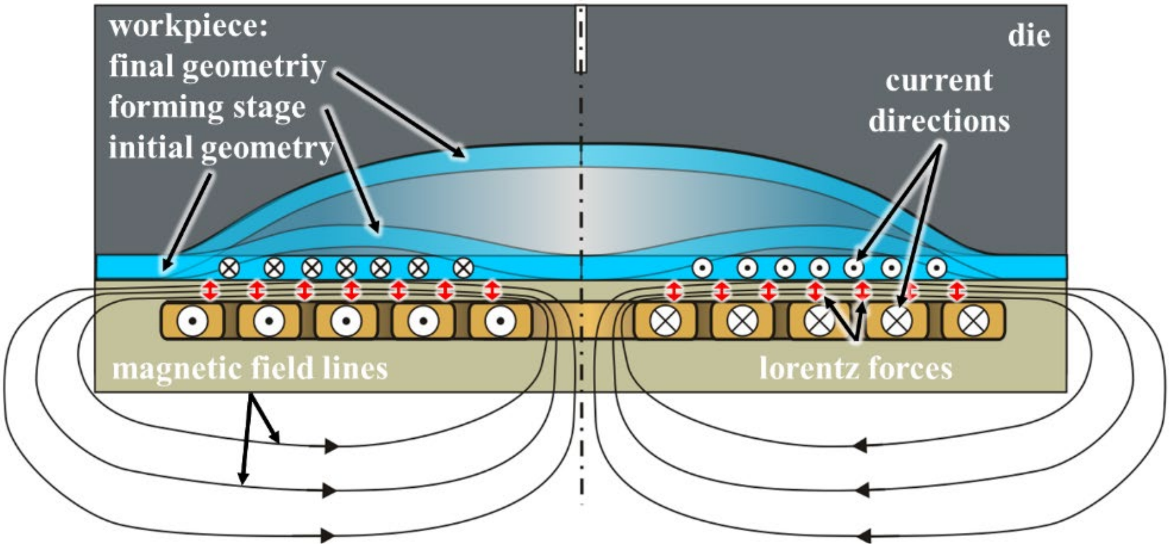

Fig. 1. Principle electromagnetic forming.

One way to reduce the rebound-effect is to vary the die material [2,3]. Upon contact with the die, high localized loads and sudden stresses can occur under certain boundary conditions. To achieve good forming results, the die material must be able to absorb high energy during the short contact period without sustaining damage.

One of the first studies on how the die properties influence the forming results was conducted by Risch et al. [2]. In a simulation of the EMF process, a spring-damper-system was substituted for the die instead of a completely meshed FE-model. The spring stiffness represents the geometrical and material stiffness. The damping coefficient represents the materials damping properties. Both parameters were varied while using the same input energy for the coil. The results show that there is an optimal damping coefficient for each of the spring stiffnesses investigated. Too little or too much damping has a negative effect on the forming result. On the other hand, the workpiece geometry achieved the best possible flatness with a relatively low spring stiffness. In fact, it was so low that the bottom of the die was moved by the workpiece at the time of impact. In [5], Liu et al. have conducted similar simulation studies with the addition of experimental tests. The outcomes are almost identical. These studies show that dissipating impact energy is a difficult task, as the mechanisms in materials with good energy absorption may involve deformation. While rebound can be reduced, the deformation of the die can also lead to deviations from the target geometry of the workpiece. In addition, a severely deformed die is no longer usable. In both studies, no specific materials were examined.

When searching for studies regarding the energy absorption of materials, in most cases the tests are destructive [7, 8, 9] as the corresponding use cases may allow damage in exchange for better energy absorption, like a crash scenario. For sheet metal forming, this is not desirable as the die will be used to produce up to thousands of parts, while delivering accurate forming results repeatedly.

The only paper investigating the energy absorption of die materials under dynamic impact conditions directly is [3]. The materials researched were steel, elastopal and wood. In a test, an impact body was accelerated in a pipe at 10 m/s and 25 m/s. Given that the impact body weights 377 g, the impact energy can be calculated as 19 J and 118 J respectively. Elastopal stores energy in form of elastic deformation, returning some part of it to the impact body. With impact absorption rates of 60-70 %, elastopal showed the worst results. With 92%, wood may have absorbed the most energy, but it gets damaged due to the impact stress. While the results with steel showed good absorption rates at low impact energies, the values dropped from 91% to around 60% at high impact energies. In summary, no suitable material for the die was identified. Until now, little research has been conducted on this topic.

Investigated Materials

In this paper, potential die materials with different physical properties and certain material combinations are analyzed regarding their energy absorption under impulsive load and damaging behavior. It is also of interest whether there is a correlation between energy absorption and characteristic material properties, such as density, hardness and Young's modulus.

Steel, compressed laminated wood and a polyurethane (PUR) modelling block were chosen as references, as they were used in [3, 5]. The new materials to be examined are agglomerated cork, a rubber granulate mat, vulcanized fibre, viscoelastic PUR and sand. According to [9], agglomerated cork can dissipate energy under dynamic loads effectively because of its cellular microstructure. At low loads, the material shows elastic behavior. With increasing loads, the stress-strain curve plateaus. The cell walls bend elastically and the air inside the cells is compressed, increasing stiffness. Under this load, the restoring forces of the elastic cell walls are high enough that the agglomerated cork returns to its original state when slightly dented. At higher loads, the cell walls of cork collapse progressively and the damage gets irreversible.

Rubber on the other hand is commonly used for impact absorption in footwear [11] and playground safety mats [12], which is why it may be of interest for the given use case. Rubber and other elastomers, such as elastopal, absorb energy through elastic deformation upon impact. Part of the energy is converted into heat through internal friction, but a significant amount of impact energy may be returned to the impact body.

In contrast, viscoelastic PUR behaves differently under dynamic loads. First, the impact also causes elastic deformation, with part of the energy being turned into heat. The difference lies in the energy return behavior. Compared to the contact time of the impact body, the viscoelastic PUR takes significantly longer to regain its original shape after the initial deformation. In conclusion, a substantial amount of energy is stored instead of returning it to the impact body. This effect reduces rebound significantly [10].

A material whose energy absorption properties have not yet been investigated is vulcanized fibre. It is a highly sustainable, cellulose-based material which consists of multiple paper layers laminated over a chemical reaction [13].

The last material examined is sand. It is used in roadside barriers or rock sheds to mitigate impact forces. In general, the main mechanism for dissipating impact energy in sand is grain friction. If the sand has air between the grains and enough room for deformation, the energy absorption is at its highest. But for the use in dies, the impact behavior must be repeatable. The loose grain structure results in sand changing its shape when impacted. Thus, a container with a rigid top layer is required. For the top layer, steel appears to be suitable. As explained in [6], the impact energy traverses steel in form of an elastic deformation wave. This enables steel to transfer a great amount of impact energy to a larger area of the underlying material while maintaining its shape. To prevent the volume of sand from changing, a sufficient pre-compaction is needed. Compacted sand tends to expand under shear forces, causing the particles to rearrange themselves, but due to the confined space, the grains are pushed on top of each other. Besides grain friction, this effect also contributes to the dissipation of energy [14]. All the materials investigated are listed in table 1.

Table 1. Overview of the examined materials.

Die material	Density in kg/m^3	Young‘s-modulus in N/mm^2	Hardness	Compressive strength in N/mm^2	Thickness of sheet/ stacked material in mm
Steel (S355JR)	7850	210000	180 HB	355	10/40
Compressed laminated wood	800	14000	Shore D 70-80	55	40/40
PUR modelling block	1350	3400	Shore D 83	95	40/40
Agglomerated cork granulate	200	<10	Shore A 50	<2	10/40
Rubber granulate mat	800	<10	Shore A 40	<2	20/40
Vulcanized fibre	1300	4500	Shore D 70-80	150	6/36
Viscoelastic PUR	800	10	-	-	12,5/37,5
Sand (+ Steel Plate)	1500	-	-	-	30 (+10)

As indicated in [2, 3], depending on the mechanisms at work in the material to dissipate energy, higher thickness can have a positive effect on energy absorption. The material thickness was set to approximately 40 mm to keep the variable parameters of the tests manageable. Materials that were only available in smaller sheet thicknesses were stacked.

Experimental Setup and Implementation

The energy absorption is characterized by three different model tests. All three test setups are based on the rebound hardness test by Leeb [15]. In these tests an impact body with a defined mass, velocity and resulting energy strikes the surface of the material sample. Figure 2a shows the principle test setup, which is the same for all three implementation variants. The front of the impact body has a hemispherical shape with a radius of 25 mm. To prevent damage to the hemispherical impact body, it was made of steel instead of aluminum, which is usually used as workpiece material. The material samples are placed in a material holder and secured with a fixing plate.

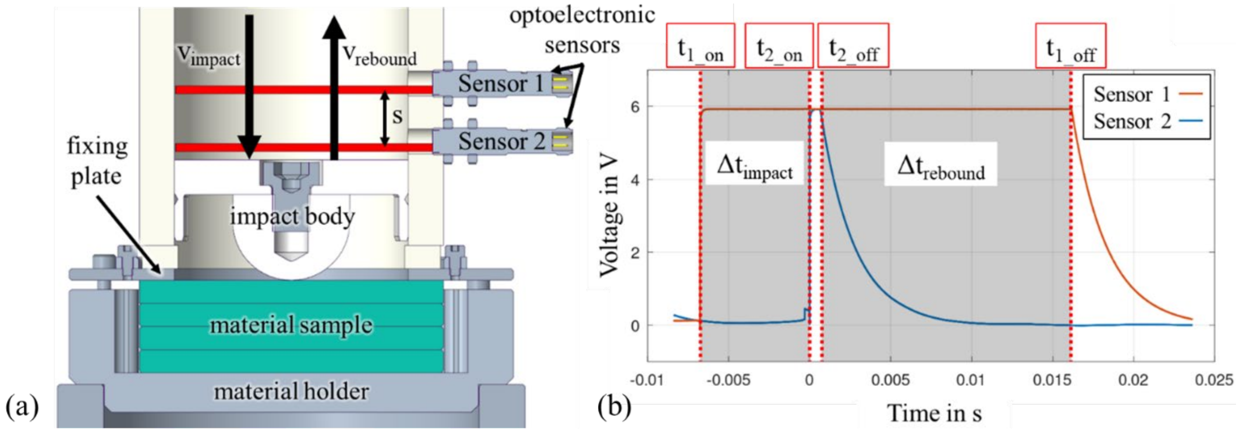

Fig. 2. Measuring setup (a) and data (b) for calculation of impact and rebound energy.

To determine the impact and rebound energies, the corresponding velocities are needed [6]. Optoelectronic sensors were used to determine the time which the impact body needs to overcome a defined distance s directly before and after the impact. In all tests, they were placed as low as possible to ensure accurate measurements. The sensors send a signal when there is no object in front of them. Using the distance s between the two optoelectronic sensors (fig. 2a) and the difference in trigger times Δt_{impact} and $\Delta t_{rebound}$, the impact velocity v_{impact} and the rebound velocity $v_{rebound}$ are calculated as shown in equation (1) and (2). Δt_{impact} is the difference between the trigger times t_{1_on} and t_{2_on} during impact, as shown in figure 2b. $\Delta t_{rebound}$ is the difference between the trigger times t_{2_off} and t_{1_off} during rebound.

$$v_{impact} = \frac{s}{\Delta t_{impact}} \tag{1}$$

$$v_{rebound} = \frac{s}{\Delta t_{rebound}} \tag{2}$$

The impact energy E_{impact} and rebound energy $E_{rebound}$ can be calculated using the following equations, given the known mass m of the impact body.

$$E_{impact} = \frac{m}{2} \cdot {v_{impact}}^2 \tag{3}$$

$$E_{rebound} = \frac{m}{2} \cdot {v_{rebound}}^2 \tag{4}$$

The relative energy absorption η is calculated by dividing the absorbed energy $E_{absorbed}$ by the impact energy.

$$\eta = \frac{E_{impact} - E_{rebound}}{E_{impact}} = \frac{E_{absorbed}}{E_{impact}} \tag{5}$$

The initial investigations of the die materials were carried out using a drop pipe, as shown in figure 3a. It consists of a drop pipe, under which the material holder is placed. The die materials were analyzed using the already mentioned hemispherical impact body. The drop pipe tests are conducted with an impact body weight of 0.5 kg at heights of 1, 2 and 3 meters. This corresponds to impact velocities of 4.2, 5.3 and 6.5 m/s as well as impact energies of 4.5, 6.5 and 10.3 J. To investigate the influence of higher impact energies, a second test setup shown in figure 3b was created. The drop tower comprises a drop weight and the material holder positioned under it. The hemispherical impact body is attached to the drop weight. This results in a combined drop body mass of 10.75 kg. The drop height can be varied from 0.4 to 1.8 m, generating impact velocities from 2.6 to 6 m/s and impact energies from 37 up to 192 J. The material that demonstrated the highest energy absorption in the initial two test setups was then analyzed in a third setup. The goal was to investigate the dependence of impact velocity on energy absorption. The test setup is shown in figure 3c. By adding an aluminum body, the hemispherical steel body was electromagnetically accelerated using a tool coil. This results in an overall impact body weight of 0.77 kg. To guide the impact body, a polyoxymethylene (POM) tube was used. The tube material was chosen because of good sliding properties. The drop height was set to be 0.35 m. The material holder used in the first two test setups is located under the POM tube. By gradually increasing the charging energy of the tool coil and thus the impact body velocity, a curve is generated showing the dynamic energy absorption behavior of the material. Several tests were conducted at impact energies ranging from 3.6 to 31.2 J and velocities of 3 to 9 m/s, respectively.

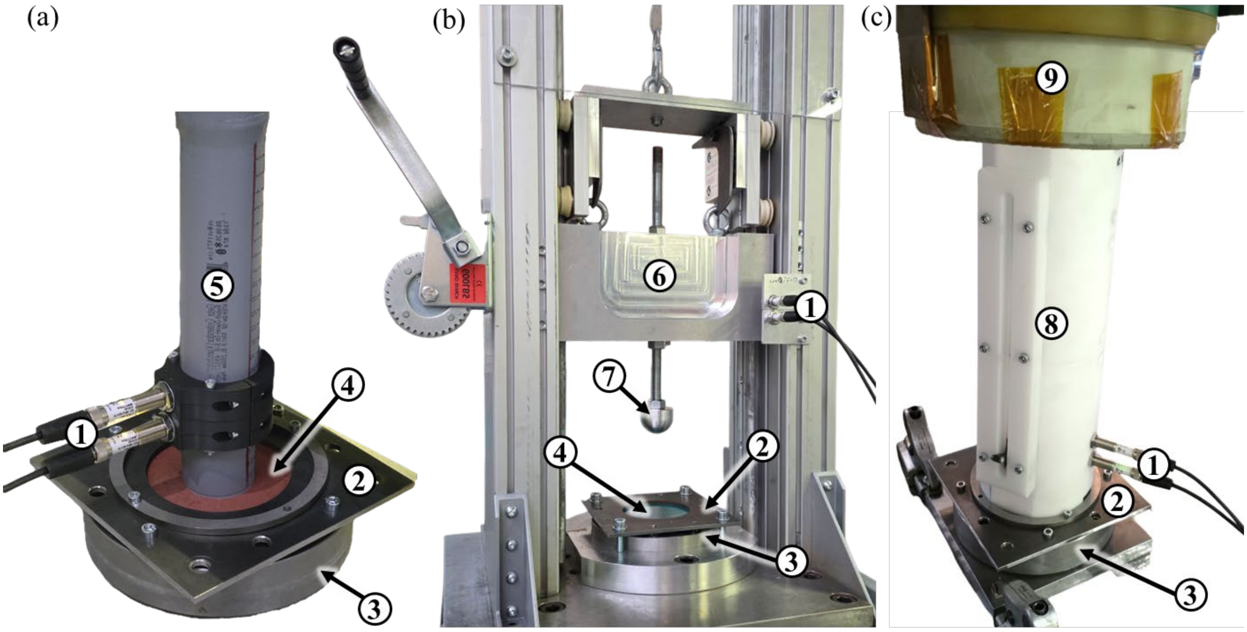

Fig. 3. Drop pipe (a), drop tower (b) and electromagnetically accelerated impact body (c) test setups: (1) optoelectronic sensors, (2) fixing plate, (3) material holder, (4) material sample, (5) drop pipe, (6) drop weight, (7) hemispherical impact body, (8) POM tube, (9) tool coil.

Results and Conclusion

First, the drop pipe tests were carried out. The results are summarized in figure 4. The red error indicator shows the range in which the results fluctuate. It must be mentioned beforehand that there was no clear correlation between the energy absorption rate and the impact energy for this test series. In the following discussion, the results from the three drop heights are averaged. For all drop heights, the PUR modelling block showed the worst results with an average energy absorption of 50%. With around 57%, the vulcanized fibre was only slightly better. The rubber mat achieved an absorption rate of 67%, which is similar to the elastopal investigated in [3]. While agglomerated cork is slightly better at 70 %, a dent is formed at 2 m drop height. It regains shape after a short period of time. At 3 m, the damage gets irreversible. The compressed laminated wood achieved an absorption rate of 72%. What should be noted is that the material was damaged at all drop heights. By comparing the hardness, density and E-modulus with the wood used in [3] and [4], the selected material variant may have been too soft for a valid comparison. On the other hand, it is already known that even harder compressed laminated woods are damaged when used in an EMF process. In summary, none of the materials mentioned up to this point can be recommended for making dies.

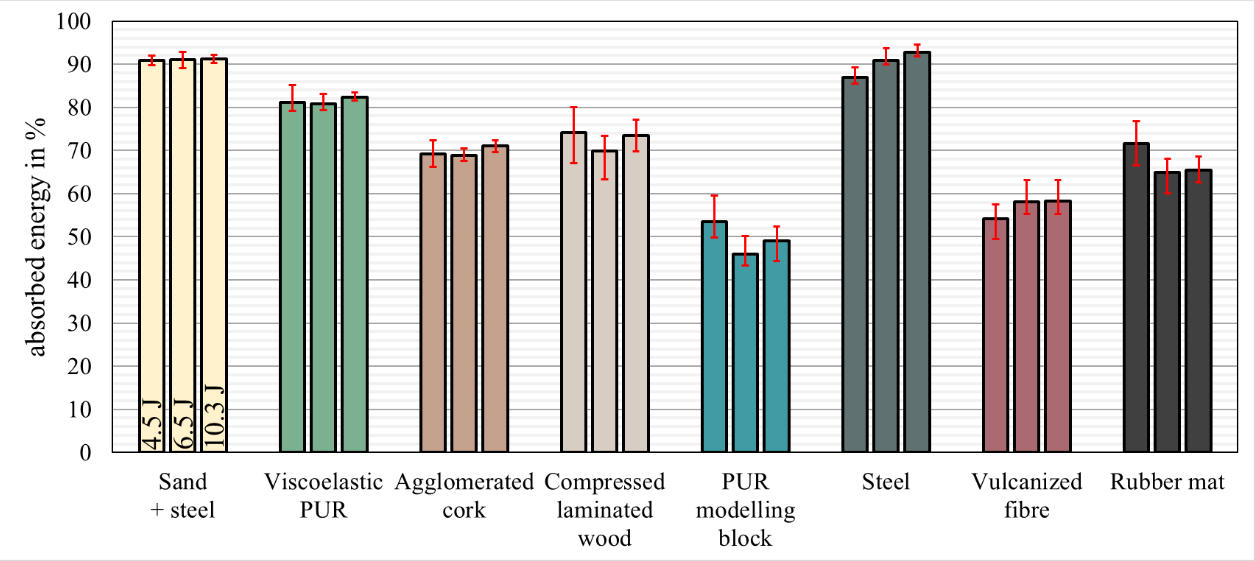

Fig. 4. Drop pipe test results at 4.5, 6.5 and 10.3 J impact energy with error indicator (red).

The first material that seems promising is the viscoelastic PUR at 81% energy absorption. It is important to mention that there was no indentation after the impact. In conclusion, the impact energy in these tests was too low to engage the viscoelastic material behavior, which limits the materials ability to absorb energy. With an absorption rate of 90%, steel was the second best material tested, followed only by the sand-steel combination at 91%.

To test the materials under higher impact loads, the drop tower test with a drop height of 0.4 m was conducted, which corresponds to an impact energy of 37 J. Besides the already mentioned agglomerated cork and compressed laminated wood, which were not tested again, vulcanized fibre and the PUR modeling block were also damaged. The only useful measurements were taken for the viscoelastic PUR, steel and the sand-steel combination. As expected, the energy absorption of viscoelastic PUR increased to around 85%. The impact body caused a temporary indentation, which means energy is stored in the material after the impact. The indentation left behind disappears after a finite period and the same amount of energy can be absorbed again. At 91%, the sand-steel combination remains the best, independent of impact energy.

By further increasing the drop height to 1.8 m, which corresponds to an impact energy of 192 J, only the viscoelastic PUR stays undamaged. Its absorption rate further increases to 88%. With 6 m/s, the impact velocity is similar to 6.5 m/s in the drop pipe test. The material shows a clear correlation between impact energy and energy absorption but is independent of impact velocity.

With a direct impact of the hemispherical impact body, the load is concentrated on a spot. By adding a steel plate, the load is distributed more evenly on the material below. Some of the materials damaged in the previous tests might benefit from this. In another drop tower test, all materials were reduced to 30 mm in thickness and covered by a 10 mm thick steel plate. Figure 5 shows the results of the drop tower tests of the materials in combination with a steel plate. As drop height, 0.4 m was chosen. The test setup for steel and the sand-steel combination remained the same, as steel was already used for the top layer.

As desired, none of the tested materials were damaged. Starting with the rubber mat, the energy absorption stays at 72%, which is similar to the previous tests without the steel plate. The absorption rates of vulcanized fibre, the PUR modelling block, the compressed laminated wood and agglomerated cork all increased to 83%, 85%, 85.5% and 86.5% respectively. As stated in [3], the impact absorption of steel decreases with increasing impact energy. The value dropped to 83%. In conclusion, steel can be used as a die material, provided that the impact energies are low. Lastly, the energy absorption of viscoelastic PUR increased to 90%, which makes this combination almost as good as sand and steel. As shapeless sand is difficult to handle, the combination of viscoelastic PUR and steel may be more attractive for the application in dies.

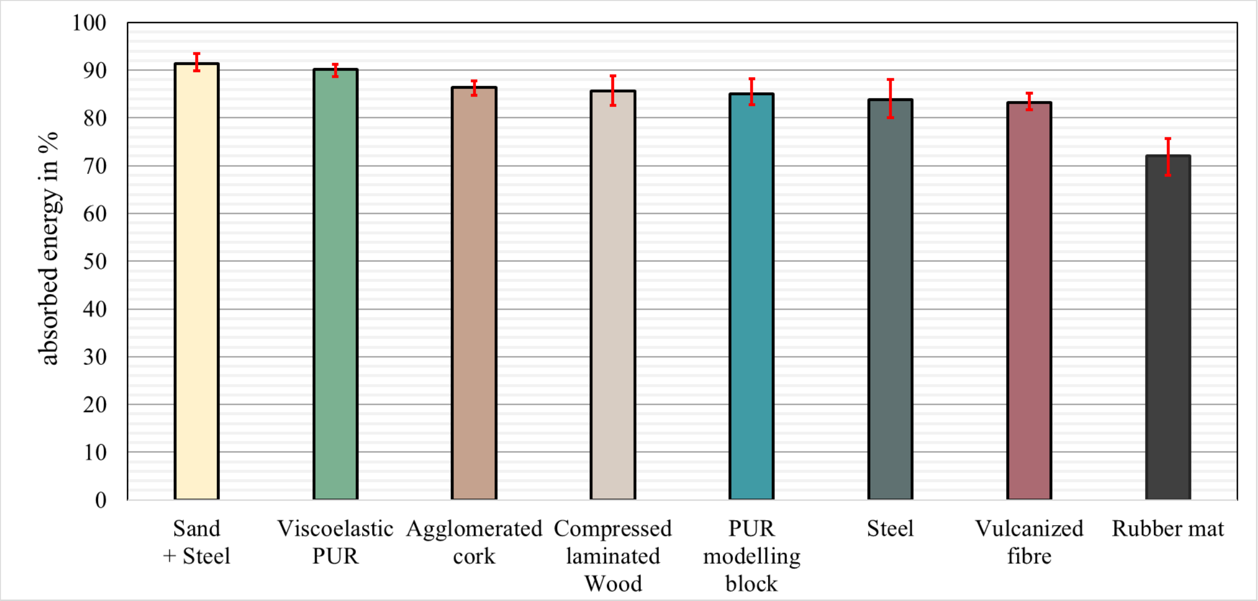

Fig. 5. Drop tower test results at 37 J impact energy and indirect impact on steel plate with error indicator (red).

Since sand with a steel cover plate had the best overall results, a series of tests was carried out with an electromagnetically accelerated impact body for investigating the absorption behavior at higher velocities.

One factor also investigated in this test is the influence of momentum on energy absorption. The same impact energy can be generated with different combinations of speed and mass, as shown in equations (3) and (4). In [7], Artero-Guerrero et al. summarized many previous studies on this topic. The results showed that the momentum had no significant influence. In [8], different standardized drop weight test systems produce slight differences in results. Mathe et al. found that a longer contact time at high momentums, particularly with softer materials, results in larger indentations and potentially small differences in the energy absorption rate compared to a low momentum impact at the same energy level. The momentum can be calculated using the following equation [8].

$$p = m \cdot v \tag{6}$$

That results in a momentum of 30 kg·m/s for the drop tower test and 6.8 kg·m/s for the accelerated impact body test at impact energies of 37 and 31 J respectively. To take the momentum into account, the velocity of the impact body was increased steadily. Figure 6 shows the results of the electromagnetically accelerated impact body tests.

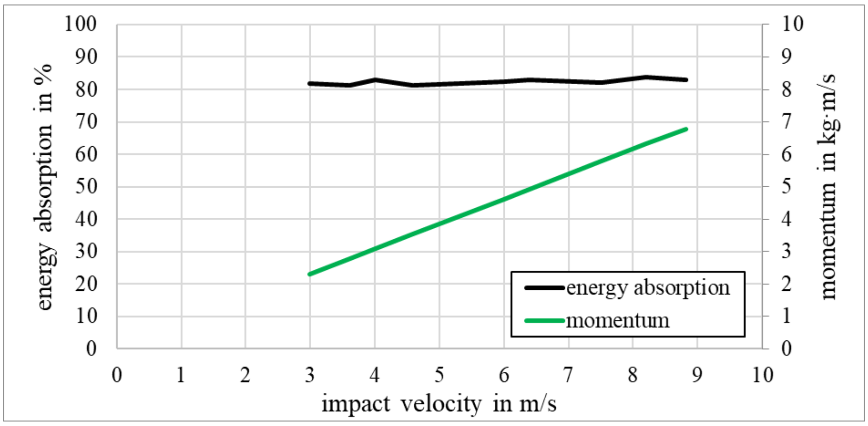

Fig. 6. Relation between energy absorption, momentum and impact velocity for the sand-steel combination.

First, no significant influence of impact velocity could be determined, as the energy absorption stays consistent. The lower average energy absorption values of approx. 83% instead of 91%

determined in the earlier experiments (see fig. 4,5) are due to the test setup. To fix the POM tube in place during the tests, the top of the machine table is lowered until the tube can no longer move. This exerts additional pressure on the metal plate, which limits the movement of the sand grains. To verify whether the properties of the sand-steel combination changed during this test series, the impact body was dropped in the POM tube without additional acceleration or pressure exerted on the steel plate. This was done before and after the test. The results were an energy absorption of 91% for both cases. In conclusion, the energy absorption properties of the sand-steel combination are independent of impact velocity. By comparing the results of the drop pipe, drop tube and accelerated impact body tests, no influence of momentum was shown, as the results are 91% throughout. For all examined velocities, momentums and impact energies, the energy absorption of sand and steel remains consistent.

Lastly, it was of interest if there were correlations between the energy absorption and material properties, like density, E-modulus and hardness. With its lose grain structure, only the density could be determined for sand at approx. 1500 kg/m^3. When comparing steel and the viscoelastic PUR, which show comparable energy absorption rates depending on the impact energy, the densities differ significantly at 7850 kg/m^3 and 800 kg/m^3 respectively. While the E-modulus for steel is at 210000 N/mm^2, the value for viscoelastic PUR is at 10 N/mm^2. Consequently, no correlation between the material properties and the energy absorption could be established for the examined materials. The main reason is the difference in mechanisms at work to dissipate energy in the materials.

Summary and Outlook

In this paper, materials with different physical properties were investigated in three impact body tests. The goal was to determine the material with the best energy absorption to reduce rebound for EMF. Especially compared to previously used materials like compressed laminated wood or the PUR modelling block, alternatives with significantly better energy absorption and no signs of damage were found. The combination of sand with a form-stable steel cover plate as well as the viscoelastic polyurethane both seem promising as potential die materials to reduce rebound in the EMF forming process. The energy absorption of the sand-steel combination is independent of the impact energy in the range of values examined. In contrast, the energy absorption of viscoelastic PUR improves as the impact energy increases, while that of steel decreases. For all Materials, no dependence of impact velocity or momentum on energy absorption was found. In the future, the results must be validated by using the materials as dies in a real EMF process. If the absorption rates are different compared to the model tests, the material of the impact body may influence energy absorption. This has yet to be investigated. As the results for steel showed good absorption rates at low impact energies, comparative tests should be carried out. Further tests are also required to verify the optimal material thickness or depth of the sand container for maximum energy absorption.

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