The effect of test parameters on the impact resistance of a stainless steel/rubber/composite hybrid structure

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Abstract

In the present study, high velocity impact tests were carried out on stainless steel/rubber/composite hybrid plates. The projectile velocity, impact angle, number of impacts, sample temperature, and prior ageing were used as variables in order to investigate the effect of test parameters on the impact behaviour of the samples.

In general, the energy absorption and the damage behaviour of the studied hybrid structure were rather immune to the changes in the test parameters. Only the impact angle showed a stronger effect with increasing plastic deformation and dissipated energy with increasing impact angle. Similar but not as strong effect was found with increasing sample temperature. In addition, the effect of increasing impact angle on the damage size was found to be stronger than the effect of increasing impact energy at a constant impact angle. The repeated impact studies showed that the structure does not lose its ability to withstand dynamic loading even when there is a gradually progressive damage. The results support the potential of the studied steel/rubber/composite hybrid structure to be implemented in real life applications.

Keywords: Hybrid structure, high velocity impact, impact angle, strain rate, repeated impacts, temperature, ageing.

1. Introduction

When designing lighter and more economic products, hybrid structures offer great advantages because they enable tailoring the properties of a product in a way which is unattainable by any material alone [1]. In addition to lighter weight, hybrids can introduce, for example, more beneficial manufacturing methods [2] or improved damping properties [3]. However, the implementation of such new structures requires in-depth knowledge of their behaviour in different loading conditions and environments.

Layered, adhesively bonded structures are prone to damage caused by out-of-plane impacts due to their susceptibility to delamination. In addition, composite materials, which are typically used as one of the components in hybrids, are prone to damage caused by transverse loads themselves [4]. Thus, to enable the prediction of a hybrid's behaviour in an application, it is essential that the impact behaviour of the structure is known. In a previous study [5], we investigated the properties of steel/rubber/composite structures in high velocity impacts, which typically cause in-service impact voids [6]. By varying the rubber thickness and the impact energy, we found that even a thin rubber layer can decrease the impact damage area remarkably and that the dependence between the impact energy and damage area is linear at the studied energy range [5], when other test parameters are kept constant. However, in real life applications the impact conditions may vary remarkably. Examples of the possible variables in addition to the impact energy are projectile velocity, impact angle, surrounding temperature, as well as structure's prior exposure to harsh environments. In the literature, impact studies where the impact test parameters are varied can be found to a large extent for single materials, whereas the studies on hybrid structures can be found to a much lesser extent.

The impact angle determines the normal force of the projectile and thus has an effect on the deformation. If the impact angle is 90°, i.e. the projectile enters the surface at a perpendicular angle, the deformation is more compression-like in the impact area, whereas a small impact angle leads to a shear-like deformation. Thus, through different deformation modes the impact angle has an effect on the impact behaviour of materials. However, the effect of impact angle on the behaviour of materials is not widely studied, probably because the impact test set-ups rarely enable adjustment of the impact angle. For example, Walley et al. [7] have investigated polypropylene under high velocity impacts and found that increased impact angle results in more severe deformation [7].

The strain rate behaviour of materials is a widely studied area. Since steels [8], rubbers [9] and composites [10] are known to exhibit strain rate dependent behaviour, it can be assumed that a hybrid structure consisting of these components would do that as well. Typically the strain rate dependence is presented in a logarithmic scale. For example, Okoli [11] found linear relationship between expended energy and the logarithm of strain rate for glass fibre reinforced epoxy laminate.

Although a single impact event could leave the material rather intact, the accumulation of impact damage in a certain area may affect seriously the mechanical properties of the material. Thus it is important to study the effect of repeated impacts. In our previous study [5], we found that the primary damage mechanisms of the steel/rubber/composite hybrids were interfacial delamination and fibre/matrix debonding. Thus the possible increase in delamination and the damage accumulation in composite are at highest concern. For glass fibre reinforced epoxy composite, Hosur et al. [12] found that the amount of absorbed energy per impact does not change during repeated impacts, and the increase in damage size becomes insignificant after a number of impact events.

In addition to the dimensions of the sample and the parameters of the projectile, the environmental conditions, such as exposure to low/high temperatures or to humidity before or during the impact event, are important variables as well. For composite structures, some impact test studies can be found in the literature that concentrate on the effect of the environment. Sayer et al. [4] studied carbon-glass fibre reinforced epoxy composites and found that the energy absorption capability of the composite is highest at room temperature and decreases towards colder and hotter temperatures. The effect of prior cold-dry and cold-moist environments on the carbon fibre reinforced epoxy composite has been studied by Hosur et al. [13]. They found that the exposure to cold-dry environment improves the impact response of the structure until the duration of the exposure exceeded a certain limit and the damage size increased again [13]. For the cold-moist environment Hosur et al. [13] found that the plasticization of the matrix improved the impact response properties but the extent of damage was similar to the cold-dry results.

In this study, the effect of impact test parameters on the damage mechanisms and dimensions as well as on the amount of absorbed energy was investigated under high speed impact loading. The effect of varying strain rate with fixed impact energy was studied by using different mass/velocity combinations for the projectiles. In addition, the effect of sample damage on the energy absorption properties was studied by repeated impacts. Other variables used were the impact angle, temperature of the samples, as well as ageing of the samples in harsh environments prior to impact loading. The failure modes of the impacted samples were studied from the cross-sectional samples with scanning electron microscopy.

2. Experimental

2.1 Materials

In this study, the influence of test parameters on the impact behaviour of a steel/rubber/composite hybrid structure was investigated. The steel grade of the structure was stainless steel AISI 304 (provided by Outokumpu Stainless Oy, Finland). Thickness of the steel sheets was 0.5 mm. The surface finish was industrial 2D (cold rolled, heat treated, pickled). Prior to rubber bonding, the steel sheets were rinsed with acetone and ethanol. Other pre-treatments, such as grit blasting, were not used.

The glass fibre reinforced epoxy composite sheets were manufactured in-house by vacuum infusion from stitched 0/90 E-glass fibre fabrics (682 g/m^2, from Ahlstrom Oyj, Finland) and Sicomin SR 1660 / SD 7820 epoxy (from Sicomin Composites, UK). The glass transition temperature of the matrix is 150 °C. The nominal thickness of the composite sheets was 3.5 mm consisting of 6 layers of fabrics, and the fibre content was approximately 46 vol-%. A heat resistant epoxy was chosen to provide resistance for the composite sheet to the vulcanizing temperature of the rubber. From the adhered composite surface, a HexForce® T470 (Hexcel Co., USA) peel ply was removed prior to rubber attachment.

The EPDM based rubber was manufactured by Teknikum Oy, Finland. The trade name of the rubber grade is Teknikum TRA10. The Shore D hardness of the rubber was 41 [14] and the glass transition temperature -38 °C. The hybrid structures were manufactured by vulcanizing the rubber between the metal and the composite layers under heat and pressure (1.2 MPa at 160°C). The nominal rubber thickness was 1.0 mm, which is the intermediate one used in the previous study [5]. Thin metal plates between the steel and the composite sheets ensured uniform rubber thicknesses during the vulcanization.

2.2 Methods

The impact test equipment was an in-house developed High Velocity Particle Impactor (HVPI). In this device, compressed air is used to fire a 9 mm diameter projectile towards the sample. The velocity of the projectile is determined by a computer-controlled pressure reservoir, and the projectile velocity is recorded with a commercial ballistic chronograph placed in front of the target assembly. The test setup allows a wide range of impact angles to be studied approximately from 10° to 90°. The impact event is recorded with a high speed camera (NAC Memrecam fx K5, NAC Image Technology). The high speed video images were recorded at a constant frame rate of 40000 fps. The HVPI equipment is fully computer controlled. A schematic presentation of the test set-up is illustrated in Fig. 1.

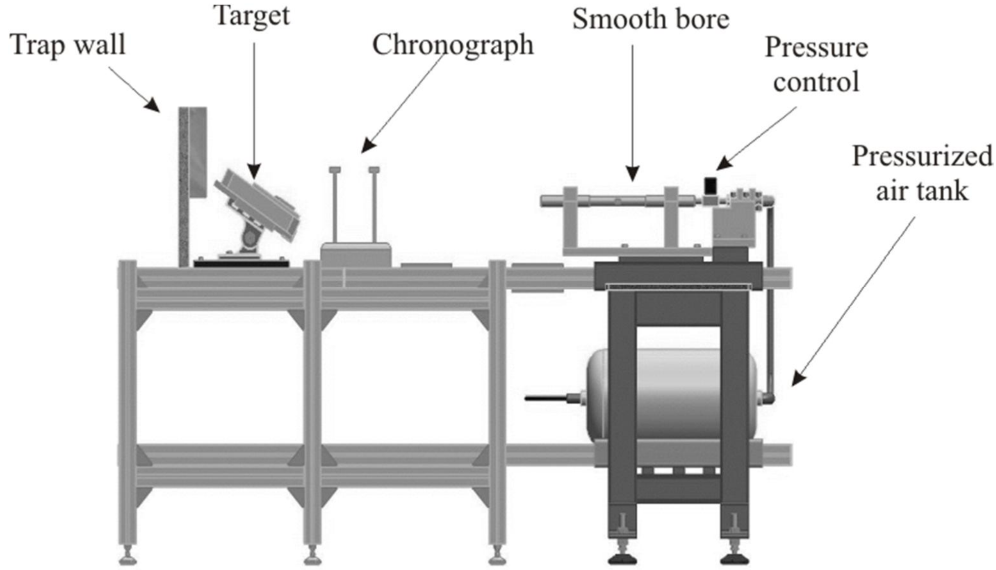


Fig. 1: *A schematic presentation of the high velocity impact test set-up* [15].

In this study three different balls were used as projectiles: steel (2.98 g in weight), tungsten carbide (WC, 5.73 g in weight) and silicon nitride balls (Si_3N_4, 1.25 g in weight). Specimen angle was either 30°±1°, 45°±1° or 60°±1°. The impact angles very close to 90° were avoided due to safety risks. The used pressure range was 1-14 bar, and it was adjusted to provide a suitable kinetic energy for the projectiles. Some of the samples were heated in an oven or cooled in an ethanol/liquid nitrogen bath together with the sample holder just before testing to investigate the influence of different temperatures. Heating the samples over the ageing temperature of 85 °C was avoided, which set the upper limit of the temperature range. The lower limit was chosen to be above the glass transition temperature of the rubber. The impact temperatures of the samples were recorded by type K thermocouples welded to the sample surface and a Fluke 52 II Thermometer. The temperatures shown in Table 1 are temperatures before the projectile was launched. The launch switches strong halogen lights on, which may have raised the specimen temperatures slightly. Other tests were done in room temperature (RT). To study the effect of ageing, some samples were exposed to a hot/moist environment (85 °C and 85 %RH) for 20 days prior to impact testing. In our previous study [14], it was observed that the adhesion properties of this structure do not change during the ageing process. Three samples were tested per each test parameter combination. Summary of the test conditions is shown in Table 1.

Table 1: *A summary of the test parameters.*

Projectile	*Projectile velocity [m/s]*	*Impact energy [J]*	*Specimen angle [°]*	*Number of impacts*	*Specimen temperature [°C]*	*Ageing*
To study the effect of impact angle						
Steel	*100*	*15*	*30*	*1*	*RT*	*-*
Steel	*100*	*15*	*45*	*1*	*RT*	*-*
Steel	*100*	*15*	*60*	*1*	*RT*	*-*
To study the effect of strain rate						
Si_3N_4	*157*	*15*	*45*	*1*	*RT*	*-*
Steel	*100*	*15*	*45*	*1*	*RT*	*-*
WC	*71*	*15*	*45*	*1*	*RT*	*-*
To study the effect of repeated impacts						
Steel	*43*	*3*	*45*	*10*	*RT*	*-*
To study the effect of temperature						
Steel	*100*	*15*	*45*	*1*	*-25*	*-*
Steel	*100*	*15*	*45*	*1*	*RT*	*-*
Steel	*100*	*15*	*45*	*1*	*80*	*-*
To study the effect of ageing						
Steel	*100*	*15*	*45*	*1*	*RT*	*-*
Steel	*100*	*15*	*45*	*1*	*RT*	*85 °C and 85 %RH*

The 50×50 mm size samples were fixed with the steel side upwards in a 130×130 mm aluminium clamp. The clamp had a circular opening of 40 mm in the centre. The geometry enables the sample to bend during the impact. A schematic presentation of the clamp and the sample geometry is shown in Fig. 2.

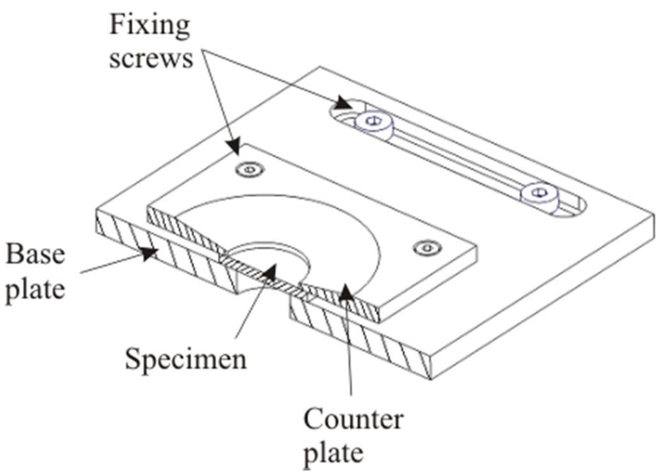


Fig. 2: *A schematic section view of the sample holder* [5].

The dissipated energy E_d of the projectile was calculated by comparing the initial and post-impact kinetic energy of the projectile according to Equation 1:

$$E_d = \frac{1}{2} m_p \left(v_i - \frac{\Delta s}{\Delta t} \right)^2 \quad (1)$$

where m_p, v_i, Δs, Δt are the projectile's mass and initial velocity, displacement of a sample point between two images, and the time consumed for this displacement of the projectile, respectively. The initial velocity was measured with the ballistic chronograph placed in front of the sample. A custom image analysis suite was used to estimate the velocity of the projectiles after the impact by overlaying two post-impact images from the high speed photographs, where the projectile is no more in contact with the specimen. Since the spherical shape of the projectile allows tracking of the same material point in the images, e.g. the centre of the sphere, the distance travelled by the projectile was calculated from the overlaid image and divided by the time consumed for this displacement. A small error is involved in the distance calculations due to a slightly angular position of the camera, but due to its negligible influence on the accuracy of the results, it was omitted. The mass change of the projectile during the impact was also assumed to be negligible since the projectile remains intact and has no sign of noticeable wear or increase in mass due to adhesion from the counter-surface.

After the impact tests, the samples were further studied visually by photographing them from the impacted steel surface and from the composite (back) side. In addition, cross sectional studies were done with Scanning Electron Microscope (SEM) Zeiss ULTRAplus. Conventional metallographic cross-sectional sample preparation method, including cutting the sample from the original specimens, mounting in epoxy, grinding, and polishing, was used to prepare the cross-sectional samples for SEM. Prior to SEM investigations, the samples were coated with a thin gold coating to ensure their conductivity under the electron beam.

3. Results

Impact craters on the steel (front) surface and impact induced damage in the composite layer were observed. Fig. 3 shows a representative example of the impacted samples. The impact craters were elliptical in shape exhibiting higher length in the direction of the projectile path. The damage areas in the composite layers exceeded the size of the impact craters. The damage area values were defined from the photographs by an image processing program (similar to Fig. 3.c).

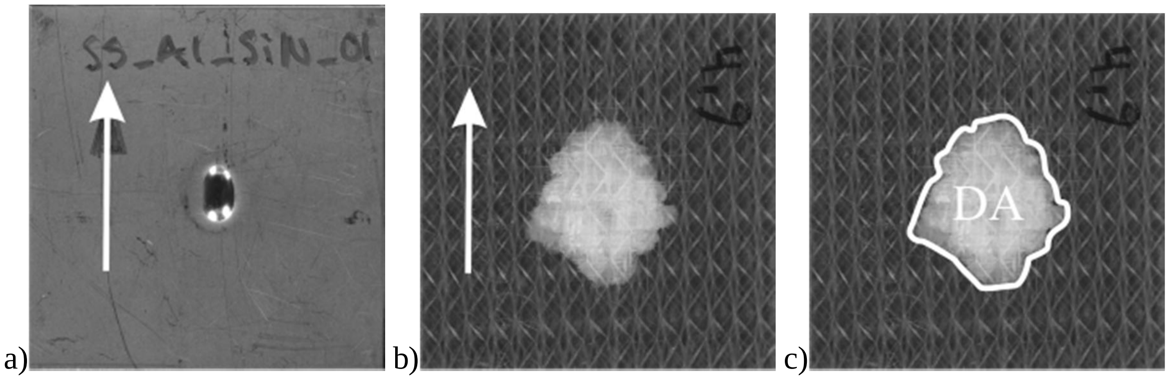
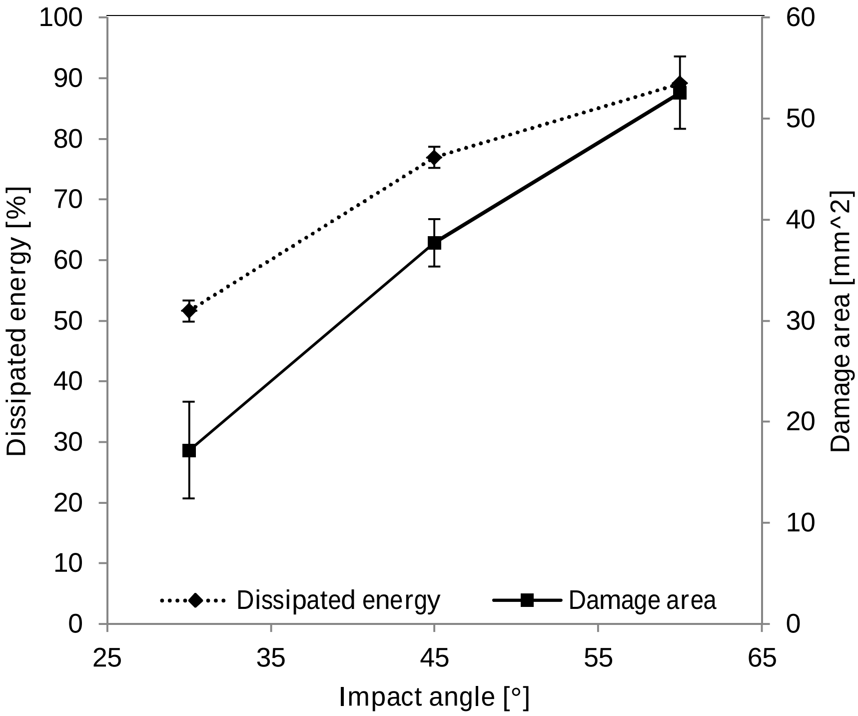


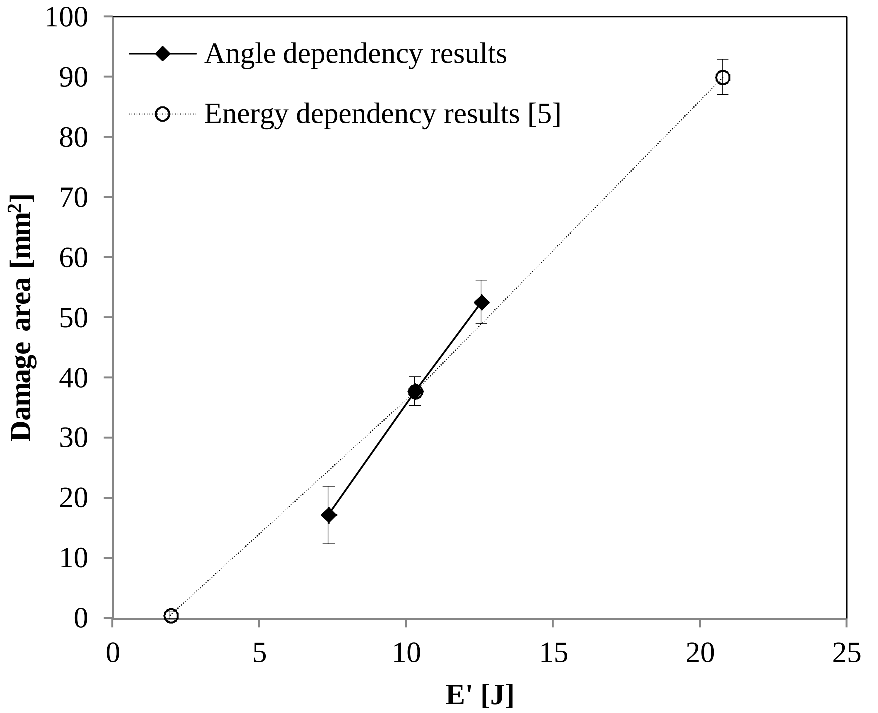
Fig. 3. *An example of the hybrid sample after impact: a) from the steel side, b) from the composite side. In c) the damage area (DA) is shown. The arrows in a) and b) show the direction of the impact.*

3.1 Energy absorption behaviour and visual inspection

An increase in the energy absorbed and in the damage area was observed with increasing impact angle (Fig.4.a). The absorbed energy values are expressed as percentages of the original impact energy of 15 joules. If only the normal component of the impact force is taken into account ($E' = Esin(\theta)$ where E is the impact energy and θ is the impact angle), the results are linear (Fig. 4.b). Fig. 4.b compares the *E'* vs. damage area of the impact angle dependency results obtained in the present study and the impact energy dependency results derived from our previous study [5].



a)



b)

Fig. 4: *a) absorbed energy and damage area vs. impact angle at constant impact energy of 15 J. Figure (b) illustrates the damage areas versus the normal component of the impact energy E' for different impact angles and energies [5].*

Increasing projectile velocity resulted in a slight increase, from 72 % to 80 %, in the absorbed energy together with an increase of 21 % in the damage area, as shown in Fig. 5. Figure 6 shows the effect of repeated impacts on the amount of absorbed energy. Although the energy absorption seems to fluctuate, the results stay broadly within the standard deviation limits. The scatter of the results increases with increasing number of impacts, but this can be explained by the slightly different projectile paths and impact positions. The average damage area size of the samples impacted once with 3 joules was 0.53 mm^2 [5], 7.76 mm^2 for the samples impacted ten times with 3 joules, and 89.94 mm^2 for the samples impacted once with 30 joules [5].

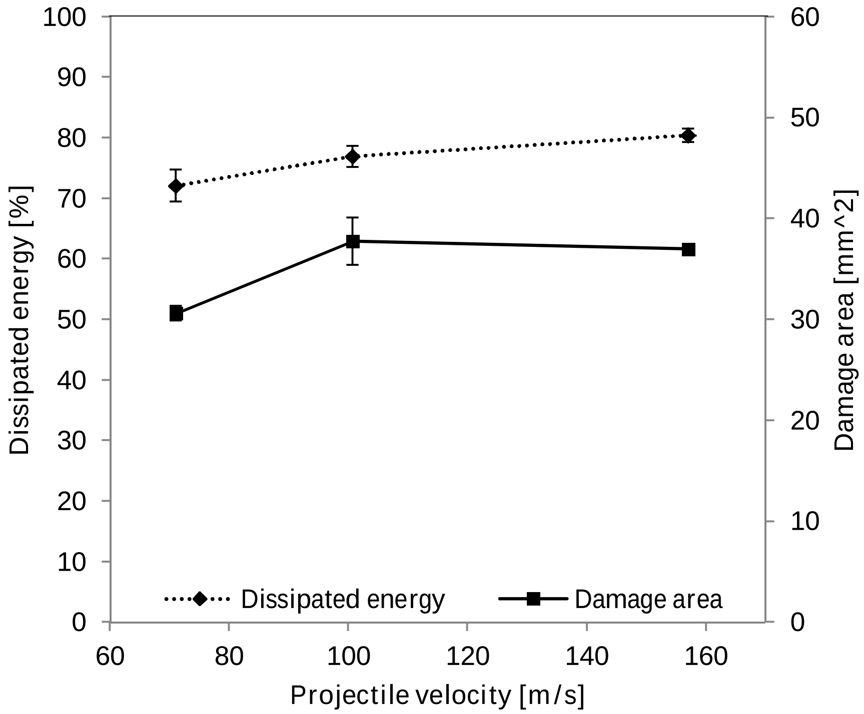


Fig. 5: *Absorbed energy and damage area vs. projectile velocity at a constant impact energy of 15 J.*

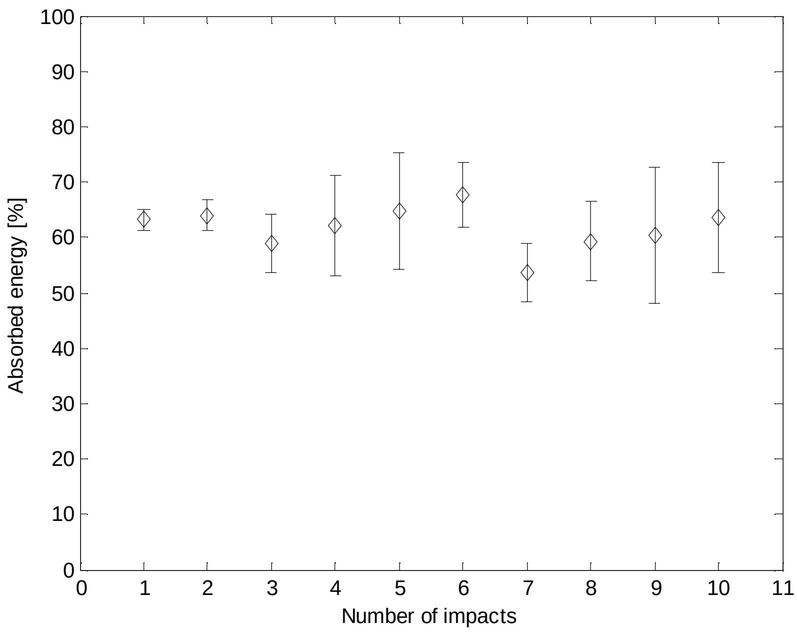


Fig. 6: E*ffect of repeated impacts on absorbed energy at constant impact energy of 3 J.*

The temperature dependence of the steel/rubber/composite hybrid was marginal especially as concerns the damage area (Fig. 7). Higher scattering in the damage area values was observed for the frozen samples. The increase of approximately 100 degrees in temperature caused an increase of eleven percentage units in the absorbed energy, whereas the damage area stayed within the standard deviation limits. The impact crater depth increased from 0.7 mm to 1.1 mm with increasing temperature.

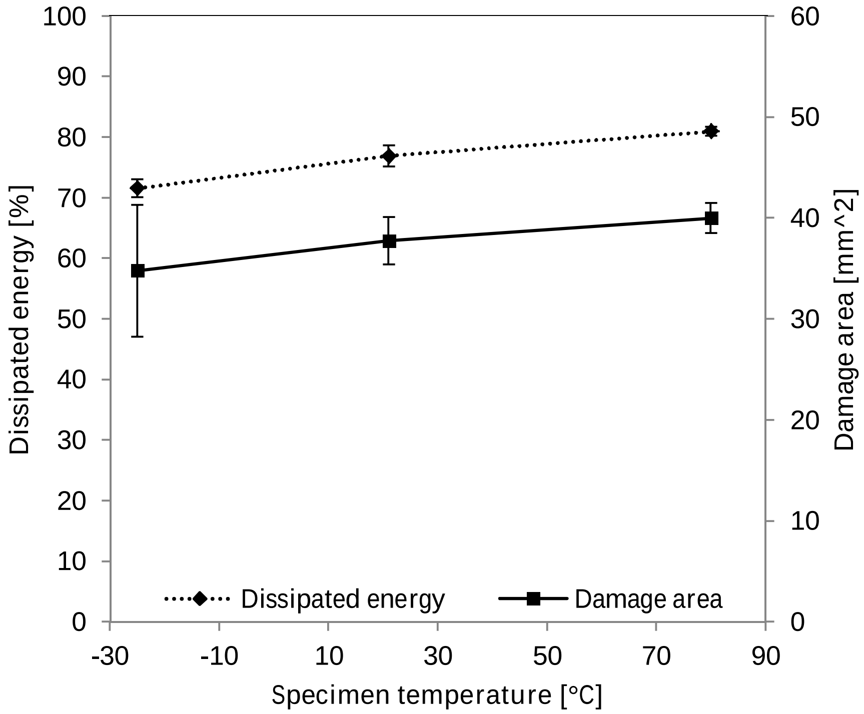


Fig. 7: *Absorbed energy and damage area vs. sample temperature at a constant impact energy of 15 J.*

Ageing did not have an effect on the impact properties of the steel/rubber/composite hybrid structure. The damage area for the non-exposed samples was 37.7 ± 2.4 mm^2 and for the aged samples 32.7 ± 3.0 mm^2. Thus, the results were similar within the standard deviation. Similarly, the energy absorption results were 76.9 ± 1.8 % and 78.5 ± 2.6 % for the non-exposed and aged samples, respectively.

3.2 SEM characterization

For all studied test parameter combinations, one sample with intermediate damage area was studied with SEM. Similar to the previous impact test study [5], the primary damage mechanism of the studied samples was interfacial delamination between the components in the areas where plastic deformation of steel was strongest and fibre/matrix debonding occurred in the composite layer. However, different test parameters revealed some special characteristics in the damage mechanisms.

In addition to the increasing damage area (Fig. 4), increasing impact angle caused higher damage density (Fig. 8). The composite damages were concentrated on the back surface of the sample, whereas the damage density close to the composite/rubber interface was smaller. The differences between the impact angles of 30° and 45° were smaller than between the impact angles of 45° and 60°. In addition, the crater depth was higher for the sample impacted at 60° (0.8 mm) than for the smaller angles (0.7 mm).

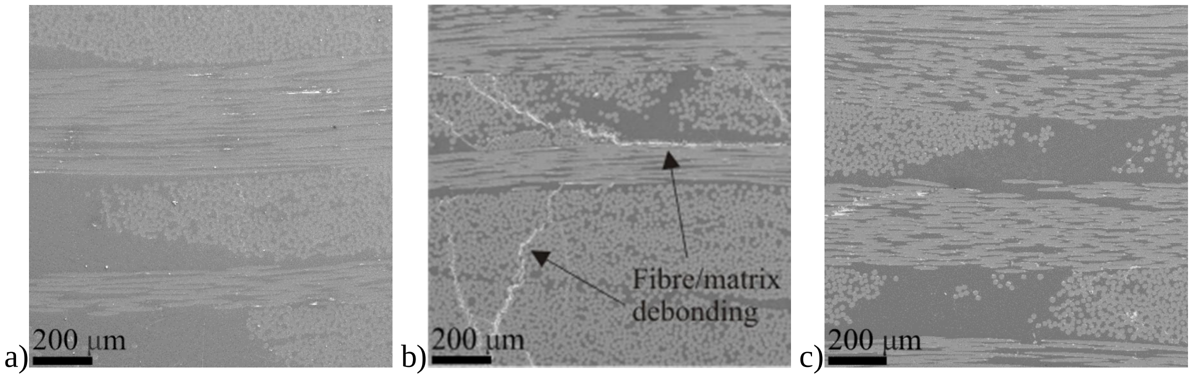


Fig. 8: *Representative images of the composite damages a) impact angle 30° (back side), b) impact angle 60° (back side), and c) impact angle 60° (close to the composite/rubber interface).*

Although Fig. 5 shows the clearest difference between the projectile velocities of 71 m/s (WC ball) and 100 m/s (steel balls), the highest velocity of 157 m/s (Si_3N_4 balls) caused clearly higher damage density into the composite layer. This is illustrated in Fig. 9. Again, the damage density in the samples impacted with Si_3N_4 balls was higher on the back side of the sample.

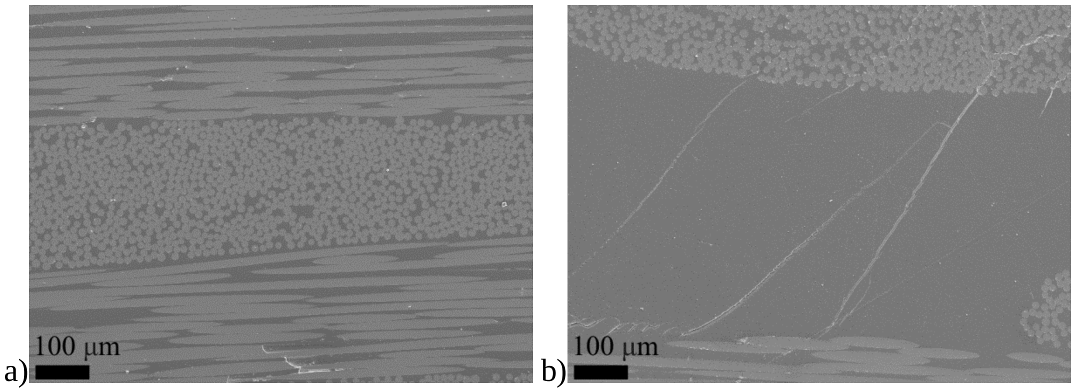


Fig. 9: *Composite damage in specimens impacted with a projectile velocity of a) 71 m/s and b) 157 m/s.*

Fig. 10 shows the cross-sections of specimens loaded with 3 J and 30 J once and the specimen loaded with 3 J ten times. The two former specimens were examined in more detail in the previous study [5]. When comparing the impact craters of the specimens loaded with 3 J once or ten times, the length of the impact crater is higher after repeated impact. However, this may be partly due to small alterations in the exact impact location. The impact crater is also deeper after repeated impacts (approximately 0.5 mm vs. 0.3 mm). In addition, delamination at the composite/rubber interface is more severe after multiple impacts. When comparing the craters of the specimens loaded ten times with 3 J and once with 30 J, the damages after repeated impact are not as severe even though the energies subjected to the samples are the same.

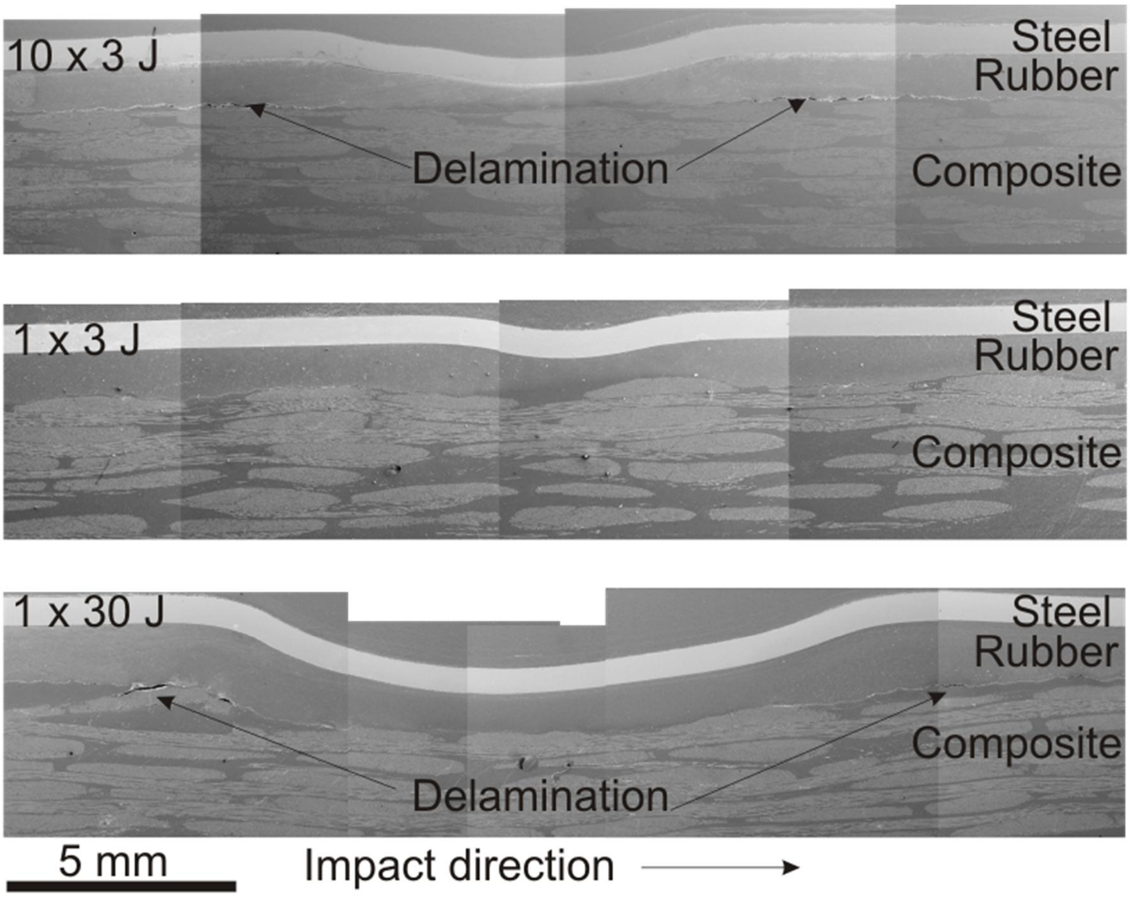


Fig. 10: *Cross-sectional SEM images from the samples impacted ten times with 3 J energy, once with 3 J energy, and once with 30 J energy.*

The main damage mechanisms did not show any difference between the samples loaded at different temperatures. Some fractures on the steel surface were observed in the frozen specimen, which was an exception among the test parameter combinations. However, since the used steel sheets were in as-received stage, it cannot be said if these fractures were already in the steel before hybrid manufacturing, if they were induced by the impact or if they were artefacts of sample preparation process. Also, rubber fracture at the composite/rubber interface of the hot specimen was found (Fig. 11.b), which again was an exception. In addition, the crater depth of the hot specimen (1.1 mm) was higher than the depth of the samples impacted at lower temperatures (0.7 mm). No differences were found in the aged samples when compared to the non-exposed ones.

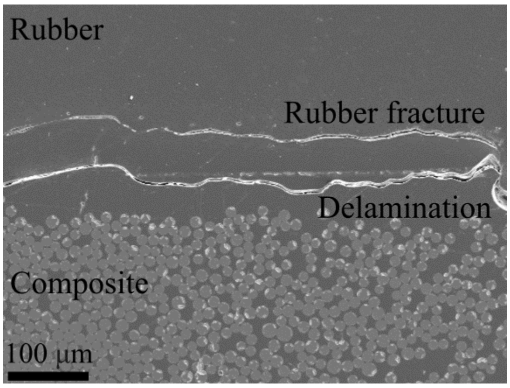


Fig. 11: *Rubber fracture in the hot specimen at the composite/rubber interface.*

4. Discussion

As expected, impact angles closer to perpendicular induced more damage and higher level of penetration. At low angles, the surface steel exhibits more shear type loading, whereas at high angles the energy is increasingly consumed in more severe plastic deformation in the surface steel. It can be seen from Fig. 4.b that an increase in the impact angle has slightly stronger effect than an equivalent increase in the impact energy. If this kind of behaviour will be verified by further tests, it should be taken into account when evaluating the stress state and the suitability of the hybrid structure in an industrial application. Especially applications where the material is exposed to erosion, the wear rate at low impact angles will be high regardless of the good damping properties of the underlying composite structure. Yet, the results are promising even at high impact angles with relatively high impact energy since the present composite structure does not undergo a catastrophic failure. This is also backed up by the multiple impact results.

Since the absorbed energy does not change after repeated impacts, the degree of damage increases with increasing number of impacts. The increase in the damage area was not directly proportional to the number of impacts, but the damage area was after 10 impacts approximately 15 times the size of the specimen impacted only once. The behaviour indicates that the composite structure has not lost its ability to withstand dynamic loading even when the interface layers have undergone damage. However, the determination of a correlation coefficient would need further studies.

The observation that the sample impacted with the intermediate projectile has a higher damage density although having similar energy absorption when compared to the intermediate projectile velocity agrees with the results of Chen and Ghosh [16]. They have simulated that for a certain microstructure, higher strain rate causes higher stress which would cause more damage. In addition, they found that the energy absorption depends mainly on the loading type [16], which is also in line with the present results. The higher damage density further from the impacted surface, i.e., the conical shape of the impact damage, is typical for composite structures [12, 17], but it has been observed in other materials as well [7].

Similar to the projectile velocity, ageing of the sample before the impact event did not have any effect on the impact resistance of the studied hybrid structure. Increasing the sample temperature increased slightly the energy absorbed and damage induced. In addition, the overall deformation at the steel surface of hot samples was greater, which is supposed to be due to the softening of the rubber layer at high temperatures. The softening would allow greater plastic deformation of the steel and thus higher energy dissipation during impacts. The increasing deviation with decreasing temperature of the composite damage area results may be due to the thermal stresses of the composite layer. The stress-free temperature of the composite is close to its cure temperature and the propensity for cracking towards colder temperatures is increased [18]. If the fracture behaviour of the steel at low temperatures is induced by the impact, it may be caused by the effect of strong temperature gradients: the impact induced local heating in cold steel may increase the effect of shear deformation and cause cracking. All in all, they were not the primary damage mechanisms and it can be concluded that the structure has potential to be used in different environments.

5. Conclusions

In the present study, the effect of test parameters on steel/rubber/composite hybrid structure was studied under high velocity impacts. Impact angle, projectile velocity with constant energy, number of impacts, specimen temperature, and prior exposure to harsh environments were used as variables.

The main findings of this study were that higher impact angles lead to more severe plastic deformation of the impacted steel surface and thus to higher energy dissipation behaviour. In addition, the effect of increasing impact angle to the damage size was found to be stronger than the effect of increasing impact energy at a constant impact angle. The effect of projectile velocity was small within the studied range. The repeated impact studies showed that the structure does not lose its ability to withstand dynamic loading even when there is gradually progressive damage. The structure was immune to ageing prior to the impact testing, and increasing temperature increased the plastic deformation and energy absorption ability of the structure slightly. However, excluding the impact angle, the varied test parameters did not have a significant effect on the energy absorption or damage behaviour of the studied hybrid structure, which supports its potential to be implemented in real life applications such as impact loaded stressed-skin constructions.

Acknowledges

The work was funded by the Doctoral Programme of TUT's President (E. Sarlin), by FIMECC Ltd and its Demanding Applications program (M. Apostol, M. Lindroos and V.-T. Kuokkala) and Light and Efficient Solutions program (J. Vuorinen). The authors acknowledge Outokumpu Stainless Oy for the stainless steel sheets and Teknikum Oy for the rubber. We are grateful for Kosti Rämö, Niko Polet, Olli Partanen and Atte Antikainen from Tampere University of Technology (TUT) for preparing the samples used in this work.

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