

Numerical investigations for simultaneously processing metal and plastic using impact extrusion

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Abstract. Combining different materials for producing high performance parts opens a broad range of high functionality and applicability. Scope of this project is the investigation of a new method to process metal and plastic within one single production step using impact extrusion. In this study, first FEM results of the combined impact extrusion of metal and plastic will be presented. The aim of the numerical investigation is to achieve a plastic flow of the polymer material during the metal forming process.

1 Introduction

Hybrid components are gaining more and more importance in the field of mechanical engineering due to the fact that weight has to be reduced, demands for special component properties are growing, and the pressure to lower manufacturing costs is rising. Due to their complementary material properties the main focus is on hybrid components made from plastic and metal. Usually, metals are less resistant to aggressive media, but can transform vibrations very well, and are good thermal and electrical conductors. In contrast, plastics normally have inferior mechanical properties, but combine better thermal insulation, media resistance and good damping properties [1 - 3].

Down to the present day, the production of hybrid components has been characterized by serial production. Basically, there are two different ways of production [2]. In both cases, the forming process of the metal component takes place separately from the production of the plastic component. Figure 1a) shows a component produced in a form fit joining/bonding process. This process consists of at least three steps: the production of the metal component, the separate production of the plastic component, and the following joining process. A connection of the complementary properties is only partially possible by simultaneous processing.

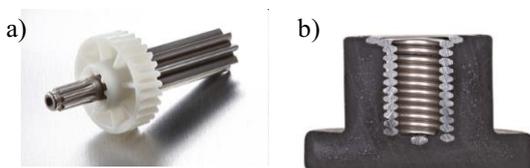


Figure 1. Manufacturing of hybrid components by a) joining and b) injection molding around metal inserts

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Figure 1b) shows an alternative, but very common option for producing hybrid components. As described in the production process before, the metal component is produced before joining. The finished metal component is afterwards back injection molded and thereby encapsulated with molten plastic. Therefore, classic joining operations as shown in in figure 1a) have become redundant. It is, however, necessary to have at least two process steps (forming and back injection molding). Furthermore, the geometric requirements of the metal component have to be taken into account; e. g. a way of demolding must be implemented and the flow path of the plastic has to be optimized in order to achieve acceptable mechanical properties. This results in a more complex tool structure [2 - 5].

1.1 Process description

A new manufacturing process for hybrid components, developed at the Institute for Metal Forming Technology (IFU) and the Institut fur Kunststofftechnik (IKT) of the University of Stuttgart, Germany, provides the possibility of manufacturing both material components within one single processing step. This new method allows to precisely include plastic granulates into the forming process in order to simultaneously form the metal blank and the plastic (cf. figure 2). Fundamentally, this approach to production opens a new spectrum of light weight constructional components, isolation- / damping components, and high performance components.

This new process also allows to reduce the wall thickness of metal components in the field of lightweight construction without losing rigidity. Components in less stress loaded areas can contain a light plastic phase. Due to the low density of plastics (e. g. 0.917 g/cm³ for polyethylene [6] and 1.13 g/cm³ for polyamide [7]), the

weight can be reduced as well while the component properties remain the same.

Another new field of application is the manufacturing of NVH-components (noise, vibration, harshness) which offer vibration damping properties. The components are made of an outer metal shape and an inner plastic core. This kind of components allow to transfer specific properties of plastic on the whole component. Similar concepts have already been implemented successfully in the field of sheet metal forming (damping plate) [6].

Further scopes of application for metal-plastic-components are high performance components subjected to special requirements. For example, it is possible to produce pipes with a protective metal coating to increase properties regarding mechanical wear. Another possibility of use is the production of plastic components with a metal and thus electrical conductive outer layer. The processing of plastic and metal in one processing step has further advantages such as shorter cycle times, better utilization of machines, and increased production efficiency.

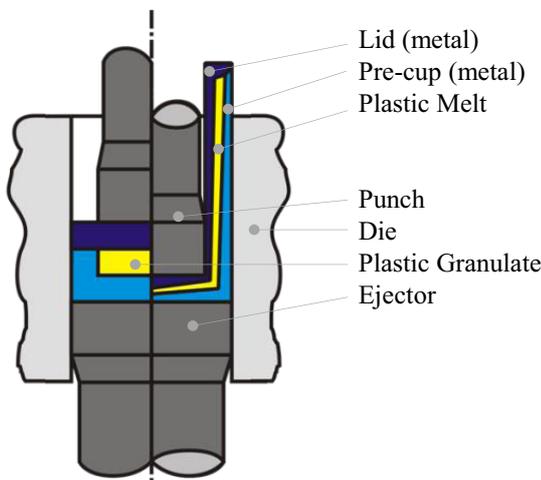


Figure 2. Scheme of the cup-backward-extrusion; left: initial state; right: process sequence during forming process

As described, the new approach developed by IFU and IKT deals with the combined processing of plastic granulates and bulk metal forming by impact extrusion, which is well-established in bulk metal forming technology. The forming process can be seen in Figure 2. The figure shows the initial situation of the process on the left and the process sequence during the forming process on the right. For the manufacturing of hybrid components, two forming processes can be considered: full-forward extrusion and cup-backward-extrusion, which will be described in more detail. At the beginning of the forming process the prepared raw part is inserted in the forming tool. This raw part consists of three components: a metallic lid (dark blue), a metallic pre-cup (light blue), and plastic which is inserted as granulate (yellow) without being compacted before.

At the beginning of the forming process, the raw part is upset and the granulate is compacted before the material begins to yield. After the compaction is complete (bulk density ≈ 1), the basic forming process

starts and the cup begins to flow (figure 3). The temperature developed by the forming process and the initiated shear lead to plasticization of the granulate.

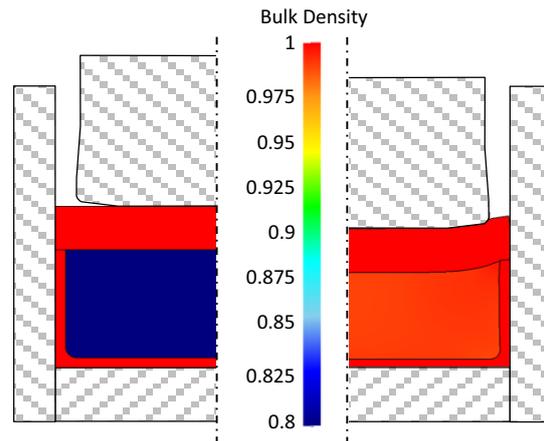


Figure 3. Compression of the bulk good

As the degree of plasticization depends on the resulting heat, it is attempted to achieve the highest temperature possibly attained in order to ensure a complete in-situ processing of the polymers.

The principle of full forward extrusion is identical to backward extrusion. First, the plastic granulate is compressed and plasticizes due to high pressure and temperature development. After processing, cooling of the plastic and metal phase take place.

The materials used are aluminum alloy EN AW 6082 and steel alloy 16MnCr5. The lid and the pre-cup always consist of the same metallic material. The two used thermoplastics are polyethylene and polyamide, which are often used standard and technical plastics, respectively [7, 8, 9]. The plastic is always added to the process in granular shape. Following, the material characterization of metal and plastic will be described and the forming simulations will be analyzed.

2 Material characterization

A simplified simulation of the forming process is to be executed using the software STFC Deform. Therefore, all material groups used (metal and plastic) have to be characterized in terms of modelling its material behaviour during the forming process. In order to display the metal materials, the established upsetting test was used. The plastics can be displayed with a rheometer shear test, which is well-established in plastic processing. The observed amplitude sweep will be converted into a stress-strain curve.

2.1 Recording of Flow Curves

The flow curves were determined with simple cylinder upsetting tests in order to characterize the aluminum alloy AlMgSi1 (EN AW 6082) and the steel 16MnCr5. The flow curves were recorded using the Institute's thermo-mechanical testing system (Gleeble 3800). The forming velocities for both materials were chosen to 1 s^{-1} . The temperature ranged from room temperature to $400 \text{ }^\circ\text{C}$.

The upsetting samples were heated up straight before the forming process. For the regulation of the sample temperature thermocouples were welded on the test specimen's lateral surface. These thermocouples allow recording the temperature of the test specimen's shell during the forming process. In order to minimize the friction at the sample's front surface, graphite foil was placed between the front surface and the carbide crush areas. The heating rate was given to 4 Ks^{-1} . The maximum temperature was afterwards held for 60 seconds in order to achieve a homogeneous temperature distribution in each sample. The elastic strain of the machine can be corrected depending on force. Every flow curve was recorded three times.

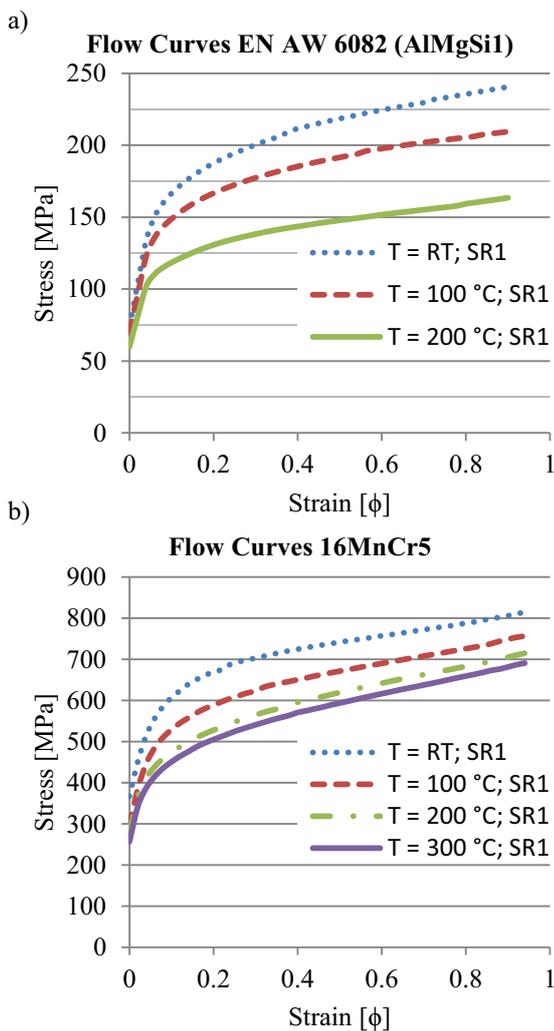


Figure 4. Determined flow curves of a) EN AW 6082 and b) 16MnCr5 at different temperature levels and constant strain rates of 1 s^{-1}

Figure 4 shows the determined flow curves of the aluminium alloy above and steel below. The starting yield point of the aluminium alloy ranges near 90 MPa at room temperature. As the forming process goes on the yield stress increases to 235 MPa ($\phi = 0.8$) at room temperature. Steel has a significantly higher yield stress of 400 MPa right at the beginning, while the yield stress is rising up to 800 MPa ($\phi = 0.8$) during the further course of forming. Due to the different starting stress

curves, the pressure for compressing the plastic granulate can be varied. A high initial yield stress generates high pressure (and a high temperature) on the plastic granulate. A smaller initial yield stress creates a smaller pressure (smaller temperature development) before the forming process starts. Therefore, the material of the lid and the pre-cup influence the plasticizing of the plastic granulates during forming.

2.2 Characterization of the plastic phase

The behaviour of plastics fundamentally differs from that of metals. Characteristic temperatures of plastics such as melting temperature usually are significantly lower than their equivalent temperatures of metal. Obviously, this is both disadvantageous and advantageous for the plastics industry: disadvantageous due to the lack of high temperature applications and advantageous because of lower energy consumption (and therefore costs) during processing [9].

In order to manufacture a plastic part, a plastic granulate usually is heated to temperatures higher than its melting temperature; the resulting fluid is then deformed under pressure in order to achieve the shape of the final part and cooled afterwards. For the simultaneous impact extrusion of metal and plastic it is essential to determine whether the plastic will melt during the process. Melting temperatures of plastics may vary significantly due to the huge variety of different kinds of thermoplastics. Potential plastics for impact extrusion like polyethylene and polyamide have melting temperatures of $108 \text{ }^\circ\text{C}$ and $220 \text{ }^\circ\text{C}$, respectively [7, 8].

The temperature dependent heat uptake of a plastic can be determined using differential scanning calorimetry (DSC) as shown in figure 5 for low density polyethylene (PE-LD; Lupolen 1800 S, LyondellBasell Industries, Rotterdam, NL).

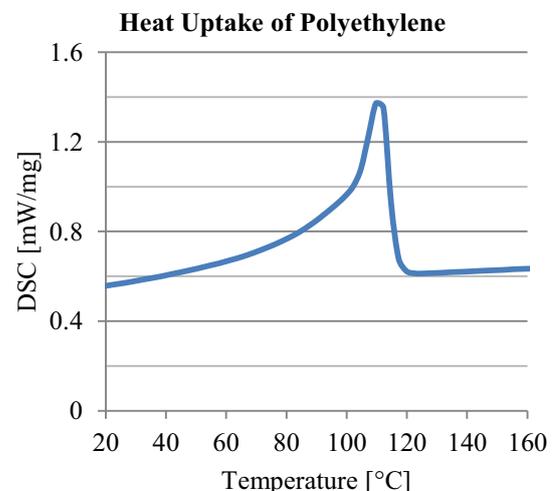


Figure 5. Heat flow versus temperature of PE-LD at a heat rate of 10 K/min

The peak near $120 \text{ }^\circ\text{C}$ is due to the melting of the crystalline phase of the plastic, which consumes huge amounts of energy [9]. The DSC data can be implemented into the simulation to set a specific heat uptake for the plastic at each temperature.

If temperatures higher than the melting temperature of the plastic are achieved, fluid state can be expected.

Assuming fluid state during processing, the plastic shows shear thinning behaviour. This means that the force required for deforming the fluid depends on the shear rate, and therefore directly on deformation speed. This behaviour is equivalent to the behaviour of solid state metals. For simulation purposes an equivalent to the flow curve of a metal needs to be discovered. Therefore, viscosity curves using specific displacements were measured at the IKT at different shear rates, as shown in figure 6 for low density polyethylene.

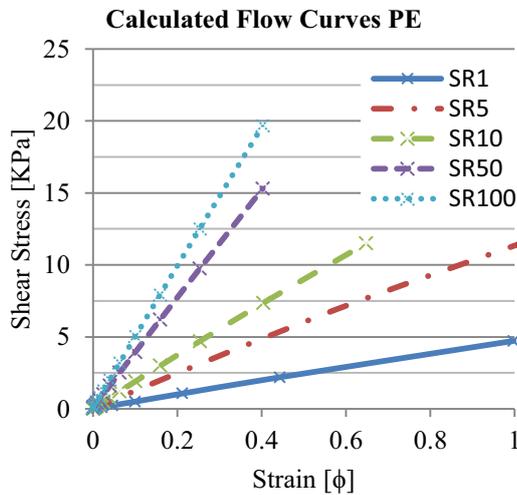


Figure 6. Shear stress versus displacement for PE-LD (T = 190 °C), measured for strain rates of 1–100 s⁻¹

The tests were conducted using a parallel plate rheometer SR 500 (Rheometrics Inc., Piscataway, NY, USA) with set deformations up to 100 % and deformation rates of 1 s⁻¹ to 100 s⁻¹. The corresponding momentum was measured, and the resulting stress was calculated. Using such obtained data, the dependency of the shear stress versus different displacements can be determined and transformed into a flow curve using equation 1 [10]:

$$\bar{\sigma} = \sqrt{3} * \tau \quad \varepsilon = \frac{\gamma}{\sqrt{3}} \quad (1)$$

Where $\bar{\sigma}$ is the resulting strain and ε the corresponding elongation of the flow curve, τ is the shear stress and γ the displacement. However, it has to be mentioned that the data is acquired at a set temperature of 190 °C (for polyethylene). Since the temperature is not constant during impact extrusion the approach is more difficult to handle. Hence, in future works temperature dependent flow curves will be implemented.

3 Design of the Forming Process

For the simulation of the forming process, the commercial program STFC DEFORM was used. Due to the component's rotational symmetry, it is possible to reduce the numeric model down to two dimensions. As material properties, the determined characteristic values (see chapter 2) are used. The metallic components were

modulated as all-plastic and the polymer was modulated as porous (density 0.8) because of its insertion as loose material. Furthermore, the friction model to shear was used with a friction coefficient of 0.3. First of all, screening simulations were carried out to study the functionality of different raw part geometries. Based on these findings, a detailed raw part design was carried out by means of DOE in the framework of this paper.

3.1 Screening

Using model properties as shown above, numerical tests were carried out to find an optimal geometry of the raw part. Therefore, four different raw part variations were simulated and evaluated at the beginning. The aim was to choose the initial geometry in a way in which the polymer is completely encapsulated between the raw part cover and pre-cup as well as to reach a satisfying form closure. The important parameters for the plasticizing will not be discussed at this point.

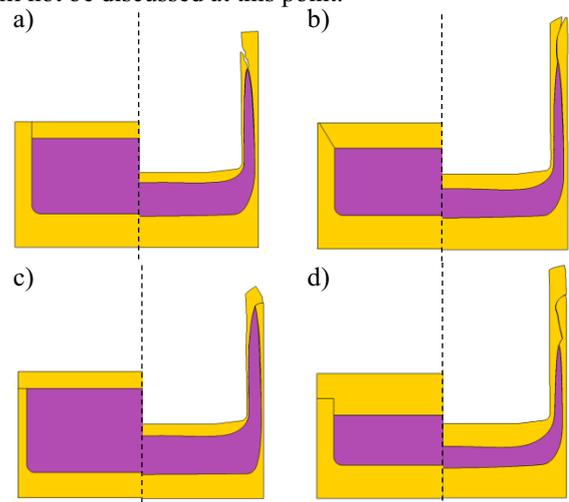


Figure 7. Depiction of the raw parts concerning the resulting form closure.

The figures a-d depicted in figure 7 show the initial situation of the processes on the left side and process sequence during forming on the right side. The preliminary tests revealed the following behavior:

- The lid was designed as large as the inner diameter of the pre-cup. Hereby, the lid was pressed inwards at the beginning of the process. During the following forming process, a gap occurs. This gap prohibits the form closure to arise and the polymer may leak out.
- The lid was designed as large as the outer diameter of the pre-cup. Additionally, it was provided with a bevel. This supports an intrusion of the lid into the polymer, preventing the occurrence of a satisfying form closure. However, the form closure tends to be more suitable at wide angles.
- The lid was designed as large as the outer diameter of the pre-cup. This prevents the penetration of the lid into the pre-cup, causing a perfect form closure between the components.
- The lid was also designed as large as the outer diameter of the pre-cup. However, a step has been added

in order to get an optimized form closure. As in the previous variation c), no gap occurs permitting an escape of the plastic phase.

As shown, set up c) and d) are suited best for the manufacturing of hybrid components by impact extrusion. As a result of the raw part's geometry in these two variations, a complete inclusion of the polymer as well as a good form fit was achieved. Due to the similar behavior in the inpatient sector of the forming process, only variation c) is optimised via DOE. Therefore, the results achieved can be transferred directly on the raw part geometry of variation d).

3.2 Design of Experiments

In order to ensure a complete plasticization, it is important to achieve the highest possible temperature during the forming process (melting point of polyethylene: 108 °C: melting point of polyamide: 220 °C). Therefore, the temperature for the selected raw part by means of DOE was optimized.

Figure 8 shows the raw part to be investigated. Gap width (S), wall thickness (W), base thickness (B) as well as lid thickness (D) are varied as parameters. Corresponding variation ranges of the parameters are shown in table 1.

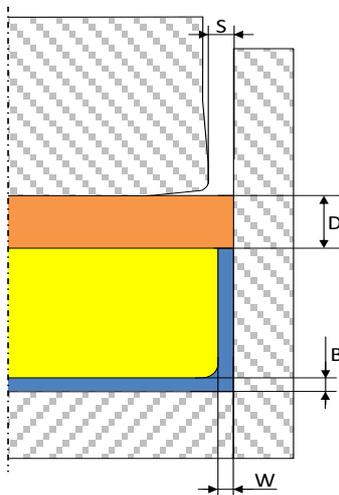


Figure 8. Definition of the used parameters for backward extrusion

Table 1. Parameter range corresponding to DOE calculation

Parameter	Min. [mm]	Max. [mm]
S (gap width)	1	3
D (lid thickness)	2	4
B (base thickness)	1	3
W (wall thickness)	1	3

The objective was to allow the inclusion of high amounts of plastic granulate without causing a decrease of the support effect, which is dominated by the metallic components of the raw part assembly. Furthermore, considerations concerning production were investigated. The influence of the parameter on the resulting temperature was determined by full factorial design.

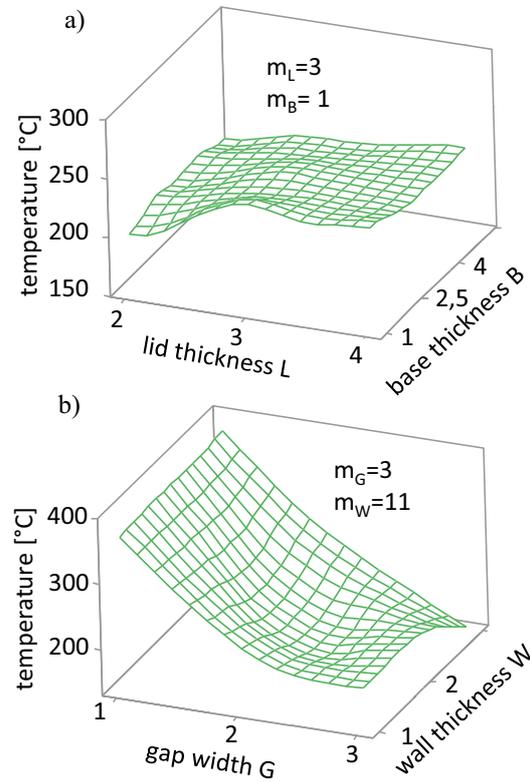


Figure 9. Response surface of the DOE

Figure 9 illustrates the response surface of the DOE as well as the strengths of influence. The resulting temperature is displayed on the applicate. The parameters lid thickness (figure 9a) and gap width (figure 9b) become apparent on the abscissae. The parameter's base thickness (figure 9a) and the wall thickness (figure 9b) are shown on the ordinate. Both unembodied parameters are kept constant (wall thickness = 1 mm, base thickness = 5 mm or gap width = 2 mm, lid thickness = 4 mm) in order to prevent a distortion by cross influences at the response field.

As shown in the figure, the resulting temperature ranges from 157 °C to 391 °C. Therefore, a processing of polyamide is not possible with regard to all variations (melting point 220 °C). As becomes evident in figure 9a, a rise of the temperature at increasing values of lid thickness and base thickness can be observed. The figure on the right side also shows a steady rise of the temperature for increasing values of the wall thickness or for decreasing values of the gap width. Based on the ratio (figure 9, m_L , m_B , m_G , m_W) of the average temperature increase and the parameter changes, the respective variable's influence can be determined: the higher the slope, the greater the influence of the value. This shows

that the gap width has the greatest influence on the temperature of the forming zone. Furthermore, it becomes apparent that the values wall thickness and lid thickness have a considerable influence on temperature, even though they are weaker than the gap width. The parameter base thickness has a negligible effect on the resulting temperature. Therefore, the parameters S, D, and W are set with regard to achieving a high resulting process temperature. The base thickness is defined in a way of reaching the greatest possible contribution of the plastic granulates due to its minor effect on temperature. For the processing of polyethylene, all parameter variations are permitted due to the low melting point of 108 °C. For the production of components made of polyamide (melting point 220 °C) a restriction of the parameter values must be conducted.

Possible resulting raw part geometries for polyamide are shown in table 2. The table contains values for the defined parameters as well as the reachable temperature in the forming zone. The maximum achievable temperature referring to test number 8 is 391 °C. Based on the results of the DOE, experimental investigations with these defined parameters will be carried out in the next stage of experiment.

Table 2. Test parameters for a resulting temperature higher than 220 °C

Test number	B [mm]	D [mm]	W [mm]	S [mm]	Temp. [°C]
1	1	2	3	2	224
2	1	3	1	2	242
3	1	4	1	2	238
4	1	4	3	2	236
5	1	4	1	2	226
6	1	4	1	1	367
7	1	4	2	1	387
8	1	4	3	1	391

4 Conclusion and outlook

This paper deals with the manufacturing of hybrid components in one single production step via impact extrusion. It became obvious that the forming temperature has a large influence on plasticisation of the used plastics. With the assistance of the parameter variation, the raw part geometry which allows reaching a maximum of process temperature was defined. By optimising this measure, it is attempted to achieve the best possible plasticization of the polymers during impact extrusion.

Future research work will focus on the experimental validation of the numerical investigations as well as on analysis of the hybrid components. For example, the

adhesive strength and mechanism between metal and plastic have to be investigated.

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