Enhancement of the Conductor Track Quality of Electrically Conductive Plastics Parts by means of Targeted Process Control with the Integrated Metal/Plastics Injection Molding

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Abstract

In the Integrated metal/plastics injection molding (IMKS), metallic tracks are injected into a plastics carrier by means of die-casting in an integrated process. IKV investigated the influence of process management on the quality and durability of these electrically conductor plastic components. The focus of this work lies in the analysis of the metal melt, its flowing behavior and the interaction with the plastics carrier. The results show that the components produced in IMKS have a long service life with respect to electrical loads.

Introduction

In addition to conventional overmolding of conductive punched/bent parts or the subsequent metallization of injection molded parts, the integrated metal/plastic injection molding (IMKS) represents a suitable alternative to the economical production of plastic/metal hybrid parts for electrical applications [1-3]. The IMKS combines the injection molding of plastics with die-casting of low-melting tin-based metal alloys (Figure 1).

Figure 1. Principle of the IMKS process

To realize the process combination, a standard injection molding machine is extended by a special die-casting unit for casting the molten metal, which is directly flanged to the mold. The process is similar to multi-component injection molding. In the first step, the plastic carrier is produced. This has grooves, which form the tracks for the metal alloy. After the carrier has been converted into a second cavity, the metallic tracks are injected and the component can then be removed from the mold. The production of the carrier and the metal injection can be carried out in parallel. Depending on the mold technology, the preform can be transferred by means of a robot hand or by the use of an index plate in the mold [4-6].

When designing electronic plastic components, the IMKS has a number of advantages. Electrical components such as connectors, sensors, resistors and LEDs can be inserted into the mold and can be directly contacted with the metal melt, eliminating the need for subsequent steps [7]. The size, shape and position of the conductor paths in the component can be designed variably and adapted to the electrical requirements. Thus, the manufacture of sensor housings and switches for low-voltage applications or the use in lighting applications or circuit board terminals in power electronics is possible [8,9].

Electronic equipment is expected to have a high level of operational reliability, as a device failure, whether due to overloading or as a result of lifetime, often entails considerable costs [10,11]. For components manufactured in IMKS, this means that defects in the conductor tracks, caused by an insufficient filling or material degradation, can reduce the electrical properties and lead to premature failure [12]. In addition, applications require different needs with regard to the lifetime under electrical, mechanical or climatic loads. In order to be able to manufacture components that fulfill the technical requirements, design guidelines are required for circuit boards made with IMKS. The aim of the presented investigations is to produce conductor tracks without defects reducing the conductivity, which meet the requirements of durability and lifetime in the practice application.

Materials

Basically, the combinations of metals and plastics have to be suitable for the combined process. In particular, the melting point of the metal has to fit the melting range of the thermoplasics so that the thermoplastic carrier plate withstands the processing conditions of the overmolded metal and is not thermally degraded or mechanically charged inadmissibly.

Within the framework of the experimental work, a polyamide (PA GF30) with 30 % by weight of glass fiber reinforcement and a polybutylene terephthalate (PBT GF55) with 55 % by weight of glass fiber reinforcement...
of the Lanxess Deutschland Gmbh, Cologne, Germany, were used as materials for the carrier. Due to the good chemical resistance of PA and the high wear resistance of PBT together with the high stiffness and strength, these materials are often used as housings in electrical and electronic applications [13].

The low melting metal alloy used for this work (Sn95Ag produced by Felder GmbH Loettechnik, Oberhausen, Germany), is widely used as a standard lead-free electronic solder for electronics and high temperature applications for automotive industry and meets the requirements of the European guideline for electrical equipment 2011/65/EU (RoHS 2). The solder is mostly based on tin and contains 3.8 % of silver, which has a positive effect on the wetting properties of the solder and minimizes the tendency of oxidation.

The physical properties of the low-melting metal alloys differ significantly from those of technical thermoplastics. This is shown for the alloy Sn-Ag in Table 1 compared to a standard PA 6.6 (mechanical values in the conditioned state):

Table 1. Physical and mechanical properties of the alloy Sn-Ag compared to PA 6.6 at room temperature (except viscosity) [14-16]

<table>
<thead>
<tr>
<th>Property</th>
<th>Sn-Ag</th>
<th>PA 6.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity</td>
<td>Pa·s</td>
<td>0.004-0.006</td>
</tr>
<tr>
<td>Specific electrical conductivity</td>
<td>S/m</td>
<td>7.5×10^6</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>W/m·K</td>
<td>57</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>kJ/kg·K</td>
<td>0.22</td>
</tr>
<tr>
<td>Thermal diffusivity</td>
<td>mm²/s</td>
<td>35.82</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>N/mm²</td>
<td>59.4</td>
</tr>
<tr>
<td>Strain to rupture</td>
<td>%</td>
<td>68</td>
</tr>
<tr>
<td>Density</td>
<td>g/cm³</td>
<td>7.5</td>
</tr>
</tbody>
</table>

The metal alloys show a nearly newtonian flow behavior with little dependence on temperature or shear rate (Figure 2). The viscosity is less than of thermoplastics with values in the millipascal range of 4 to 5 tens. Apart from the rheological properties, the thermal properties also differ significantly from those of the thermoplastics processed in the injection molding process. The metal alloys show a thermal conductivity which is higher by 2 tens of piles and an approx. 9-fold lower specific heat capacity. These properties result in faster solidification compared to thermoplastics.

![Figure 2. Viscosity of the low melting metal alloy dependent on the temperature](image)

The alloys show a different behavior during solidification than thermoplastics. In the case of metal alloys, the temperature and the width of the phase transition from liquid to solid state varies according to the proportion of the respective alloying constituents [17,18]. In the case of alloys with a eutectic composition considered in the present work, this phase transition takes place between liquid and solid on reaching the melting point without solidification range, so that a fine, uniform microstructure is formed. The thermal and rheological properties, which differ significantly in comparison to plastics, require adapted technological approaches during processing.

Experimental Setup

A base mold with changeable inserts to permit the production of plastic carriers with different conductor track shapes, sizes and runs was used for the examinations (Fig. 2). The injection molding tests were carried out on a hydraulic Demag Ergotech 80/420 - 310 system from Sumitomo Demag Plastics Machinery GmbH, Schwaig, Germany. The metal injection was carried out by an auxiliary die-casting unit provided by the Krallmann Group, Hiddenhausen, Germany, which is flanged laterally to the mold and controlled by the core pull control of the injection molding machine.

The plate-shaped plastic carriers produced have a volume of 125×105×3 mm³.
The plastic carriers were produced with process settings shown in Table 2:

Table 2. Process settings for the plastic carriers

<table>
<thead>
<tr>
<th>Process parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection speed, cm³/s</td>
<td>30</td>
</tr>
<tr>
<td>Injection pressure, bar</td>
<td>750</td>
</tr>
<tr>
<td>Holding pressure time, s</td>
<td>5</td>
</tr>
<tr>
<td>Holding pressure, bar</td>
<td>300</td>
</tr>
<tr>
<td>Cooling time, s</td>
<td>20</td>
</tr>
<tr>
<td>Back pressure, bar</td>
<td>20</td>
</tr>
<tr>
<td>Dosing volume, cm³</td>
<td>56</td>
</tr>
</tbody>
</table>

The conductor tracks were produced with varying process settings, shown in Table 3. The tracks have a length of 137 mm and, depending on the test point, a square cross-section of 1 mm², 2.25 mm² or 4 mm².

Table 3. Process settings for the conductor tracks

<table>
<thead>
<tr>
<th>Process parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piston speed, mm/s</td>
<td>+</td>
</tr>
<tr>
<td>Mold temperature, °C</td>
<td>80</td>
</tr>
<tr>
<td>Clamping force, kN</td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 3. Setup to investigate the flow behavior

For the analysis of the track morphology and the determination of the defects, light microscopic images of the tracks were prepared and the relative defect number on different sections was analyzed using the image processing software ImageJ of the National Institute of Health, USA. For the evaluation of the electrical properties the specific electrical conductivity, the current load capacity as well as the electrical load resistance were determined.

Flow behavior during the track filling

The flow and transport processes in solidifying metallic melts can be characterized by the concept of convection [17]. During the die-casting filling process, forced convection occurs due to the force applied from the outside. From the flow engineering side, the mold filling process can be described as follows: At the beginning, the melt flows into the mold cavity at high speeds in the range of a few meters per second through the sprue system. Since no full contact is made between the metal alloy and the cavity wall, the metal melt is in contact with the residual air in the cavity. The flow resulting from forced convection is usually turbulent and has turbulence areas caused by geometric conditions in the flow channel. In the case of very thin-walled castings, however, the casting beam touches the cooled cavity wall very early and slides along it. As a result, a solidified casting skin is formed, along which the still liquid metal rolls off [19].

For the determination of the theoretical turbulence of the molten metal flow the Reynolds number for tube flows is applicable:

\[
\text{Re} = \frac{\rho \cdot v_m \cdot d}{\eta}
\]

(1)

where \( \rho \) is the density (kg/m³), \( v_m \) is the averaged velocity of the flow (m/s), \( d \) the cross-section (m²), and \( \eta \) is the viscosity (Pa·s). For the cross-sections used in this work the following Reynolds numbers were calculated for a piston speed at the die-casting unit of \( v_m = 165.6 \) mm/s:

Table 4. Reynolds number in dependence of the cross-section of the conductor track

<table>
<thead>
<tr>
<th>Cross-section, mm²</th>
<th>Re</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>121,697</td>
</tr>
<tr>
<td>2.25</td>
<td>81,616</td>
</tr>
<tr>
<td>4</td>
<td>61,544</td>
</tr>
</tbody>
</table>

With \( \text{Re} > 2300 \) for every cross-section used in this work, it can be assumed that the flow of the metal melt is always turbulent inside the cavity.

Figure 4 shows the filling of a groove at the sprue gate and at a bifurcation. At the beginning the melt front is quite stable and shows a typical profile. Even the slightest changes in the flow lead to an encapsulation of residual air in the cavity, which is conveyed by the melt. When the melt hits the bifurcation, free-jets occur. The metal melt knocks over and encapsulates further air.
Air-pockets within the conductor track have thereby been exposed as a main cause of the formation of defects. Air located in the cavity is surrounded and enclosed by the melt. If the enclosed air at the flow path’s end can no longer escape from the solidifying conductor track, it remains in the conductor track. A possible solution to overcome these challenges is an elongation of the solidification time of the targeted venting of the flow channel.

The most effective countermeasure has been a reduction in the clamping force (Figure 5). Excess air can thus vent via the parting plane. A reduction in the injection speed can also reduce the number of defects. It is assumed that due to the lower flow speed, the turbulence of the flow decreases and thus less intermixing with the air takes place. In addition, the enclosed air has more time to escape. An increase in the mold temperature and a simultaneously prolonged solidification period of the metal melt does not seem to have any influence on the number of defects.

With the determined process settings a reproducible production of fault-free conductor tracks is possible. If plastic carriers and conductor tracks are to be produced in one mold during the same injection cycle, a closing force reduction to 100 kN is, however, not practical for avoiding defects for larger components. Either the metal cavity must then be decoupled from the rest of the cavity and be closed separately, or venting elements such as sintered metal bushings are deliberately introduced over the flow path in order to allow a reliable displacement of the air.

**Electrical properties**

If there is a defect-free production of the conductor track, the qualification is to ensure that IMKS components are also suitable for electrical use under continuous operation. For this purpose, investigations were carried out to determine the specific electrical conductivity, the current load capacity and the electrical load resistance.

The produced components have a specific electrical conductivity of $\sigma = 6.1 \times 10^6$ S/m (see pure tin: $8.7 \times 10^6$ S/m) over all cross-sections. Thus the conductivity decreases slightly during processing, despite the addition of highly conductive silver. This can be affected by oxidation in the crucible, although the protective gas atmosphere should suppress this process. It is more likely to be in contact with the oxygen in the cavity.

In order to determine the current load capacity, the conductor tracks were exposed to currents of each 10, 15 and 20 A, respectively, and the heating of the conductor in the plastic carrier was recorded by thermography camera ThermoVision A600-Series of the FLIR Systems Inc., Wilsonville, Oregon, USA, at an ambient temperature of 25 °C. After reaching a stable temperature level, the temperature of the conductor track was determined (Figure 6).

As expected, the temperatures increase with increasing current. The used plastic carriers do not have a clear influence on the temperatures which can be
achieved, although the PBT + PET blend has been expected to have a lower final temperature due to the higher thermal conductivity. The larger cross-sections can, as expected, bear significantly higher currents without overheating, while a cross-section of 1 mm² at 20 A current causes a failure of the conductor. Thermal degradation of the plastic carriers during the different loads could not be detected.

As an interim conclusion it can be stated that electrical plastic parts produced with the IMKS are also suitable for high currents under continuous operation. The cross sections 2.25 mm² and 4 mm² allow even the maximum permissible rated currents for copper cables with PVC insulation (see $\sigma_{Cu} = 56 \times 10^6$ S/m) according to VDE 0298-4/2013-06 [20]. IMKS components are therefore suitable not only for lighting applications or signal transmission, but also for currents, such as are expected, in energy technology or in future e-mobility. In addition to electrical permanent loads, electrical load changes, in which high currents are alternately switched on and off, also play an important role for the life expectancy of the conductor tracks.

For the tests for the electrical load resistance, conductor paths with a cross-section of 2.25 mm² were loaded with a current of 40 A and the conductor track was heated up to $T = 30$ K below the deflection temperature of the plastic carrier (PA6 GF30: 200 °C., PBT + PET GF55: 210 °C). The current was switched off until the trace temperature had dropped to 25 °C before the cycle was restarted. The applied voltage was recorded for each cycle (Figure 7). After a short settling phase of five cycles, the voltage in the PA6 carrier oscillates between 0.237 and 0.211 V (fluctuation range 11.6%) while the PBT carrier voltage is measured between 0.201 and 0.213 V (fluctuation range 5.8%). As a result, the dropping power decreases lower for the PBT carrier, but the transmission is more stable. Nevertheless, for both carriers it was concluded that over 1000 cycles no drop in the voltage could be determined, so that conductor tracks produced in the IMKS have a long service life with regard to the electrical properties.

![Graph](image.png)

Figure 7. Detected voltage over 1000 electrical load resistance cycles

**Conclusions**

The results of the completed research have shown that integrated metal/plastics injection molding allows plastic components with integrated metal conductor tracks to be produced without defects.

The results show an obvious turbulent flow behavior of the metal melt inside the cavity, which lead to encapsulation of residual air and therefore defects in the latter conductor track. By an adapted selection of the process settings, e.g. a reduction of the clamping force or the injection speed, the conductivity-reducing air pockets can be switched off reproducibly.

The electrical investigations have shown that IMKS components meet the high requirements with regard to the service life and the endurance characteristics and, in some cases, even surpass them.

The actual research focused on the flow behavior of the metal melt and the resulting quality in terms of defects and electrical properties. Further research will investigate the direct contacting of metallic inserts with low melting alloy. By understanding the thermal interaction between the solidifying melt and the insert a material bond between the conductor track and the insert is to be achieved.

**Acknowledgments**

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**References**