Ultrasonic welding of micro plastic parts

W. Michaeli\textsuperscript{a}, E. Haberstroh\textsuperscript{b}, W.-M. Hoffmann\textsuperscript{a}

\textsuperscript{a} Institute of Plastics Processing (IKV), RWTH Aachen University, Aachen, Germany
\textsuperscript{b} Lectureship and Research Field of Rubber Technology, RWTH Aachen University, Germany

Abstract

Due to the ongoing miniaturisation in many industrial branches plastics are increasingly applied in microsystems technology. To guarantee the functionality of the system suitable joining processes must be applied to join separate components. Most of the welding processes commonly used for series production are not suitable for welding micro parts made from plastics, since either the mechanical or the thermal load of the joining partners during the welding process are too high. Only laser transmission welding and ultrasonic welding are applicable for welding complex micro components. Since with ultrasonic welding a certain frictional load of the components cannot be avoided totally with standard welding equipment, specially adapted machinery has to be used as it could be shown at the Institute of Plastics Processing (IKV) at RWTH Aachen University. While micro parts with two-dimensional weld seams have already been successfully welded in previous investigations, recent research deals with the ultrasonic welding of micro parts with a more complex three-dimensional weld seam geometry. It could be shown that for appropriate welding parameters this can be accomplished, whereby the mechanical load of the parts has to be kept as small as possible.

Keywords: welding, ultrasonic welding, adapted welding equipment, tensile strength, weld seam morphology

1. Introduction

Due to low material costs and the great variety in design plastics are becoming more and more important in microsystems technology. By means of micro injection moulding and micro hot embossing, micro parts can be produced in high numbers and short cycle times.

However, microsystems often consist of several components which have to be joined together in order to ensure the functionality of the system. In general, adhesive bonds of plastic parts can be realised by welding or glueing \cite{1, 2}. Welding has the advantage that there is no need for additional material and that the achievable bond strength are higher compared to glueing. Moreover, there is no need for curing times.

There are several welding processes applicable for welding plastics in the macro-range which use different mechanisms of energy input. However, the micro technology has special requirements to a suitable welding process. Therefore, only few welding processes can be applied for the welding of micro plastics parts.

A welding process for plastics which is suitable for the application in microtechnology has to meet the following demands \cite{3, 4}:

- precisely controllable energy input
- low mechanical load on the parts
- low thermal load on the parts
- single-stage process
- small flash and no abrasion
- high positioning accuracy during welding

On account of these requirements most welding processes for plastics are not suitable for microtechnology. With the heated tool welding, for example, the energy input cannot be controlled exactly enough, so that filigree structures would be destroyed. Besides, all processes, which melt the joining parts by means of friction, i.e. moving both parts relatively to each other, are not applicable in the micro-range, because the mechanical load of the components is too high. So sensitive structures would be demolished \cite{4}.

Solely the laser transmission welding as well as the ultrasonic welding are suited for the application in microtechnology. Laser radiation can be focused very well so that the energy can be put locally and precisely metered into the joining area. Moreover, it is a contactless process, i.e. there is no mechanical load of the parts during the welding process. Although the ultrasonic welding uses friction as an energy source, it is nevertheless a possible joining process in microtechnology, since the material is plasticised mainly by internal, dissipative friction between the polymer molecules. The polymer is heated inside so that the mechanical load of the components due to boundary friction is relatively low \cite{1}.

At the Institute of Plastics Processing (IKV) at RWTH Aachen University complex micro parts with two-dimensional weld seam geometries could successfully be welded by ultrasound in previous investigations \cite{5}. In the following it is indicated that this process can be also applied to the welding of micro parts with a three-dimensional seam geometry.

2. Ultrasonic welding

Ultrasonic welding is a joining process for thermoplastics which is often applied in series production. The reason is that this process features very short cycle times in the range of 0.1 to 1.0 seconds. Since there are physical restrictions limiting the maximum size of the welding tool, also called ‘horn’, the process is constrained to small and middle-sized components with a weld seam length up to 300 mm. If the joining surface or the weld length are too big, a homogeneous oscillation of the horn and thus a homogeneous energy input cannot be ensured \cite{2}.

With ultrasonic welding the joint is realised by melting the polymer due to dissipation, i.e. the
transformation of mechanical oscillation energy into heat [2, 6]. A longitudinal ultrasound wave forms a standing wave within the component between the horn and the bottom of the component by reflection of the wave. The areas of maximum heating of the polymer are located where the acoustic cyclic stress has its maximum (Fig. 1).

Their location depends on the wavelength of the sound wave amounting to approximately 5 cm to 10 cm depending on the polymer. So ideally, the parts should be designed in such a way that the joining zone is located in these areas of maximum cyclic stress. Generally, this is not possible in practice, since this would limit the part design extremely. However, a cross section narrowing can be realised by constructive measures, which locally increases the mechanical cyclic stress and therefore the energy conversion [3]. This can be achieved in form of an energy director or a shear joint. Thus the location of the joining area can be chosen freely.

Apart from the longitudinal oscillation, also transversal oscillations occur which originate among other things from the flexural oscillation of the horn. Due to the transversal oscillation there is to a relative movement between the joining components and thus to boundary friction. This leads to a not negligible mechanical load of the components which would damage filigree structures. That is why without modification standard ultrasonic welding equipment cannot be applied in microtechnology.

3. Ultrasonic welding equipment for micro parts

On account of the small component and joining area dimensions in microtechnology there are certain demands which the ultrasonic welding equipment and the joining process have to fulfill:

- A sufficient energy input into the joining area has to be possible.
- Small joining areas (<1 mm²) must be realisable.
- The reproducibility and the positioning accuracy have to be very high.
- Flash should be as small as possible in order to ensure the functionality of the microsystem.
- The mechanical load of the joining parts during the welding process must be as low as possible.
- The energy input should be adjustable by variation of the welding parameters.

Because there is no standard ultrasonic welding machine which fulfills these requirements, an ultrasonic welding unit was developed at IKV which has been adapted to the abovementioned requirements, see Fig 2.

One of the most important aspects of the modification of the welding unit is the frequency of the ultrasound. Instead of a frequency of 20 kHz which is often used for standard welding machines a frequency of 40 kHz is applied. So lower amplitudes can be chosen in order to bring nearly the same amount of energy into the joining area. The lower the amplitude the lower is the mechanical load of the components during the welding process. To allow for an exact movement of the oscillation system, a servo electric moving unit is used. It features a traversing range of 100 mm with an accuracy of ± 1 µm. The oscillation system is mounted to this moving unit. Furthermore, the horn and the fixture are adapted to the sample geometry.

4. Methodology

Ultrasonic welding has already been applied successfully for joining plastic micro parts [1, 5]. However, the components had only two-dimensional weld seam geometries so far. The two-dimensionality of the weld seam is according to the state of the art of the ultrasonic welding technology a precondition for the successful joining of macro-ranged parts. The welding surfaces should be parallel with the front surface of the horn and in one plane to allow for a favorable and homogeneous ultrasound energy input.

Components in microsystem technology have very small dimensions. So even if the weld seam geometry has three-dimensional properties, this will have a
smaller influence on welding process compared to welding parts of the macro-range.

Therefore, within the scope of the investigations carried out at the IKV Aachen it was examined if it is possible to join micro parts with a three-dimensional weld seam geometry by ultrasound. For this purpose, the sample part shown in Fig. 3 was developed. The square-shaped sample part features a wall thickness of only 300 µm with a step of 1 mm in height at a length of 2 mm. The joining surfaces of the upper joining component are equipped with energy directors.

The sample parts were made from the amorphous polymer polycarbonate (PC) whose weldability by ultrasonic welding is rather good. The sample parts were welded with the parameter settings of the amplitude of the ultrasonic wave $\hat{a}$, the joining displacement $s_w$ and the welding velocity $v_w$ indicated in Table 1. With each set of parameters 10 parts are welded out of which 8 samples are taken for the determination of the breaking force by tensile tests. The results are statistically evaluated within the scope of an analysis of variance (ANOVA) [7]. Besides, the weld seam morphology was determined by microscopic analyses.

Since the welding velocity had no significant influence on both the breaking force and the weld seam morphology only the results regarding the parameters amplitude and joining displacement are considered in this paper. The welding velocity amounts to $v_w = 0.6$ mm/s for the following discussion. At this velocity the cycle time ranges from approximately 0.2 s up to 0.5 s.

Table 1 Welding parameters

<table>
<thead>
<tr>
<th>amplitude $\hat{a}$ (µm)</th>
<th>16.5</th>
<th>22</th>
<th>28</th>
</tr>
</thead>
<tbody>
<tr>
<td>joining displacement $s_w$ (mm)</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>welding velocity $v_w$ (mm/s)</td>
<td>0.1</td>
<td>0.6</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4 Breaking forces depending on the welding parameters

Fig. 5 Weld seam morphology for different amplitudes

5. Results

Fig. 4 shows the results of the tensile tests of the welded samples. Average breaking forces up to $F_b = 180$ N can be realised depending on the amplitude and the joining displacement. Thereby, the amplitude has the biggest influence on the breaking force. An amplitude of $\hat{a} = 16.5$ µm leads to a breaking force of $F_b = 174$ N averaged over all settings of the joining displacement. An increase of the amplitude to $\hat{a} = 28$ µm causes a decrease of the breaking force to an average of $F_b = 136$ N. Thereby, the level of significance exceeds 99 %. This indicates that the energy input is too high during the ultrasonic welding process, so that the polymer decomposes and weakens the weld.

These findings can be confirmed by microscopic analyses. In Fig. 5 the weld seam morphologies for two parts are shown which were welded with the same joining displacement of $s_w = 0.1$ mm, but with different amplitude settings of $\hat{a} = 16.5$ µm and $\hat{a} = 28$ µm, respectively. It can be recognised that the left web of the upper component - here the distance between the welding zone and the horn is the largest - is decomposed at an amplitude of $\hat{a} = 28$ µm (on the left side at the bottom of Fig. 5). This decomposition occurs for all components which are welded at this amplitude. So there is no circumferential weld seam resulting in a decrease of the breaking forces. An explanation for this could be an elevated mechanical load for higher amplitudes originating from boundary friction.

For small joining displacements the influence of the amplitude is significantly higher than for $s_w = 0.3$ mm. At a joining displacement of $s_w = 0.1$ mm the breaking force is decreased from $F_b = 163$ N down to $F_b = 104$ N when increasing the amplitude from $\hat{a} = 16.5$ µm to $\hat{a} = 28$ µm. At a joining displacement of $s_w = 0.3$ mm the amplitude has no influence any more, see Fig. 6. As microscopic analyses indicate the reason is that in this case the components are not only welded in the intended weld area, but also between the positioning structures, see Fig. 7. Even though the upper welding component is partly decomposed, the welded area contributing to the breaking force is larger and the breaking force increases accordingly.

Regarding the joining displacement, an increase from $s_w = 0.1$ mm to $s_w = 0.3$ mm results in an increase of the average breaking force from $F_b = 131$ N to...
Fb = 166 N averaged over all settings of the amplitude. The reason is that the meltflow is improved since the joining parts are moved towards each other. Thus the molecules can entangle themselves better, so that the mechanical properties of the weld get better. Moreover, as mentioned above, the parts do not get in contact only in the intended welding area, but also in adjacent regions.

6. Conclusion

To sum up, good results can be realised with PC. This is reflected in the high breaking forces. However, the three-dimensional weld geometry leads to an inhomogeneous ultrasound energy input and thus to an irregular plasticising of the weld area. This results in partial decomposition at high amplitudes which could be shown in microscopic analyses. At an amplitude of \( a = 16.5 \, \mu\text{m} \), a joining displacement of \( s_w = 0.1 \, \text{mm} \) and a welding velocity of \( v_w = 0.6 \, \text{mm/s} \) the best result could be achieved for PC, both regarding mechanical properties and the outer appearance of the weld.

Welding trials have also been carried out with the semicrystalline material polyoxymethylene (POM). Normally, POM features a good weldability with ultrasonic welding. However, it was not possible to prevent the partial decomposition recognised at high amplitude with PC when welding the depicted sample part geometry with the three-dimensional weld seam geometry. Even for welding parameters with low amplitude and joining displacement the inhomogeneous ultrasound energy input due to the three-dimensionality of the weld interferes with the welding process. On the one hand, this leads to lower breaking forces since no circumferential weld line could be realised. On the other hand, the outer appearance is deteriorated by a relatively large amount of decomposed material.

This problem does not occur when welding samples made from POM which have a more suited weld seam geometry, i.e. the weld seam is in one plane with the same distance to the horn along the whole weld contour. In this case, good weld results are possible also for POM. Figure 8 depicts the results achieved with a similar sample geometry without the step in height of 1 mm. As it can be seen, there is no decomposition and thus no imperfection in the weld. So the breaking force is quite high, as well. Depending on the welding parameters the formation of flash can be totally avoided which is an important aspect concerning the possible application of this welding process in microtechnology, see Fig. 8. at the top.

Acknowledgements

The authors gratefully acknowledge the financial support of the Deutsche Forschungsgemeinschaft (DFG) within the Collaborative Research Centre SFB 440 "Assembly of Hybrid Microsystems". Moreover, we gratefully thank Bayer MaterialScience AG and Ticona GmbH for providing the required material for the investigations presented in this paper.

References