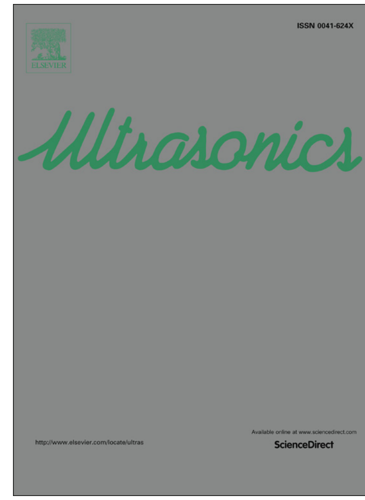

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Review on ultrasonic fabrication of polymer micro devices

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Abstract

Fabrication of micro devices from thermoplastic polymers by ultrasonic processing has become a promising new technology in recent years. Microstructures are generated on polymer surfaces with cycle times of a few seconds and are tightly sealed in even shorter times. Investment costs and energy consumption are comparatively low and processes are very flexible enabling economic fabrication even for small-scale production. For large-scale production role-to-role fabrication has been shown reducing costs even more. A variety of micro devices have been introduced up to now mostly for microfluidic applications. Besides this, electronic circuit boards are fabricated by ultrasonic processing.

Keywords: ultrasonic fabrication, polymer, micro devices, ultrasonic hot embossing, ultrasonic embossing, ultrasonic welding

1. *Introduction*

In recent years fabrication of micro devices by ultrasonic treatment of thermoplastic polymers has been emerging paving the way for fast and low-cost manufacturing. By ultrasonic techniques micro structures are generated and welded together with cycle times as short as a few seconds. Besides this, not much more than a commercially available ultrasonic welding machine and micro patterned tools are required for fabrication. The investment costs of an ultrasonic welding machine are on the order of some 10,000 €. Besides low-cost manufacturing, the fast change to a new design is an important advantage of ultrasonic fabrication of micro devices. New tools are milled from an aluminum plate within some hours and several micro devices with the new design are fabricated within another hour.

This paper describes some variants of ultrasonic fabrication such as ultrasonic hot embossing, welding, thermoforming, punching, and riveting and applications such as flow sensors, heat exchangers, micro mixers, predetermined breaking points in yarns, and electronic circuit boards.

Early papers showed already in 1974 and 1981 that plastic powders can be welded together by employing ultrasound and adapt to the shape of a tool [1-2]. More recently it has been demonstrated that with this technique micro structures can be generated into polymer surfaces [3-18] and that micro devices can be fabricated by a combination of ultrasonic hot embossing and welding [19-24].

Ultrasonic welding is already known for decades and applied in industry for many purposes [25-30]. The welding of polymer micro pumps, micro valves, and other microfluidic devices showed that this process can be employed in micro technique also [31-38]. Table 1 lists polymers employed for ultrasonic fabrication of micro devices and typical properties of these polymers. The properties may vary as a function of additives, fabrication and environmental conditions.

Table 1: Thermoplastic polymers employed for ultrasonic processing so far and some of their typical properties [39].

Symbol	Polymer type	Young's modulus at 22°C [GPa]	Glass transition temperature [°C]	max. operating temperature [°C]	Density [kg/m³]
PA 6	Polyamide	1.5 - 3.0	40 - 132	80 - 160	1084 - 1230
PVC	Polyvinyl chloride	2.5 - 4.0 [31]	68 - 110	60	1385 – 1440
PVDF	Polyvinylidene fluoride	1.2 - 1.6	- 40	148 - 190	1750 - 1800
PP	Polypropylene	0.3 – 1.7	- 20	85 - 120	880 - 910
HDPE	High density polyethylene	0.6 - 1.1	- 140 – -100	90	940 - 970
LDPE	Low density polyethylene	0.1 - 0.3	< - 40	88	910 - 955
PET	Polyethylene terephthalate	2.7 - 4.1	67 - 125	150	1333 - 1365
MABS	Methyl methacrylate acrylonitrile butadiene styrene copolymer	1.9 - 2.0	93	75	1080
PC	Polycarbonate	2.2 - 2.4	145	100 - 140	1196
PEEK [41]	Polyether ether ketone	3.7	143	250 [31]	1260 - 1300
PS	Polystyrene	2.4 - 3.5	85 - 110	105	1050 - 1080
SAN	Styrene-acrylonitrile copolymer	3.9	104 - 127	85	1070 - 1080
PMMA	Polymethyl-methacrylate	2.2 - 3.8	43 - 160	80 - 100	1170 - 1230

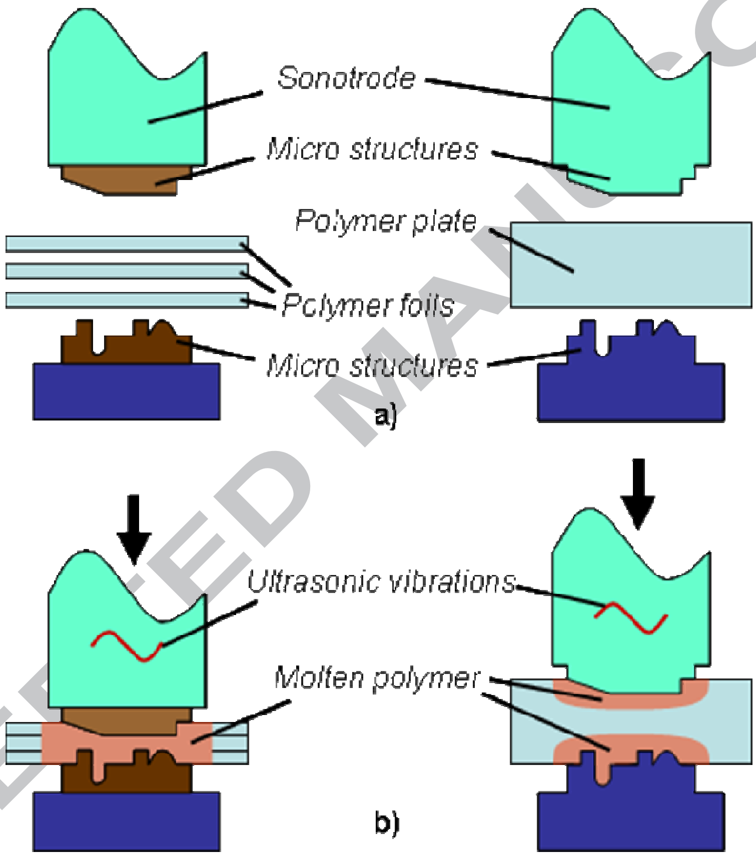
2. *Ultrasonic hot embossing*

Ultrasonic hot embossing, also called ultrasonic embossing or ultrasonic imprinting, is similar to micro hot embossing [42] but heating of the polymer is generated by ultrasound. A plate, up to several millimeters in thickness, or a stack of polymer foils, each in the thickness range of 50 to 400 µm, are placed on a tool with protruding micro structures (see Fig. 1a). The sonotrode of a commercially available ultrasonic welding machine is pressing the sample onto the tool and emitting ultrasonic vibrations generating friction heat where protruding structures are in contact to the sample.

When a stack of polymer foils is used, friction is also generated between the foils heating the stack from its inside. This way, some control is obtained on the distribution of heat over the thickness of the sample. Where more heat is required, more and thinner foils should be placed in the stack. Due to the enhanced heat generation a stack of foils is embossed with less ultrasonic power, less pressing force, and within a shorter time than a plate.

Besides this, when a stack of foils is employed, the produced melt partially drains between the foils and a smooth surface of the embossed structures is obtained. When a plate is patterned by ultrasonic hot embossing, the melt is forced in the direction of the tool leaving flow rims at the surface of the embossed product. Furthermore, compared to the stack of foils, more pressing force is needed.

Protruding micro structures can be placed on an anvil below the sample and/or on the sonotrode. These micro structures either are milled into the sonotrode / anvil or special tools containing the micro structures are fixed onto anvil / sonotrode.



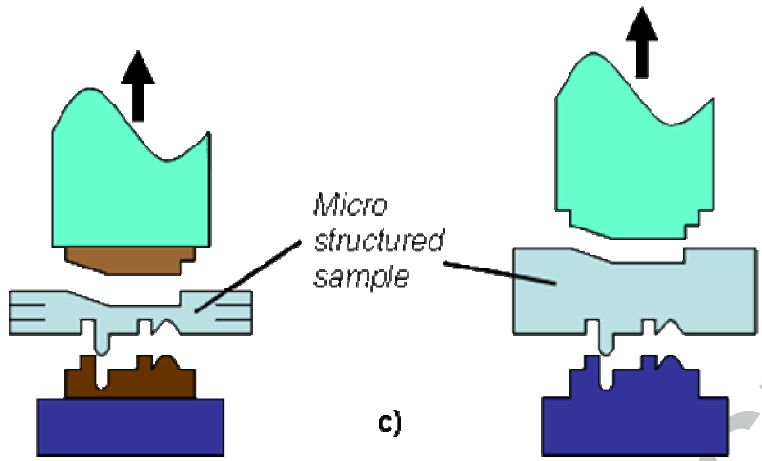


Fig. 1: Ultrasonic hot embossing of a stack of foils (left) and a plate (right).

The polymer is molten within a few 100 ms and adapts to the shape of the micro structures on the tool (Fig. 1b). Then ultrasound is switched off and the sonotrode is continuing pressing the polymer down until it is cooled and solidified again typically within 500 ms to 1 s. When a stack of foils is used, after solidifying the foils are joint to a single piece of polymer in the near of all protruding micro structures. After solidification of the polymer the sonotrode is moved up again and the micro structured sample is removed from the tool (Fig. 1c).

To fill recessing micro structures it is necessary to arrange protruding ones in the near, displacing the material required for filling the cavity.

2.1. Tools

Tools for ultrasonic hot embossing need to be rugged enough withstanding the acting forces and temperatures [43]. The inverse of the desired micro structures has to be patterned on the upper surface of the tool and the opposite side must be parallel to the upper surface allowing alignment to the sonotrode. The tool should preferably show large heat conductivity and heat capacity enabling quick cooling after embossing. As a consequence, tools from metals are a good choice. Silicon for most designs is too brittle and therefore can be used only a few times before they break. However, especially when very small micro structures had been required, silicon molds patterned by photolithography and dry etching were employed also [11].

There is a variety of processes available manufacturing tools for ultrasonic hot embossing [3-6, 43]. Micro milling [3, 43] of aluminum or brass appears to be the most flexible and low-cost way of tool fabrication because virtually every three-dimensional micro structure which can be replicated, can also be milled. On the other hand, milling is limited with respect to achievable small structures and material hardness. Significantly smaller micro structures can be generated by combining dry etching [6, 7, 9], lithography, especially electron beam [5] or x-ray lithography, and electroplateing. Also micro electrical discharge machining (µEDM) is a promising way of tool fabrication because very hard metals can be patterned [4]. Even more tool designs become possible when fabrication processes are combined to manufacture a template which is then turned into a nickel tool by electroplating [43].

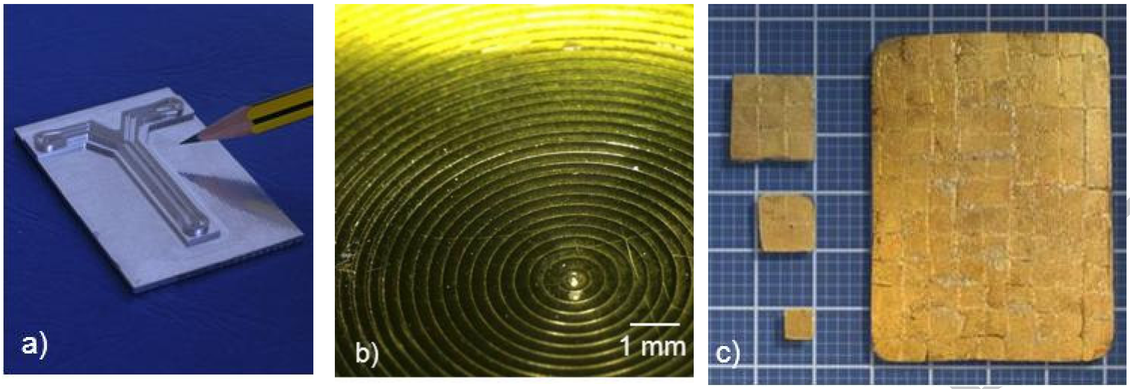


Fig. 2: Tools for ultrasonic hot embossing milled into aluminum (a), electroplated onto a polymer lens (b) [43], and electroplated after multiple embossing of the tool at the lower left into a PMMA plate (c) [43].

Figure 2a shows a tool milled into an aluminum plate, 4 mm in thickness. A tool fabricated by electroplating nickel onto a polymer Fresnel lens is shown in Fig. 2b and Fig. 2c displays on the lower left a tool made by electroplating nickel on a PMMA plate patterned by milling holes, 250 µm in diameter. The tool on the lower left of Fig. 2c was then employed for multiple ultrasonic hot embossing into larger PMMA plates and subsequent nickel electroplating. The largest tool manufactured this way is shown on the right of Fig. 2c. It has an area of 40 mm × 56 mm.

2.2. Heated tool

Already the first publication on ultrasonic hot embossing investigated the influence of tool temperature on replication [3]. Studies have shown that a heated tool has a considerable impact on the filling of micro grooves [10]. Energy consumption of the process is enhanced when a heated tool is employed, but is still smaller than in the variotherm processes usual for micro injection molding and hot embossing, because the temperature of the tool is held constant and not cycled for each molding step.

The influence of tool heating was investigated employing an ultrasonic welding machine at 35 kHz and tools with several grooves, 150 µm, 250 µm, and 300 µm in width, respectively, 8 mm in length, and up to 800 µm in depth, on a boss, 500 µm in height.

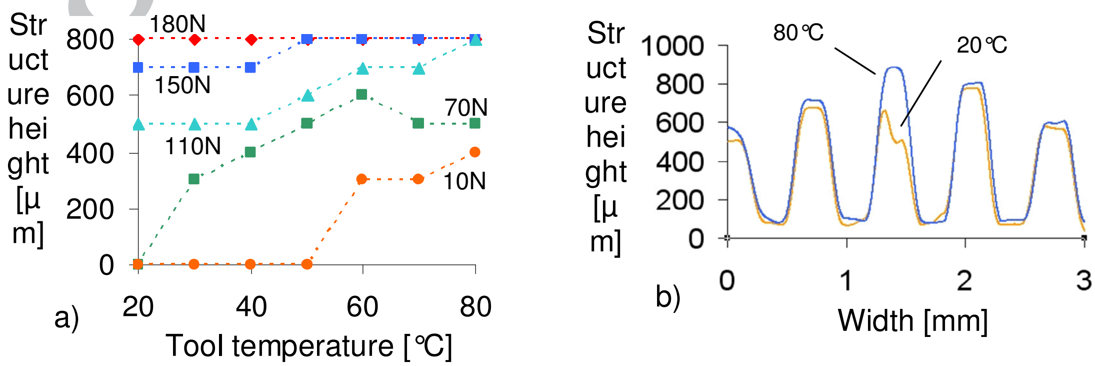


Fig. 3: Completely filled structure heights as a function of embossing force and tool temperature for PVC (a) and surface profiles measured on samples embossed at 20 °C and 80 °C, respectively (b).

Figure 3 shows the heights of protruding bars generated by ultrasonic hot embossing of a stack of 3 PVC foils, 250 µm in thickness. The heights were measured with a digital microscope. In Fig. 3a there is shown the maximum height measured at bars generated by filling 800 µm deep grooves as a function of embossing force and tool temperature. The heating of the tool leads to a retardation of the solidification process, therefore a better filling of small structures is achieved. It needs to be taken into consideration that the tool should not be heated over a certain temperature (e.g. 80°C for PVC) otherwise the polymer is deformed when demolded or even becomes colored by chemical decomposition.

Compared to ultrasonic time the tool temperature has comparatively less influence on the embossing result of larger structures (1 mm in width, 0.7 to 1.2 mm in depths). Nevertheless it has been observed that an increased temperature of the tool and hence of the polymer foils has a positive effect on the optical transparency of the embossed samples. Melt flow lines and discoloration are avoided or at least diminished.

2.3 Effect of vacuum

An attempt avoiding the decomposition of polymers during ultrasonic hot embossing and facilitating filling of grooves in the tool was employing a gastight chamber (Fig. 4). That way, it was possible to emboss structures in a vacuum (1 Pa) or inert atmosphere.

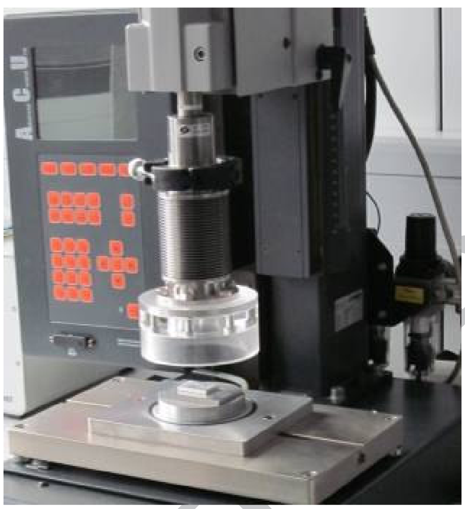


Fig. 4: Gastight chamber on a 35 kHz-machine for the ultrasonic hot embossing process in a vacuum or inert atmosphere.

However, investigations with argon, nitrogen and reduced pressure did not show any considerable distinctions compared to embossing results at ambient air. The only visible effect of using vacuum was the generation of a higher amount of melt. This can be explained by the larger embossing force due to the pressure applied to the sonotrode by the vacuum.

2.4. Pre-structured samples

Embossing large flat areas with shallow structures, such as several millimeters wide or a few micrometers high bars or grooves, does not work for most polymers. The ultrasonic energy is distributed over the whole area, without producing a sufficient amount of melt. This is countered by employing a pre-structured polymer surface next to the tool. For this purpose a mesh of energy directors was generated by ultrasonic hot embossing a pyramidal structure (Fig. 5) into a stack of 4 PS foils, each 125 µm in thickness.

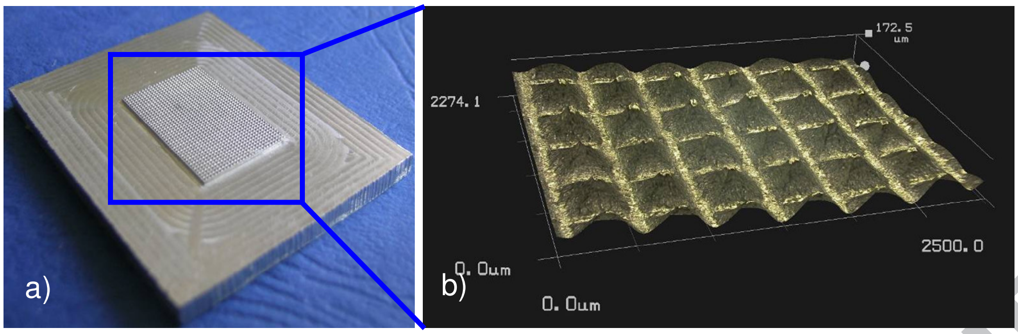


Fig. 5: Tool with pyramidal structures (a) for ultrasonic hot embossing of energy directors on polymer foils and magnification (b).

This way, the contact surface was reduced, concentrating the ultrasonic energy onto the protruding polymer bars.

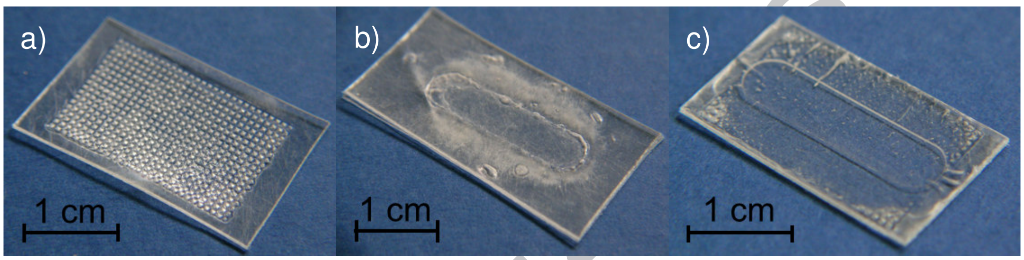


Fig. 6: Pre-structured stack of foils with a mesh of protruding polymer bars (a). A stack of PC foils after ultrasonic hot embossing a channel, 20 mm in length, 5 mm in width, and 0.2 mm in height, (b) and the same channel embossed into pre-structured foils (c).

Pre-structuring enables the replication of structures with a large area to height ratio into comparably rigid and smooth materials such as polystyrene (Fig. 6) and also of narrow cavities (width / length 15 µm, height 50 µm) on flat surfaces.

2.5. Role-to-role production

If large-scale production is desired, cycle time is limited by manual handling of the samples. Therefore, role-to-role ultrasonic hot embossing has been demonstrated [16, 44]. E.g., the micro channels of a mixer and a heat exchanger were produced this way [44]: Up to five roles of thermo-plastic polymer foils from PE and PVDF were mounted on unwind units and fed together between tool and sonotrode (cf. Fig. 7). A fixing unit ensured that the foils stack was well aligned and demolded from the tool. After ultrasonic hot embossing, the foil stack with the embossed micro grooves was rewound onto a take-up.

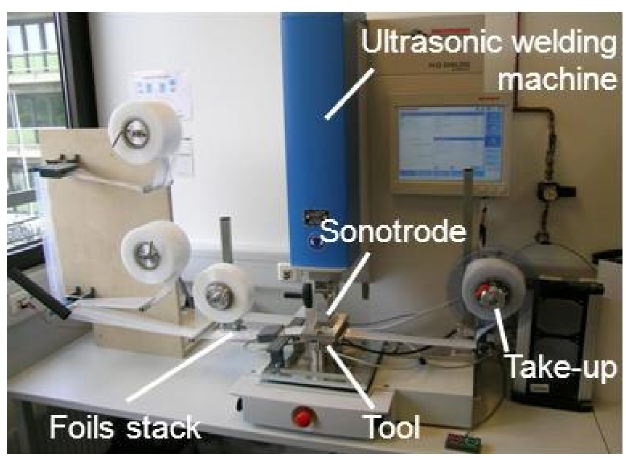


Fig. 7: Automatic roll-to-roll ultrasonic hot embossing machine [44].

It turned out that the cycle times are limited by overheating of tool and sonotrode. If the frequency of the ultrasonic hot embossing process was enhanced too much, the micro structures were damaged during demolding. Measurements inside the tool recorded a temperature rise of up to 100°C in less than 100 s. The suitable production frequency is a strong function of both the polymer type and the geometry of the micro structures to be generated (cf. Fig. 8).

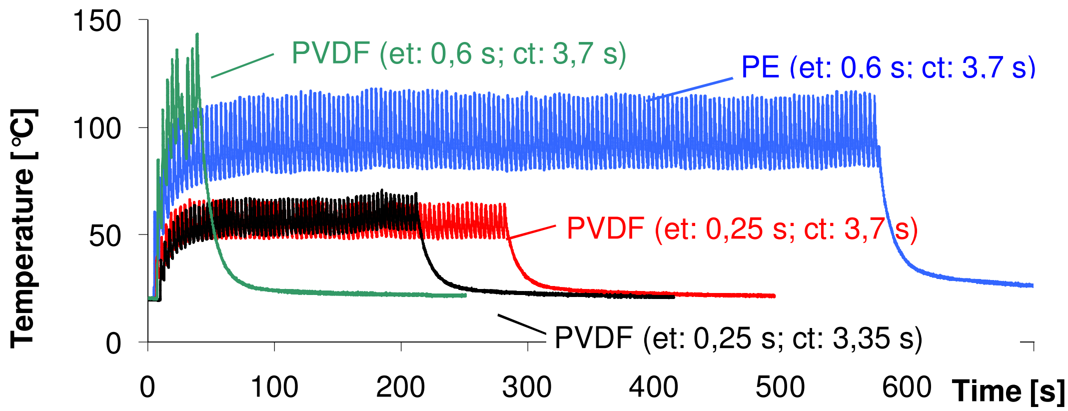


Fig. 8: Progression of the temperature for the ultrasonic hot embossing of a micro structure into PE and PVDF foils with different cycle- (ct) and embossing times (et).

For a simple PE micro groove, 20 mm, 3 mm, and 0.4 mm, in length, width, and depth, respectively, the cycle time could not be reduced below 3 s. It is expected that shorter cycle times can be achieved when a temperature control is employed for sonotrode and tool.

3. *Ultrasonic welding*

Ultrasonic welding is a process known for decades [45]. Nowadays a variety of products such as tubes for toothpaste and car dashboards are ultrasonically welded in industrial applications. One of the parts to be welded needs to show small protruding structures from thermoplastic polymer, so called energy directors. These energy directors get into contact to the joint partner first and are plasticized when the ultrasonic vibrations generate friction heat. After switching off the ultrasound, the former energy directors are cooling down and solidify. This way, a kind of glue is generated in approximately one second joining the two parts.

When a lid has to be provided onto a groove fabricated by ultrasonic hot embossing, energy directors are generated already during the embossing process. The energy directors typically have a semicircular cross-section with a radius of 125 µm. The sample with the groove is placed on an anvil and similar as for ultrasonic hot embossing, a sonotrode is pressing a lid foil onto the sample (Fig. 9). Applied force and ultrasound amplitude are smaller than for ultrasonic hot embossing, and, therefore, only the energy directors are molten without deformation of the micro grooves. As soon as the energy director is molten, the lid foil gets into contact to a larger area and the energy of the ultrasound is distributed more, significantly reducing its effect on the remaining polymer structures.

Ultrasonically welding in the near of micro cavities which shall not be filled with molten polymer is more difficult on a large area because the ultrasonic amplitude usually is not homogeneous over the sonotrode area.

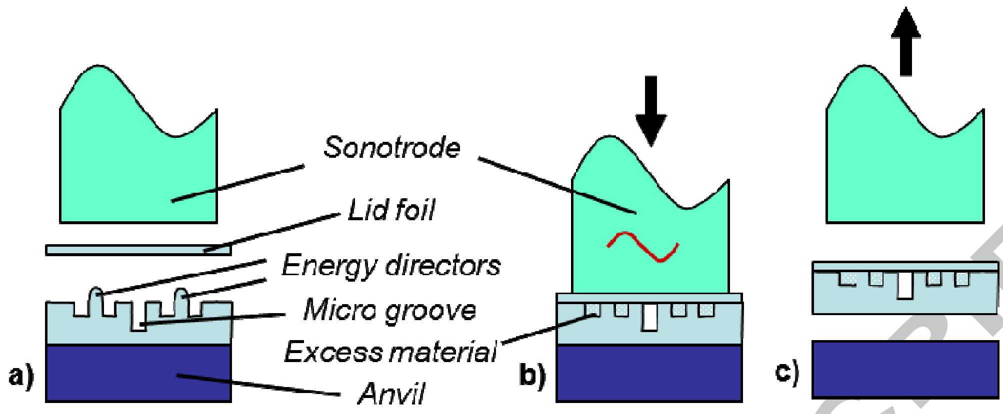


Fig. 9: Ultrasonic welding of a cover layer onto an ultrasonically hot embossed micro groove.

It needs to be avoided that the material of the molten energy director enters the microfluidic structures. This can be achieved by designing the energy directors comparatively far from the microfluidic structures and by surrounding them by grooves collecting excess material.

3.1. Material combinations

Several combinations of thermoplastic polymers have been tested for their welding compatibility (cf. Table 2).

Table 2: Thermoplastic welding compatibility of ultrasonically embossed polymer channels and lids.

Channel → / Lid ↓	PS	PP	PEEK amorphous	PEEK semi crystalline	SAN	PE	PLA	PVDF	PA	PVC	PET
PS	+	-	-	-	+	-	+	-	-	-	-
PP	-	+	-	-	-	+	-	-	-	+	-
PEEK amorphous	-	-	+	+	-	-	-	-	-	-	-
PEEK semi crystalline	-	-	-	+	-	-	-	-	-	-	-
SAN	+	-	-	-	+	-	+	+	-	-	+
PE	-	+	-	-	-	+	-	-	-	-	-
PLA	+	-	-	-	+	-	+	+	-	+	-
PVDF	-	-	-	-	-	-	+	+	-	-	-
PA	-	-	-	-	-	-	-	+	+	-	-
PVC	+	-	-	-	-	-	+	-	+	+	+
PET	+	-	-	-	+	-	-	-	-	+	+
FEP	-	-	-	-	-	-	-	-	-	-	-
PFA	-	-	-	-	-	-	-	-	-	-	-
Green	Polymers weldable for both options (Channel-Lid, Lid-Channel).										
Gray	Welding of two identical polymers.										

For this purpose one polymer (e.g. PVC) has been used for embossing a channel with energy directors, another one (e.g. PC) as the sealing lid and vice versa. Most of the results were according to known thermoplastic compatibility guides [46, 47] but also deviations have been found.

Contrary to the guides, combinations like PET/SAN and PC/PVC have been ultrasonically welded with each other. This may be due to the change of the crystalline structure of a polymer after the ultrasonic hot embossing process.

Heating and cooling rates of ultrasonic hot embossing are very high and hence increase the level of amorphousness of a polymer. This could result in a better compatibility of two polymers [48]. Table 2 shows a "+" for every combination which could be ultrasonically welded.

3.2. Electrical and fluidic connections

Electrical connections into a cavity are easily obtained when a metal wire, more than 200 µm in diameter, is placed between sidewall and lid foil before ultrasonic welding. When the ultrasound is switched on, friction heat is generated between wire and polymer. Thus the polymer is molten similar as an energy director, and after solidification the wire is tightly enclosed (cf. Fig. 10c). For thin filaments, e.g., 50 µm in diameter, the wire was placed between conical tips serving as energy directors (Fig. 10a / b). This way, fissuring of the wire was avoided.

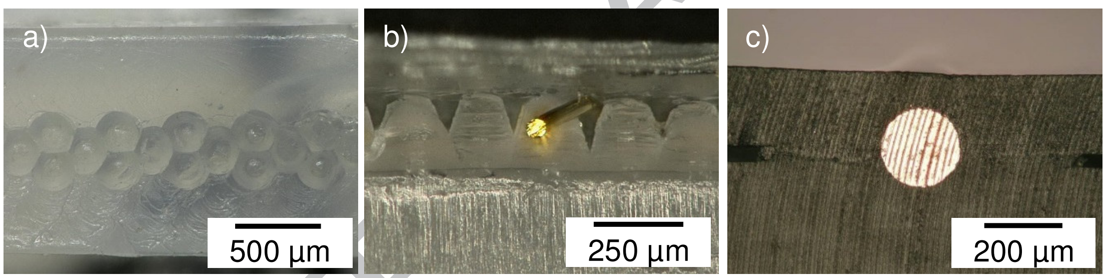


Fig. 10: Top view (a) and cut through (b) specially shaped energy directors for ultrasonically welding thin metal wires between polymer layers, and cut through a thicker copper wire after welding (c).

Fluidic connections to cavities have been constructed in different ways. Orifices had been punched into the lid foil before welding and afterwards the fluidic connectors have been glued or ultrasonically welded over these orifices (cf. Fig. 11a). Another approach is the application of a connection plate for either standard fittings (Fig. 11b) or force fitted hoses (Fig. 11c). Thereby the micro channels are welded onto the plates and thus the combinations of the used materials need to be compatible.

Fig. 11: Ultrasonically welded or glued fluidic connectors on a meandering micro

channel produced by ultrasonic hot embossing and welding (a). PVDF connection plate with 1/4"-standard fittings (b). Injection molded connection plate made of PC with force fitted hoses and T-shaped micro mixer (c).

Metallic tubes have been placed into grooves before welding. The grooves had been a bit smaller than the outer dimensions of the tubes (Fig. 12a), and therefore, the tubes have been enclosed by molten polymer (Fig. 12b).

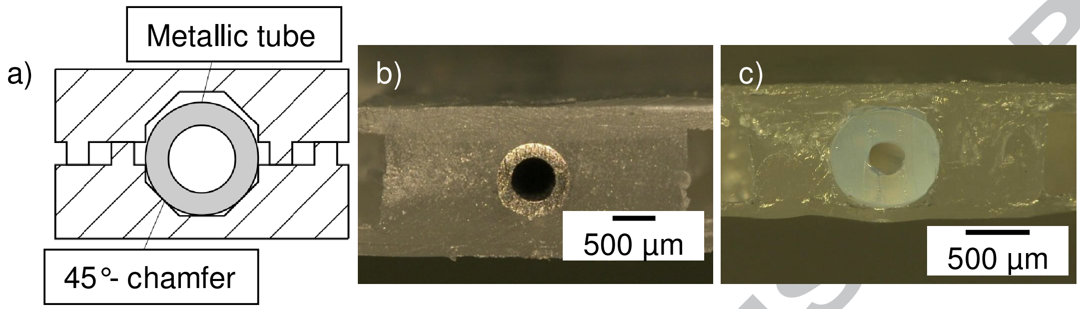


Fig. 12: Schematic design of the intake (a), and cut through the welded intake and the employed metallic tube (b) / polymer hose (c).

Instead of metallic tubes polymer hoses have been employed also (Fig. 12c), but it turned out being more difficult obtaining tight and rugged connections for this option.

4. *Ultrasonic thermoforming*

For the ultrasonic thermoforming process a combination of non-weldable polymers are used. A thin foil, e.g., PEEK is placed on a tool with the desired surface pattern and covered by a stack of polymer foils with a low softening temperature (Fig. 13), e.g., PE. When ultrasound is applied, the PEEK foil is thermoformed and the PE buffer foils are embossed by ultrasound.

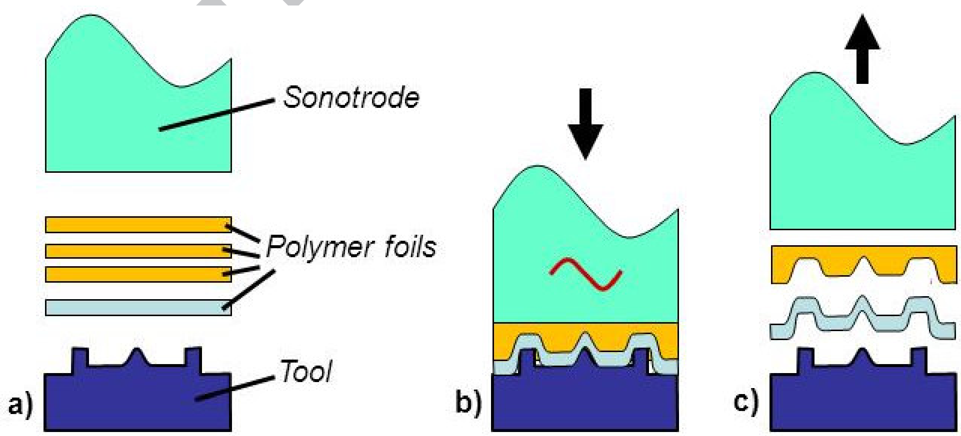


Fig. 13: Ultrasonic thermoforming by using two non-weldable polymers.

Afterwards the buffer foils may be discarded or used for further purposes. Contrary to ultrasonic hot embossing, the entire foil and not only one side is adapted to the surface pattern of the tool (Fig. 14).

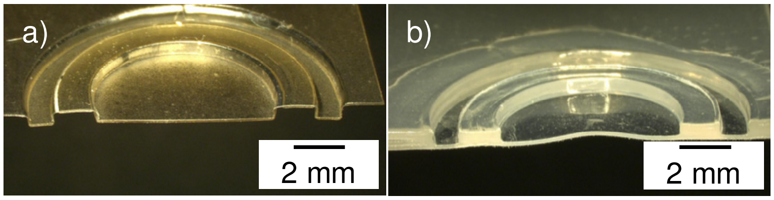


Fig. 14: Cuts through ultrasonically thermoformed PEEK-foil (a) and embossed PE-buffer foils (b) [49].

Buffer materials like silicone which are reversibly deformed have also been tested. It was apparent that silicone is not suitable for this purpose since it leads to a concentration of the ultrasound in one spot resulting in a rupture of the thermoformed foil.

5. *Ultrasonic punching*

An approach similar to ultrasonic thermoforming is used for ultrasonic punching. A stack of buffer foils is placed on top of an already embossed micro structure or a single foil (Fig. 15) preventing damage to the tool and the sonotrode.

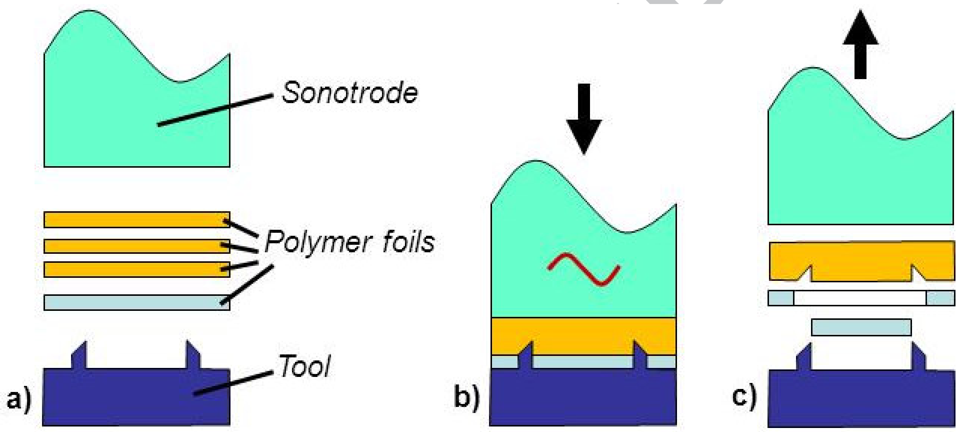


Fig. 15: Ultrasonic punching for the selective releasing of defined structures out of their surrounding foils.

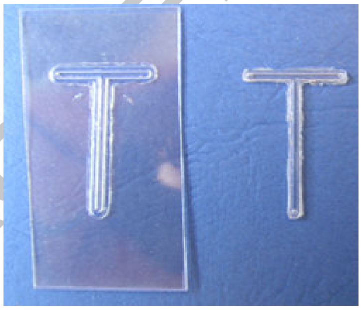


Fig. 16: Micro channel before and after ultrasonic punching [50].

Again, it is important that both materials are non-weldable with each other. The punching tool possesses cutting edges where the applied ultrasound is concentrated punching out the desired structure from its surrounding foil (Fig. 16).

By concentrating the ultrasonic energy in the separation section the polymer is plasticized and, therefore, compared to mechanical punching, less contact pressure is needed.

6. *Ultrasonic riveting and beading*

Ultrasonic riveting and beading allow the form-locked joining of two non-weldable materials (plastic, metal, glass, etc.), whereby one needs to be a thermoplastic polymer (Fig. 17).

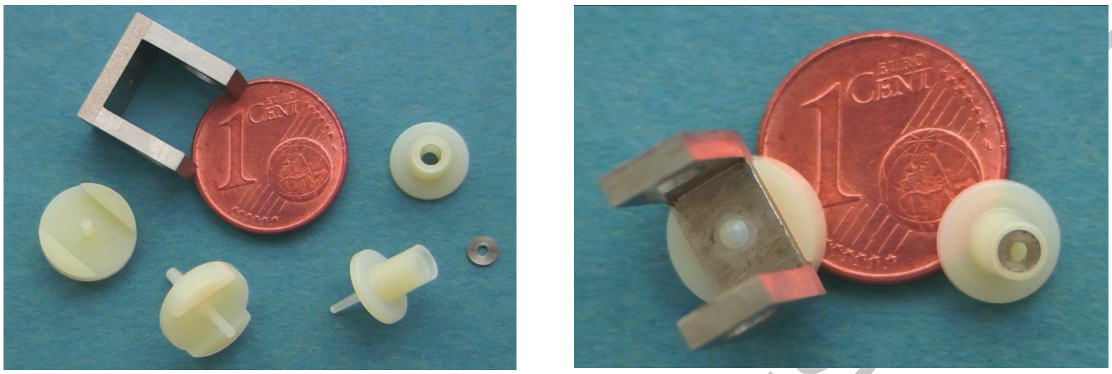


Fig. 17: Samples from ABS before (left) and after (right) riveting and beading [51].

The rivet shank is inserted into an orifice in the other material and vibrational energy is concentrated onto it. The rivet shank is molten and solidified as a dome blocking the orifice. For the rivet head commonly a specially shaped sonotrode is used. For micro applications however, a tool can be employed instead. Figure 18 shows the general process of ultrasonic riveting of micro systems.

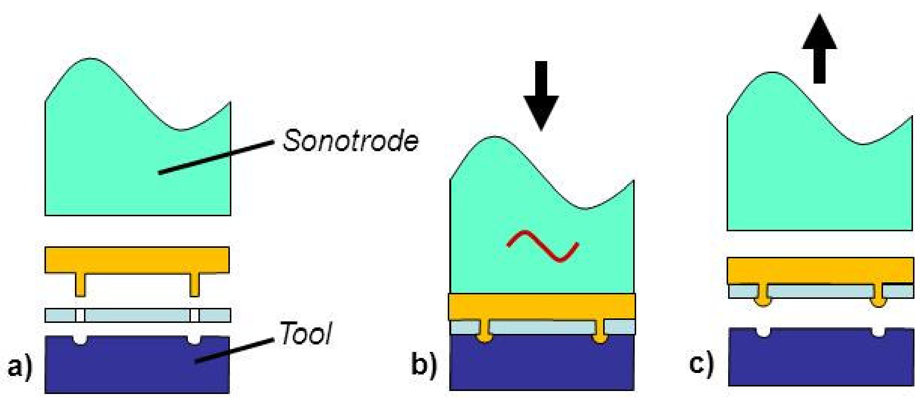


Fig. 18: Ultrasonic riveting of two non-weldable materials for micro applications.

Beading is similar to riveting, but instead of a shank extending through an orifice in the non-polymer part molten polymer is flowing around its rim joining the two parts.

7. *Limitations*

Since ultrasonic processing of micro structures is comparatively new, the limitations up to now are not known in detail. However, it appears to be clear that over all dimensions that can be processed in one step are limited by the contact area of the sonotrode to the sample. The sonotrode area is limited by the maximum ultrasonic energy output of a piezo stack in the ultrasonic welding machine. The piezos are driven in resonance to achieve large amplitudes of the ultrasonic vibrations. For a higher energy a larger stack is required and this is entailed with a lower resonance frequency. As a consequence, if the energy output shall be enlarged the frequency leaves the ultrasonic range. Typical dimensions of sonotrode areas today are 40 mm × 60 mm.

Also due to the limited energy available, the depth of grooves generated by ultrasonic hot embossing is limited to not much more than 1 mm. The design needs to take into account that every cavity in the tool which shall be filled needs protruding structures nearby generating the required molten polymer.

8. *Applications*

Patterning of surfaces is an obvious application of ultrasonic hot embossing. However, the combination with other processes, especially ultrasonic welding, allows for a variety of applications such as micro pumps, valves, and sensors or disposable systems for the analysis of chemical or biological samples. Also micro reactors for the production of chemical or biological products appear to be possible. Even electronic devices such as electronic circuit boards and RFID antennas have been demonstrated.

8.1. Patterning of surfaces

The first applications of ultrasonic hot embossing described in literature were patterning the surface of polymer plates with micro pyramids [3, 5, 6], pillars and holes [8]. Micro structures from PE as small as 1 µm were generated on top of pillars, approximately 20 µm in height [9] (cf. Fig. 19a). This is an extremely difficult task because the polymer needs to fill grooves, 1 µm × 1 µm in width and length, at the bottom of a capillary.

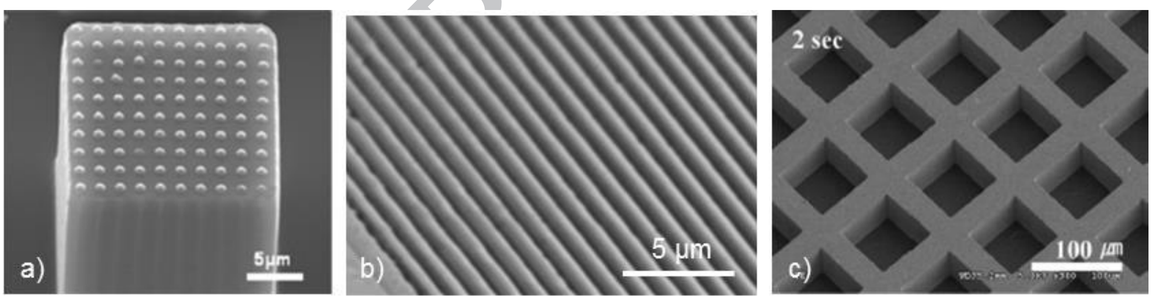


Fig. 19: Micro patterned surfaces: 1 µm wide structures on a pillar from PE [9] © IOP Publishing. Reproduced by permission of IOP Publishing. All rights reserved (a), 0.5 µm wide lines and spaces from PC [7] (b), and 70 µm wide square holes from PMMA [8] (c).

Even narrower lines and spaces, just 500 nm in width, have been hot embossed into 0.5 µm thick PC films employing a tool from etched silicon [7] (Fig. 19b). When hot embossing was assisted by ultrasonic vibrations the molding accuracy was improved and higher patterns were obtained.

Pillars, approximately 70 µm in width and length, and 54 µm in height, have been imprinted into PMMA by ultrasonic hot embossing generating a grid on the polymer surface [8] (Fig. 19c).

It has been shown that superhydrophobic surfaces can be generated by ultrasonic hot embossing [9, 52]. The bottom of a 96-well titer plate from PS has been patterned with micro pyramids offering liver-derived human cells a three-dimensional environment [12].

8.2. Micro fluidic applications

The combination of ultrasonic hot embossing and welding allows fabricating a variety of microfluidic systems. E.g., a simple micro pump [23] and a micro valve with an integrated electromagnetic drive [53] have been developed. The upper and lower parts of the housing of the micro valve were fabricated by ultrasonic hot embossing into a stack of PVDF foils. The drive was assembled from two permanent magnets glued and a copper coil placed into the housing. The electrical connections to the coil were welded in when the two parts of the valve were joined by ultrasonic welding. Figure 20a shows the micro valve together with an Euro cent. Outer height and diameter of the micro valve are 3.6 mm and 17 mm, respectively. The micro valve is bistable and remains to be closed up to a pressure of 125 kPa supplied to its inlet. Switching is achieved with an electrical power of 200 mJ at 15 V. The flow achieved through the open valve at a pressure difference of 100 kPa is 0.88 L/min and 26 mL/min for air and water, respectively.

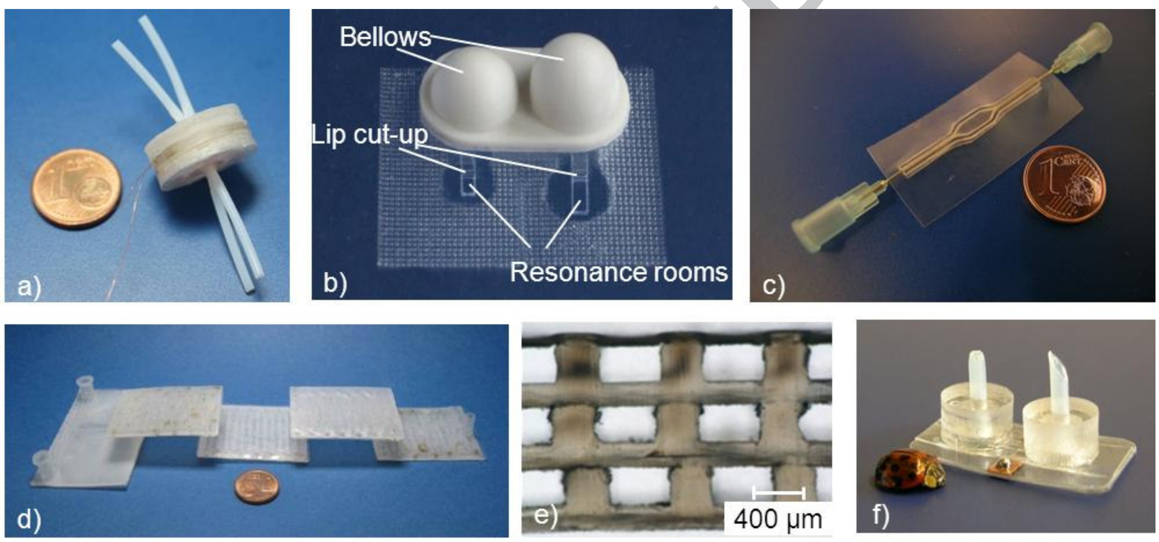


Fig. 20: Micro devices fabricated by ultrasonic hot embossing and welding: (a) bistable micro valve with an electromagnetic drive [53]; (b) two micro whistles [54]; (c) micro cuvette with metal tubing; (d) micro reactor consisting of different micro channel modules [56]; (e) cut through a micro heat exchanger [22]; (f) anemometric flow sensor [20].

Micro whistles generating a tone at an ultrasonic frequency in the non-auditable range have been employed for signal transmission (Fig. 20b). This way, a remote control without batteries and electronics has been demonstrated for, e.g., room light, air conditioning, or TV [54]. The same whistles have also been employed detecting their position enabling following the path of people wearing a shoe with an integrated micro whistle or of an autonomously moving robot in a room [55]. Micro whistles have been fabricated by ultrasonic hot embossing grooves into a stack of PP foils, three 250 µm in thickness and two 150 µm in thickness. Embossing of the grooves had been facilitated by micro pyramids on the foil next the tool. The grooves became resonance rooms, flues, and feed channels of the whistles. The grooves are sealed by ultrasonic welding a lid foil from PP on top. Before welding orifices for lip cut-up and air inlet are punched into the lid foil. When a bellow from silicone above the inlet orifice of a whistle is pushed, an air flow is generated causing the whistle to produce a tone for approximately 10 ms.

Micro channels for the biological or medical analysis of small samples are easily connected to the environment by metal tubes inserted into grooves before welding a lid on top. In Fig. 20c there is shown a cuvette welded from two symmetrical PVDF parts. The height of the grooves in which the metal tubes had been placed before welding was 20 µm less than the outer diameter of the tubes (0.6 mm) and the side walls were produced with a slope of 45°. Thus, generating enough molten polymer for the sealing of the tubes during welding.

A micro reactor system was constructed from modular micro channels connected to each other by slip tip connectors (cf. Fig. 20d) [56]. This way, micro reactors can be adapted to the needs of a certain chemical reaction.

Three layers of micro channels from PVDF were ultrasonically welded on top of each other constructing a micro heat exchanger (cf. Fig. 20e) [22]. The dimensions of the micro channels of each layer are 600 µm, 400 µm, and 10 mm in width, depth, and length, respectively. Each layer was manufactured by ultrasonic hot embossing into a stack of four PVDF foils, 150 µm in thickness. For the inlets and outlets of the micro heat exchanger, a massive cylindrical piece of PVDF with a thickness of 10 mm and a diameter of 20 mm with drilled holes for connecting tubes was welded to the first layer of the heat exchanger. Warm water was fed through the middle layer while cold water was flowing through the outer layers. At a temperature difference of 44 °C between warm and cold water and a flow rate of 50 mL/h of the warm water, the heat exchanger achieved a heat transfer of 1 W.

An anemometric flow sensor was the first micro system generated by ultrasonic processing for a sensor application (Fig. 20f) [20]. The flow sensor consisted of a 100 µm high, 500 µm wide, and 1 cm long channel from PP crossed by a gold wire, 50 µm in diameter. For measurements with water the wire of the sensor was heated up with an electrical current by 15°C and the electrical resistance of the wire was measured. The wire is cooled by a water flow through the channel lowering the resistance. The responds time of the sensor was measured to be 24 ms.

8.3. Predetermined breaking points in yarns

Ultrasonic hot embossing was also employed patterning single polymer filaments, 400 µm in diameter [57]. The objective of this work was fabricating overload sensors for ropes. The ropes were braided from polymer yarns and some of the yarns were replaced by filaments radially patterned by ultrasonic hot embossing (Fig. 21). Ultrasonic hot embossing of a single breaking point is finished within less than 0.1 s. The cycle time for a period of 500 mm of the breaking points is 5 s. 7 km of filament have been micro patterned this way with an automatic embossing machine (Fig. 7) in 20 hours.

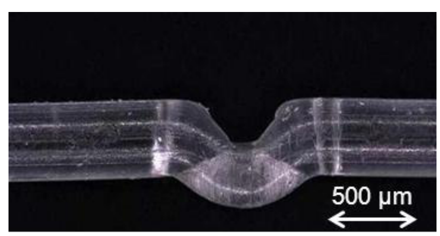


Fig. 21: Predetermined breaking point in a PA filament [57].

The filaments patterned by ultrasonic hot embossing were covered with a silver layer and a layer of thermoplastic polyurethane. With the silver layer an electrical resistance of 700 to 1000 Ω/m was achieved. When a rope is overloaded, the predetermined breaking point breaks and this can be detected by measuring the resistance even a long time after the overload has occurred.

8.4. Electronic circuit boards

Another promising application of ultrasonic hot embossing is the fabrication of electronic circuit boards [58]. If the polymer foil next to the tool in a stack is covered with an electrical conductive layer such as 20 µm copper, that layer can be punched out and transferred into the insulating polymer. This way, several levels of conductor paths are generated in a second. Different levels are insulated from each other if the tool has perpendicular side walls (cf. Fig. 22). If the side walls are sloped, also a conductive connection between different levels can be established.

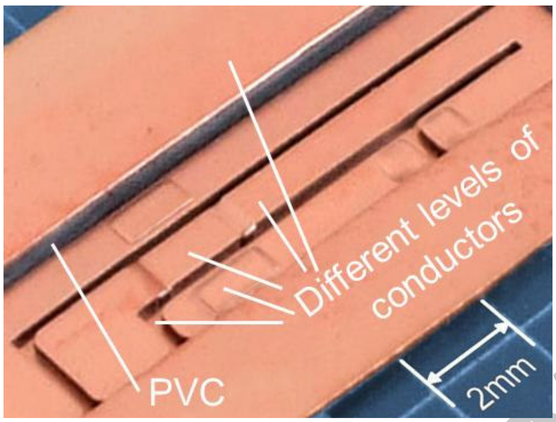


Fig. 22: Electronic circuit board fabricated by ultrasonic hot embossing [58].

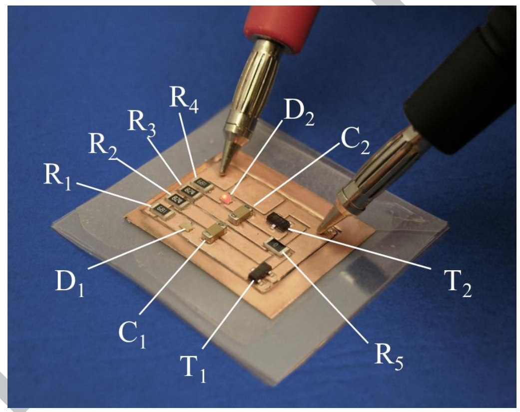


Fig. 23: Multivibrator circuit fabricated by ultrasonic hot embossing and ultrasonic welding [58].

Since soldering on top of a polymer foil is not possible, electrical connections to electronic components are established by ultrasonic welding: The electronic components are placed onto a holder such, that their contact pads are on the same level (Fig. 24a). Then a so called anisotropic conductive foil is placed on top of the electronic elements. The anisotropic conductive foil is from a thermoplastic polymer containing conductive particles distributed so rarely that they are not in touch to each other. The electronic board is pressed down onto this arrangement and ultrasonically welded to the electronic components (Fig. 24b). When the anisotropic conductive foil is compressed by ultrasonic welding, the conductive particles in it get in contact to the contact pads on one side and to the conductors paths on the opposite side of the foil. This way, both the electrical contacts and the fixation of the electronics on the board are provided in approximately 0.3 s. Figure 23 shows a multivibrator circuit fabricated this way, containing 5 resistors, 2 capacitors, 2 transistors, and 2 LEDs. When the circuit is supplied with 5 V, the two LEDs are flashing alternately with a frequency of 0.9 Hz.

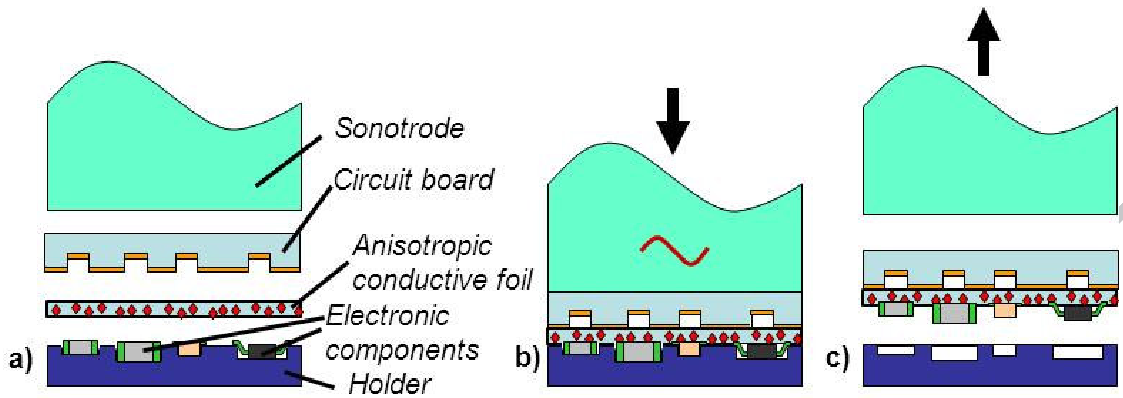


Fig. 24: Fabrication of an electronic board by ultrasonic hot embossing and welding.

9. *Conclusions*

Ultrasonic processing of thermoplastic polymers including ultrasonic hot embossing, welding, thermoforming, punching, and riveting are emerging techniques which have been proven being a valuable extension of the pool of micro fabrication approaches. The required equipment is affordable even for small enterprises and short cycle times of a few seconds enable economic fabrication also when only small-scale production is envisaged. On the other hand, scaling up to a roll-to-roll production is quickly done, and development times are significantly reduced compared to other replication processes.

Simple tools are manufactured in a few hours. Therefore, ultrasonic processing is also interesting for research institutions. Often it is quicker manufacturing a new device by ultrasonic processes than generating the corresponding mesh for FEM calculations. Therefore, the development processes for micro devices may also be altered by ultrasonic processing.

Principal limitations of the new processes are the maximum contact area between sonotrode and polymer and the maximum depth of embossed structures caused by the limited ultrasonic energy provided by ultrasonic welding machines. Besides this, the design needs to be adapted to the requirements of ultrasonic processing.

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Highlights

- Cycle times of a few seconds
- Investment costs of some 10.000 €
- Change of polymer type in a few minutes
- Fast change to a new design
- Economic for both small- and large-scale production