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## SPECIAL VARIANTS BASED EMBOSsing PROCESS FOR POLYMER MICROFABRICATION (A REVIEW)

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### ABSTRACT

Hot embossing is becoming an increasingly important alternative to silicon-and glass-based Microfabrication technologies. Continuous enhancement of this process, however, is needed to overcome some process limitations. Several special variants, including rapid-thermal-response embossing, room-temperature embossing, two-station embossing and localized embossing. By means of these embossing variants, economic efficiency and part quality can be enhanced for materials and geometries which are difficult-to-emboss can be incorporated.

**Keywords:** Polymer Microfabrication, Micromolding, Hot Embossing, Embossing,

### INTRODUCTION

Polymeric materials, due to their versatile properties and mass-production capability, have considerable advantages in Microfabrication [1-3]. One widely used technique in polymer microfabrication for conversion of raw materials into useful devices is hot embossing [4-6]. The popularity of this technique can be partially attributed to its simplicity in tool and process setup as compared with other competing techniques, such as microinjection molding. Hot-embossed polymer devices and systems have demonstrated a great commercial potential, especially for biomedical, telecommunication and optical applications.

However, hot embossing is subjected to some inherent process flaws limiting its capability. One major drawback is caused by the use of a large mass in thermal cycling, resulting in a long cycle time. The long dwell time at elevated temperatures could further result in degradation of the embossing polymer, especially for thermally sensitive polymers. The problem exacerbates when thick polymer substrates are used. Another drawback lies in the difficulty in reaching high embossing pressure and thus in replicating high aspect ratio features, because in nature hot embossing is an open-die compression molding process.

Several embossing-based process variants, including rapid-thermal-response embossing, room-temperature embossing, two-station embossing, and localized embossing, have been investigated for further improvement of the hot embossing process. The goal of the efforts is not only to enhance economical efficiency and replication fidelity, but also to expand the scope of the process capability. This paper will describe study and principles of the sevariant methods and discuss their salient features and advantages.

### **RAPID-THERMAL-RESPONSE EMBOSSING**

The hot embossing process involves several sequential steps. First, a preheated thermoplastic film is placed between two heated mold platens with temperature above the softening temperature of the polymer. The elevated mold temperature is considered necessary for pattern transfer because a cold mold will result in premature freezing of the polymer. Next, the polymer film is pressurized and shaped by closure of the mold and the micro features on one of the platens transfer to the polymer film. Finally, the entire embossing including the polymer and the mold is cooled to below the polymer softening temperature and the platens are separated for the removal of the embossed film. From these steps, it can be seen that thermal cycling of the mold is needed during hot embossing. An inherent problem with hot embossing is caused by the large thermal mass of the mold, which results in a slow rate of thermal cycling and consequently along cycle time.

To substantially reduce the long cycle time in hot embossing, an embossing process with ability or extremely rapid thermal cycling was investigated. During the process, the embossing tool can be rapidly heated to above the polymer softening temperature in less than a couple of seconds, pressed against a room temperature polymer substrate, and subsequently rapidly cooled for mold separation. Because of this salient feature, the new process variant is named rapid-thermal-response (RTR) embossing.

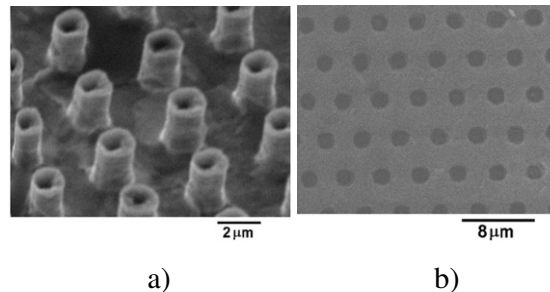
The key component in RTR embossing is the embossing mold with a rapid heating and cooling capability. To facilitate rapid thermal response, a low thermal mass should be used during thermal cycling. This can be accomplished by embedding inter-connected channels near the surface of the mold. The conformal air channels have two functions. First, they provide air pockets as thermal insulation during the heating stage. Second, they provide efficient cooling by passing pressurized air or nitrogen gas as coolants during the cooling stage. At the same time, the mold should have desired stiffness and strength to withstand the high pressure during the embossing stage. Design of this low-thermal-mass mold can be facilitated with the aid of computer-aided engineering tools. Heat can be introduced to the mold surface in different ways, including electrical heating and hot air heating.

### **ROOM-TEMPERATURE EMBOSSING**

The room-temperature embossing variant is derived from polymer solid-phase forming, resembling more the metal forging method than the standard thermoplastic melt-processing protocol. Therefore, the polymer is deformed in the solid state during the process. One advantage of using polymer forging for microfabrication is due to its stability in handling relatively thick substrates. Further, when the forging process is carried out at low temperatures or even room temperature, the cooling process can be eliminated, thus greatly enhancing productivity.

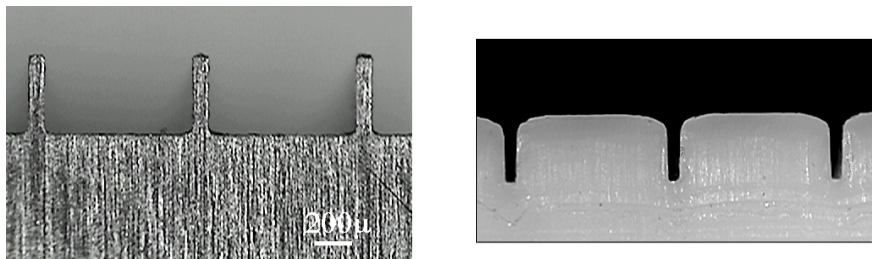
The main hurdle in polymer solid-phase forming is the elastic recovery or spring back. A polymer appropriate for room-temperature embossing should thus have low spring back. Further, high ductility of the material is desired, thus permitting large strains during the process. In general,

semi crystalline polymers such as nylon 6, poly(tetra-fluoro-ethylene) (PTFE), and polypropylene have much better room-temperature formability than amorphous glassy polymers.



**Figure 1:** RTR embossing of microholes on PMMA substrates:  
a) The master and b) The embossed microhole array

Different miniaturized features including micro square and hexagonal wells, micro circular holes, and submicron surface features were successfully produced with substantially shortened cycle times. Figure 2 shows an example.



**Figure 2:** Shows the tool patterns and the channels replicated on the PTFE substrate

High repeatability in terms of the consistency of forged channel dimension and quality were observed in the experiments. However, the dimension of forged channels was found to be dependent on several process variables, mainly the forging pressure, the forging speed and the dwell time, as well as the geometrical shape of the channel. While a prediction capability is still awaited, suitable applications of polymer room-temperature embossing could be among devices with relatively low dimensional accuracy requirement, such as scaffolds for tissue engineering and heat convective surfaces for electrical packaging.

## TWO STATION EMBOSSING

With the same driving force as that for RTR embossing, the two-station embossing variant was devised to shorten the cycle time in hot embossing. However, the two-station embossing technique is not rely on complex design of the mold insert in achieving a low-thermal-mass mold insert, but rather it is more or less developed as an strategy for rapid thermal cycling.

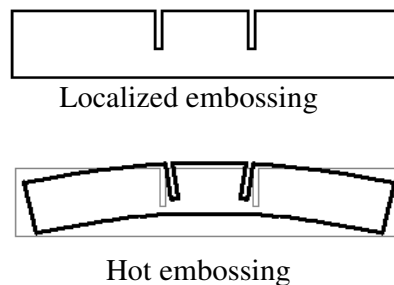
It is noted that an embossing tool typically consists of two parts: a thin stamp with a thickness of 2mm or less and a backup base. The material for the stamp can be silicon, glass, quartz, nickel, steel, or other similar materials although a durable metallic embossing, the stamp is fastened to the base to form an integrated embossing tool while heaters and cooling channels are embedded in the base to thermally regulate the entire embossing tool.

Based on the unique design of the embossing tool, a two-station embossing strategy is devised. Instead of using one backup base, two bases are employed; one is maintained at a constant hot temperature and the other is maintained at a constant cold temperature. During the embossing stage, the hot base is used as the supporting backup for the stamp. When the embossing stage finished, the backup switches to the cold base. With this tool setup strategy, the ideal embossing condition of decoupled heating and cooling can be approximated. The attachment and separation of the stamp and the two bases can be achieved in an on- mechanical manner, e.g. using vacuum force or electromagnetic force.

## LOCALIZED EMBOSSING

Localized embossing is a processing strategy for rapidly and accurately embossing micro/nano features on thick polymer substrates, by locally melting and deforming the micro/nano feature on the cold substrate. Localized embossing can significantly improve the quality and dimensional accuracy of replicated features owing to an uncoupling of microfabrication with macrofabrication.

Different from the standard hot embossing process, localized embossing employs a cold polymer substrate as a starting material. The substrate can be as thick as a few millimeters. It should be pointed out that thick substrates are highly desired in numerous miniaturization applications for the purpose of reliable alignment and assembly. During localized embossing, only localized materials are melted and deformed. This embossing strategy is considered to be an add-on to the RTR embossing and two-station embossing techniques. Localized melting is accomplished by pressing a rapidly heated stamp with protruded features against the cold substrate. When the heated die contacts the polymer substrate, localized melting occurs at the contacting locations between the substrate and the to- be-replicated microstructures. The resulting melts are confined locally, forming localized spots for compression molding. As long as the localized replication is finished, the tool is rapidly cooled to allow a minimal thermal load to the substrate during the entire process.



**Figure 3:** Benefit of uncoupling microfabrication from macrofabrication

Localized embossing improves quality and dimensional accuracy of replicated micro channels due to uncoupling of microfabrication from macro- fabrication. When the substrate and the micro channel are embossed at the same time, as occurs in the standard hot embossing process, any error or dimensional change of the substrate, which is deemed to be minor for macro applications, will be disastrous to the assembly and alignment of the microchannel. Localized embossing does not change the shape and dimension of the substrate during the embossing stage, thus eliminating coupling effects. The benefit of uncoupling microfabrication from macrofabrication is illustrated in Figure 3.

## SUMMARY

The above variants to the hot embossing process are mainly targeted for the further improvement on productivity and replication fidelity. Because of the low thermal load to the polymer during embossing, these variants will also significantly lower the possibility of material degradation during the process. Difficult-to-emboss materials, e.g. ultra-high-molecular-weight polyethylene and PTFE can be processed using the room-temperature embossing process.

The room-temperature embossing technique, however, is subjected to the spring back problem. An accurate simulation capability for room-temperature embossing needs to be developed to guide tool design and process setup. While the trial-and-error approach is expensive and time consuming, some fast design rules also need to be developed. Although the basic scenario may be similar to that in the typical extrusion practice where swell needs to be compensated die, the understanding on solid-state large deformation of polymers is a priori in room-temperature embossing. Research in this area may also be on the identification or development of more appropriate materials, which have a minimal amount of elastic recovery similar to metals.

The range of materials suitable to embossing-based processes should be expanded. Materials with improved mechanical properties, e.g. metals and ceramics may be good candidates. Similar protocols to the powder injection molding process may be adapted to the embossing process to allow high performance metallic and ceramic parts to be produced. Filled polymers with nano particulates should also add a value to the capability of embossing-based processes. Techniques for sequentially or simultaneously embossing two or more materials are also awaited to be developed in the near future. Polymers with different hardening mechanisms other than physical solidification, e.g. unsaturated pre-polymers, will greatly expand the material base for embossing.

In terms of the hot embossing process itself, other limitations such as the difficulty in building up pressure during the embossing stages should also be addressed. For this reason, hybrid processes need to be developed. Although the limitation in pressure has been partially addressed recently [11], there is still much room for improvement. Some traditional manufacturing techniques, like close-die embossing, may provide a simple solution to the problem.

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